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25 April 2012

Mr. Reid Rosnick
Chairman
Subpart W Rulemaking
United States Environmental Protection Agency
Headquarters, Ariel Rios Building
1200 Pennsylvania Avenue, N.W.
Mail Code: 6608J
Washington, DC 20460

Dear Mr. Rosnick:

Subject: Kennecott Uranium Company's Comments on the Review of 40 CFR Part 61 Subpart W

Kennecott Uranium Company is a uranium recovery licensee holding Nuclear Regulatory Commission Source Material License SUA-1350. Kennecott Uranium Company is the licensee, operator and manager of the Sweetwater Uranium Project a conventional uranium processing facility currently on standby in Sweetwater County, Wyoming.

Kennecott Uranium Company has been following and participating in the review of 40 CFR part 61 Subpart W since the presentation that you gave at the National Mining Association (NMA)/Nuclear Regulatory Commission (NRC) Uranium Recovery Workshop on April 30, 2008. Kennecott Uranium Company has participated in the quarterly conference calls and has conducted experimental work related to radon fluxes from water surfaces, which is discussed in these comments.

Kennecott Uranium Company has the following comments regarding 40 CFR Part 61 Subpart W, the review of it, potential expansion of it to include fluid retention impoundments and on radon emissions from licensed uranium processing including uranium mill tailings impoundments:

History of 40 CFR part 61 Subpart W

The inception of 40 CFR part 61 Subpart W can be traced to 1977 when Congress amended the Clean Air Act to address emissions of radioactive materials, pollution that may reasonably be expected to endanger public health. On December 27, 1979, EPA published a notice in the Federal Register listing radionuclides as hazardous air pollutants under Section 112 of the Act (44 FR 76738, December 27, 1979). To support this determination, EPA published a report entitled "*Radiological Impact Caused by Emissions of Radionuclides into Air in the United States, Preliminary Report*" *(EPA 520/7-79-006, Office of Radiation Programs, U.S. EPA, Washington, D.C., August 1979).*

On June 16, 1981, the Sierra Club filed suit in the U.S. District Court for the Northern District of California pursuant to the citizens' suit provision of the Act (Sierra Club v Gorsuch, No. 81-2436 WTS). The suit alleged that EPA had a nondiscretionary duty to propose standards for radionuclides under Section 112 of the Act within 180 days after listing them. On September 30, 1982, the Court ordered EPA to publish proposed regulations establishing emissions standards for radionuclides, with a notice of hearing within 180 days of the date of that order.

On April 6, 1983, EPA published a notice in the Federal Register proposing standards for radionuclide emission sources in four categories: (1) DOE facilities, (2) Nuclear Regulatory Commission facilities, (3) underground uranium mines, and *(4)* elemental phosphorus plants. This notice was supported by a draft report entitled "*Background Information Document, Proposed Standards for Radionuclides" (EPA 520/1-83-001, Office of Radiation Programs, U.S. EPA, Washington, D.C., March 1983)*.

On February 17, 1984, the Sierra Club again filed suit in the U.S. District Court for the Northern District of California pursuant to the citizens' suit provision of the Act (Sierra Club v Ruckelshaus, No. 84-0656 WHO). The suit alleged that EPA had a nondiscretionary duty to issue final emissions standards for radionuclides or to find that they do not constitute a hazardous air pollutant (i.e., "de-list" the pollutant). In August 1984, the Court granted the Sierra Club motion and ordered EPA to take final actions on radionuclides by October 23, 1984.

On February 6, 1985, National Emission Standards for Hazardous Air Pollutants (NESHAPS) were promulgated for radionuclide emissions from DOE facilities, NRC-licensed and non-DOE Federal facilities, and elemental phosphorus plants (50 FR 5190). Two additional radionuclide NESHAPS, covering radon-222 emissions from underground uranium mines and licensed uranium mill tailings, were promulgated on April 17, 1985 (50 FR 15386) and September 24, 1986 (51 FK 34056), respectively.

The EPA's basis for the radionuclide NESHAPS was challenged in lawsuits filed by the Sierra Club and the National Resources Defense Council (NRDC).

The National Emission Standards for Hazardous Air Pollutants; Regulation of Radionuclldes – Proposed Rule was published in the Federal Register on March 7, 1989. (Federal Register / Vol. 54, No. 43 / Tuesday, March 7, 1989 / Proposed Rules). The final rule National Emission Standards for Hazardous Air Pollutants; Radionuclldes was published in the Federal Register on Friday, December 15, 1989 (Federal Register / Vol. 54, No. 240 / Friday, December 15, 1989 / Rules and Regulations).

The Agency created the rule (40 CFR Part 61 Subpart W) in response to perceived risks to public health from radon emanating from uranium mill tailings impoundments.

Rationale for/Basis of the Rule

In the1989 proposed rule, the Agency provides the basis for the rule stating:

> *Radon is a radionuclide that is produced as a radioactive decay product of the radium which is naturally found in soil. Radon is always present in the ambient air where it poses some health risk. In addition, radon often gets trapped in homes, leading to even higher health risks. EPA has issued recommendations to homeowners for reducing these risks.*
>
> *This rulemaking deals with sources of radionuclide emissions, including radon from industrial sources. Although the amount of radiation dose that most people receive as a result of these emissions is lower than their natural background dose, the resulting risk can still be significant. A source does not present an acceptable risk simply by being less than natural background. It is important to note that total background radiation from all sources. Including naturally occurring radon, results in a calculated maximum lifetime risk of fatal cancer of approximately 1 XI0- 2• In most cases, little can be done to reduce most of this radiation exposure which people receive from natural background.*

The Agency in the proposed rule and in an associated risk assessment document discussed radon risk and procedures for determining that risk. The proposed rule continues by stating:

> *For sources that emit radon, no genetic or developmental effects and very few nonfatal cancers are expected.*
> (Federal Register / Vol. 54, No. 43 / Tuesday, March 7, 1989 / Proposed Rules page 9615)

The proposed rule discussed risk estimation procedures stating:

> *In estimating the radiation exposure to the meet exposed individual, EPA assumes that the person receiving the maximum individual risk lives for a lifetime, an average of 70 years, at the same site. EPA has assumed, a priori, that the person exposed to the maximum individual risk lives at the point of maximum exposure his whole life. EPA then makes its best estimate of the risks to the individual of living his entire lifetime under a set of certain conditions.*

The Science Advisory Board (SAB) commented on the proposed rule and the risk assessment in particular stating:

> *EPA should rigorously derive quantified uncertainty estimates for each risk assessment.*

The Agency's response was as follows:

> *This is a large task. For the short term, prior to the final rule, we will perform parameter sensitivity analysis of the most important parameters using simplifying assumptions. For the long term, an Agency task group has been formed to plan and conduct more complete studies of the uncertainty question. This longer term effort will take a number of years to complete.*
>
> *EPA acknowledges the uncertainty in risk estimates, considers them when making risk management decisions and recognizes that a quantitative expression of uncertainty would be an improvement. However, it does not believe that the quantitative expression of uncertainties, which are themselves uncertain to a degree, would change the decisions made in this rulemaking. For a more complete discussion of uncertainty, see chapter 7, Volume 1 of the EIS.*

In the proposed rule, the Agency discussed operating uranium mill tailings piles and made certain assumptions including:

> *Emissions were estimated from the radium-226 concentrations in the tailings, the amount of tailings and the assumption that 1 pCi/g of radium-226 in the tailings produces 1 pCi/m^2 -sec of radon.*

The Agency continued by stating:

> *There are twelve licensed piles that are either operating or on standby. According to EPA's analysis, the lifetime fatal cancer risk to the most exposed individual is 3.3 X 10^{-3} from these twelve piles. Uranium mill tailings are estimated to cause 1.6 fatal cancers per year to the 4.5 million persons within 80 km of the tailings piles.*

Appendices 18 and 19 contain two (2) epidemiological studies by Dr. John Boice that contradict this analysis. They examine cancer rates in two (2) uranium producing counties for fifty (50) years. Dr. Boice finds no excess cancers in these counties.

In addition a portion of the basis of the risk estimates is the assumption that an individual will reside at the point of maximum exposure his or her entire life, which is estimated at seventy (70) years. This assumption is unrealistically long.

Appendix 32 contains a paper entitled "Five-Hundred Life-Saving Interventions and Their Cost-Effectiveness". Among the highest cost (in dollars per life year saved) are interventions involving control of radionuclide emissions. The table below lists some of the interventions and their cost per life-year saved:

Intervention	**Cost/life-year**
Radionuclide emission control at operating mill tailings	$11,000,000
Radionuclide emission control during disposal of uranium mill tailings piles	$40,000,000

The Final Rule was issued on December 15, 1989. In it, the Agency made the following statement regarding the risks associated with operating uranium mill tailings impoundments:

> *EPA estimates that the lifetime fatal cancer risk to the most exposed individual is 3X10^{-5} from the twelve licensed piles that are either operating or on standby. Uranium mill tailings are estimated to cause 0.004 fatal cancers per year, approximately 1 case every 250 years to the 2 million persons within 80 km of the tailings piles. This risk is much lower than the estimated risks presented in the proposed rule. The reason for the great reduction in the risk calculated is that EPA has received and confirmed information during the comment period that these piles are mostly wet or covered with clay. This greatly reduces the rate of radon emissions from the piles, greatly reducing the risks that they pose.*

The Agency continued by stating:

> *As explained above, the risks from current emissions are very low. A NESHAP requiring that emissions from operating mill tailings piles limit their emissions to no more than 20 pCi/m2-s represents current emissions. EPA has determined that the risks are low enough that it is unnecessary to reduce the already low risks from the tailings piles further.*

In *Risk Assessments Methodology Environments Impact Statement NESHAPS for Radionuclides - Background Information Document Volume 1* the Agency discussed its approach to the estimation of radon risk stating:

> *The Agency's estimates of the risk of lung cancer due to inhaled radon progeny do not use a dosimetric approach, but rather are based on what is sometimes called an epidemiological approach: that is, on the excess human lung cancer in groups known to have been exposed to radon progeny.*

The two (2) epidemiological studies included in Appendices 18 and 19 (Cancer Mortality in a Texas County with Prior Uranium Mining and Milling Activities, 1950-2001; Boice, J.D. Jr. et al and Cancer and Non-Cancer Mortality in Populations Living Near Uranium and Vanadium Mining and Milling Operations in Montrose County, Colorado, 1950-2000; Boice, J.D. Jr. et al) show no excess cancers in the populations of these counties over a fifty (50) year period. The Agency should consider these studies in their epidemiological approach.

Experience with Radon Flux Measurements at the Sweetwater Uranium Project

The Sweetwater Uranium Project has a single sixty (60) acre (top surface area) single lined (30 mil Hypalon) partially below grade tailings impoundment containing 2 ½ million tons of tailings, additional contaminated soils from remediation activities on site and other 11(e).2 byproduct material. Method 115 tests required by 40 CFR part 61 Subpart W have been performed on this impoundment beginning in the summer of 1990 for a total of twenty-two (22) such tests. The results are summarized below:

Reported Test Results

Year	**Flux - Beaches** (pCi/M2-Sec)	**Flux – Impoundment as a Whole** (pCi/M2-Sec)
1990	19.90	9.00
1991	10.60	5.10
1992	10.60	5.60
1993	9.80	5.00
1994	8.94	5.00
1995	6.00	3.59
1996	8.85	5.47
1997	7.20	4.23
1998	4.33	2.66
1999	2.32	1.27
2000	7.63	4.05
2001	12.16	6.98
2002	6.57	4.10
2003	11.40	7.11
2004	10.40	6.38
2005	10.70	7.63
2006	4.80	3.37
2007	8.50	6.01
2008	7.26	4.59
2009	5.65	1.60
2010	7.02	1.44
2011	10.59	2.17
Average:	**8.69**	**4.65**
Median:	**8.69**	**4.80**
Maximum:	**19.90**	**9.00**
Minimum:	**2.32**	**1.27**
Standard Deviation:	**3.57**	**2.08**

Source: Annual Method 115 Test Reports, August 1990 to August 2011.

These results are very low. The twenty (20) year average for the impoundment as a whole is 4.65 pCi/M2-sec. The average for the exposed tailings is 8.69 pCi/m2-sec.

In the proposed rule the Agency stated:

> *Emissions were estimated from the radium-226 concentrations in the tailings, the amount of tailings, and the assumption that 1 pCi/g of radium-226 in the tailings produces 1 pCi/m^2 -sec of radon.*

This estimate of flux rate based upon radium-226 activity in the tailings is incorrect at least as far as the tailings at the Sweetwater Uranium Project are concerned. The average Radium-226 activity of the tailings at the Sweetwater Uranium Project is 70.9 picoCuries per gram (Final Design – Volume VI – Existing Impoundment Reclamation Plan – August 26, 1997 – Table A-5 included in Appendix 1) while the twenty-two (22) average flux rate for exposed tailings is 8.69 picoCuries per meter 2-sec. Table A-5 is included in Appendix 1 for reference. This data gathered over twenty-two (22) years does not support a relationship of 1 pCi/g of radium-226 in the tailings to 1 pCi/m^2 -sec of radon in this case. In assessing radon fluxes from tailings and radon risks from tailings impoundments a more realistic and probably site specific relationship should be used. Not all Radon-222 created by the decay of Radium-226 in tailings is released, which is why material specific emanation coefficients (radon release fractions) must be measured for each tailings type. Site specific emanation coefficient data is available (Rogers and Associates) and provided in chart form in Appendix 1.

All uranium mill tailings do not emit radon at the same rates. The rate at which radon is released from tailings is governed by a material dependent properties called the *emanation coefficient*.
Emanation coefficient is defined as follows:

> *The radon emanation coefficient, E, is the fraction of radon that is released from the tailings or soil matrix into the pore space.*
> Source: Regulatory Guide 3.64 - Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers

The average emanation coefficient for the tailings at the Sweetwater Uranium Project as determined by testing of tailings samples by Energy Laboratories, Inc. is 0.188 and is shown on table A-5 included in Appendix 1. A second chart entitled Figure 15 – Radon Emanation Coefficients for Tailings Samples is also included in Appendix 1. This table prepared by Rogers and Associates shows emanation coefficients for various uranium mill tailings sites throughout the western United States. This table shows that only a fraction of the radon generated by the decay of radium in uranium mill tailings is actually released into the pore space. The emanation coefficient varies by site (it is a material dependent property) and as such a single fixed relationship between radium activity and flux rate cannot be applied across all tailings sites.

Regulatory Guide 3.64 – Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers, uses a default emanation coefficient of 0.35 which is to be used in the absence of site specific data in radon barrier design calculations.

In conclusion, twenty-two (22) years of radon flux measurements at the Sweetwater Uranium Project have shown that:

- Average radon fluxes for tailings are substantially less than 1 picoCurie/m2-sec per picoCurie per gram Radium-226, the relationship discussed in the proposed rule. In fact at the Sweetwater Uranium Project the average radon flux is approximately 12.2% of the amount predicted by the relationship discussed in the proposed rule.
- The material specific emanation coefficient plays a large role in the actual radon flux rate.

Radiological Background Considerations

40 CFR Part 61 Subpart W makes no mention of radiological background. 40 CFR § 61.252 sets a 20 picoCurie/M2-sec standard for existing impoundments and two (2) acceptable work practices for new impoundments. The radon flux standard does not consider either background radon in the ambient air or background radon fluxes from undisturbed soils in the site vicinity.

In the 1989 proposed rule the Agency states:

> *Radon is a radionuclide that is produced as a radioactive decay product of the radium which is naturally found in soil. Radon is always present in the ambient air where it poses some health risk. In addition, radon often gets trapped in homes, leading to even higher health risks. EPA has issued recommendations to homeowners for reducing these risks.*
>
> *This rulemaking deals with sources of radionuclide emissions, including radon from industrial sources. Although the amount of radiation dose that most people receive as a result of these emissions is lower than their natural background dose, the resulting risk can still be significant. A source does not present an acceptable risk simply by being less than natural background. It is important to note that total background radiation from all sources. Including naturally occurring radon, results in a calculated maximum lifetime risk of fatal cancer of approximately 1 Xl0- 2• In most cases, little can be done to reduce most of this radiation exposure which people receive from natural background.*

The Nuclear Regulatory Commission (NRC) considers background in its regulations and standards, defining it in 10 CFR Part 20.1003 Definitions as follows:

> *Background radiation means radiation from cosmic sources; naturally occurring radioactive material, including radon (except as a decay product of source or special nuclear material); and global fallout as it exists in the environment from the testing of nuclear explosive devices or from past nuclear accidents such as Chernobyl that contribute to background radiation and are not under the control of the licensee. "*Background radiation*" does not include radiation from source, byproduct, or special nuclear materials regulated by the Commission.*

When the Commission examines doses to workers or to the general public it looks at doses above background and requires that licensees consider background in dose calculations.

In the proposed rule the Agency stated:

> *A source does not present an acceptable risk simply by being less than background.*

The issue is not that doses people receive from tailings impoundments are *less than their natural background dose,* but rather that they are indistinguishable from their background dose and lost within the natural variability of background, at least as far as the Sweetwater Uranium Project is concerned.

Uranium processing operations are located in uraniferous areas which have elevated naturally occurring levels of natural uranium and its decay products including Radium-226 (Radon-222's immediate precursor) in surrounding soils. To the northwest of the Sweetwater Uranium Project is Lost Creek. This area was described in United States Geological Survey (USGS) Bulletin 1087-J – Geology of the Lost Creek Schroeckingerite Deposits Sweetwater County, Wyoming. This bulletin describes an area that was sampled by extensive trenching by the United States Geological Survey (USGS). 820 samples were collected from the trenches and analyzed for both chemical uranium and gamma (radiometric) equivalent uranium. Analysis for gamma (radiometric) equivalent uranium is performed by the closed can method in which a weighed and dried quantity of sample is placed in a steel soil sampling container that is sealed. Radium-226 in the sample (from the decay of the Uranium-238) decays to Radon-222 which further decays to Bismuth-214 which has a distinctive 609.3 keV gamma photon. The sample is generally allowed to decay (ingrow) for ten (10) half lives of Radon-222 to assure that the Radon-222 and its decay products including Bismuth-214 reach radiometric equilibrium with the Radium-226 in the sample. This gamma energy is counted and a Bismuth-214 activity is calculated. Since the Bismuth-214 is in equilibrium with the Radon-222 and Radium-226 in the sample, the activities of the Radium-226 and Radon-222 are the same as the activity of the Bismuth-214. It is then assumed that the activity of the Uranium-238 in the sample is the same as that of the Radium-226 to calculate the concentration of gamma equivalent uranium. The sample is also analyzed for actual uranium to get a true (as opposed to gamma equivalent) uranium grade. The true versus gamma equivalent uranium grades are compared to determine an equilibrium factor for the material. The gamma equivalent uranium grade can be used to calculate the Radium-226 activity for the sample. This is done by converting the gamma equivalent grade to a Uranium-238 activity which equals the Radium-226 activity measured during the closed can analysis. This was done by Kennecott Uranium Company for the sample data presented in the paper. The results are included in the six (6) spreadsheets in Appendix 2. These sheets show the naturally occurring elevated concentrations of Radium-226 in nearby near-surface soils. Calculated Radium-226 activities vary from 0 to 10,208 picoCuries per gram. These Radium-226 concentrations would create high radon fluxes for the soils and potentially elevated levels of background radon in ambient air in the area and down wind of it.

These types of elevated naturally occurring Radium-226 concentrations in soils are not unique to areas around the Sweetwater Uranium Project. Appendix 3 contains a spreadsheet entitled **Non-Random Background Soil Radiometric Data** for the UMETCO Gas Hills site. This data was kindly provided by UMETCO. The Radium-226 activities vary from 0.8 to 504 picoCuries per gram. Again, these soils would have high radon fluxes with associated elevated activities of Radon-222 in the ambient air above these areas and down wind of them.

During the course of an excavation at the Sweetwater Uranium Project an area with elevated gamma radiation was discovered. A sample was collected in this area. This material is described below in an excerpt from the Catchment Basin Excavation Completion Report submitted to the Nuclear Regulatory Commission (NRC) on May 6, 2008 which is included in Docket Number: 040-08584:

Ore was unambiguously present in the Catchment Basin Excavation area. An area of anomalous material was discovered in and around Grid K minus 3. Sample results for it are in the table on the following page.

This anomalous material was sampled and tested as per the results above and photographed. Images of the material are shown below:

Source: Catchment Basin Excavation Completion Report – May 6, 2008

A pen has been included for scale. This image was taken on April 25, 2007, the sample date that the samples were collected.

											FINAL		Equilibrium			
Location	**Sample Type**	**Northing**	**Easting**	Diesel Range Organics (milligrams per kilogram)	Oil Range Hydrocarbons (milligrams per kilogram)	Total Extractable Hydrocarbons (milligrams per kilogram)	Natural Uranium (milligrams per kilogram)	Natural Uranium (picoCuries per gram)	Uranium-238 (picoCuries per gram)	Thorium-230 (picoCuries per gram)	Thorium-230 - Uncertainty (picoCuries per gram)	Result (picoCuries per gram)	Uncertainty (picoCuries per gram)	Uranium-238/ Thorium-230 (picoCuries per gram)	Thorium-230/ Radium-226	Uranium-238/ Radium-226	Moisture (percent)
K Minus 3 NORM Area	Black Material	148982.97	324146.97	226	804	1000	2550.00	1726.35	860.78	393.0	17.0	396	9	2.19	0.99	2.17	36.4
K Minus 3 NORM Area	Sand	148982.97	324146.97	211	650	834	2350.00	1590.95	793.27	708.0	29.0	326	6.4	1.12	2.17	2.43	18.4

Source: Catchment Basin Excavation Completion Report – May 6, 2008

A close-up image taken on the same date is included below. Please note the yellowish grains in the image's center. These grains are undoubtedly an oxidized uranium mineral such as gummite, autunite, carnotite, or zipeite.

Source: Catchment Basin Excavation Completion Report – May 6, 2008

Following receipt of the analytical results from the laboratory, the sample was sent for petrographic analysis. The results for the petrographic analysis are included in Appendix 4.

The analysis concludes:

> *"…the organic matter contained in sample #C07051289-001A were derived from terrestrial plants with secondary woody tissues that have gone through at least the initial stage of coalification. Depending upon stratigraphy and sample location in the field, the type and condition of organic matter and mineralization observed suggests that it is naturally occurring."*
> Source: Petrographic Evaluation of Sample #C07051289-001A, Catchment Basin Excavation Completion Report – May 6, 2008

The organic matter, the natural uranium occurring with it along with any decay products are natural and part of background and the radiation emitted from it is background radiation as defined in 10 CFR Part 20.1003 Definitions which states:

> *Background radiation means radiation from cosmic sources; naturally occurring radioactive material, including radon (except as a decay product of source or special nuclear material); and global fallout as it exists in the environment from the testing of nuclear explosive devices or from past nuclear accidents such as Chernobyl that contribute to background radiation and are not under the control of the licensee. "Background radiation" does not include radiation from source, byproduct, or special nuclear materials regulated by the Commission.*

This material with a Radium-226 activity in excess of 300 picoCuries per gram was within ten (10) feet of the ground surface and can create high radon fluxes at the ground surface.

Another area at the Sweetwater Uranium Project was discovered to have high background Radium-226 activity. The bottom of an excavation from which diesel contaminated soils were removed had elevated radium-26 concentrations in the excavation wall. The sampling results are shown in a spreadsheet entitled South Pit Wall Uranium Study included in Appendix 5. These samples vary in Radium-226 activity from 44.1 to 379 picoCuries per gram

In conclusion, naturally occurring background Radium-226 activities in soils around uranium recovery sites can be very high, creating high surface radon fluxes and high concentrations of Radon-222 in ambient air. These areas are, after all, uranium mining areas and uranium extraction activities would not be conducted in these areas unless there were substantially elevated concentrations of natural uranium and its decay products including Radium-226, the immediate precursor of Radon-222, present.

The issue of the variability of background and its impact on doses to the general public is explored more fully in the document entitled, " *In Search of ….Background*" dated November 29, 1994 by Dr. Gail LaPlenque a former member of the Nuclear Regulatory Commission. This document is included in Appendix 17.

In the document Dr. LePlenque discusses a dose based release standard for decommissioned sites. She states:

> *…15 mrem over a 70-year lifetime would result in a risk of about 0.04% yet another decade lower on this log scale. When added to the risks associated with low, average, and high annual doses from background it is barely distinguishable (Figure 7). Indeed, 15 mrem represents 5% of the annual average dose and is lost within the range of background…*

This statement is applicable to the issue of radon emissions from impoundments as well, especially in the case of the Sweetwater Uranium Project, where the average measured dose in the Security Trailer is 0.61 millirems and indistinguishable from background, given its natural variability. (Please see Appendix 7.)

Clearly these high naturally occurring Radium-226 activities in soils around uranium recovery sites can also create high soil radon fluxes in soils in the area. These elevated fluxes are entirely natural. When conducting the required annual Method 115 Test in the tailings impoundment at the Sweetwater Uranium Project, Kennecott Uranium Company has since 1991. The background radon flux results are included in Appendix 6 in a spreadsheet entitled Background Radon Flux.

The following are the statistics for the background radon flux measurements taken around the site area treating non-detects (results listed as <0.5 as a flux of 0.5):

Overall Average - Site Area:	17.5	pCi/M2-Sec
Overall Median - Site Area:	8.3	pCi/M2-Sec
Overall Maximum - Site Area:	114.0	pCi/M2-Sec
Overall Minimum - Site Area:	0.5	pCi/M2-Sec
Overall Standard Deviation - Site Area:	25.6	pCi/M2-Sec

Source: Annual Method 115 Test Reports – August 1991 to August 2011

The average background radon flux for the site area is almost equal to the flux limit for an existing impoundment in 40 CFR part 61 Subpart W and exceeds the flux from the tailings impoundment. One location has varied through the years (1991 to 2011) from 2.2 to 114.0 picoCuries per meter2-second.

The Nuclear Regulatory Commission (NRC) has required upwind and downwind radon flux measurements to be taken for the Sweetwater Uranium Project under Source material License SUA-1350. The data below is upwind (background/ambient) radon concentrations in air taken using the

Landauer, Inc. Radtrak device read to high precision from April 1, 1991 to July 1, 2011 a period of twenty (20) years.

Sweetwater Upwind/Background Radon Concentrations
April 1, 1991 to July 1, 2011

AVERAGE	**3.29**	pCi/L
MINIMUM	**090**	pCi/L
MAXIMUM	**6.40**	pCi/L
STD. DEV.	**1.06**	pCi/L
VARIANCE	**1.12**	pCi/L

Source: Semiannual 40.65 Reports submitted to the Nuclear Regulatory Commission

The data below is downwind radon concentrations in air taken using the Landauer, Inc. Radtrak device read to high precision from April 1, 1991 to January 1, 2010 a period of almost nineteen (19) years.

Sweetwater Downwind Radon Concentrations
April 1, 1991 to July 1, 2011

AVERAGE	**2.72**	pCi/L
MINIMUM	**1.00**	pCi/L
MAXIMUM	**4.70**	pCi/L
STD. DEV.	**0.80**	pCi/L
VARIANCE	**0.64**	pCi/L

Source: Semiannual 40.65 Reports submitted to the Nuclear Regulatory Commission

The period from April 1, 1991 to July 1, 2011 was chosen since on April 1, 1991 the facility changed from using a Passive Radon Monitor (PRM) supplied by Aerovironment to RadTrak detectors provided and read by Landauer, Inc. It is better to evaluate and compare data collected by a single, currently used, method. In addition, during the period of time when monitoring was performed by the Passive Radon Monitor (PRM) method, the location of the downwind monitoring station was moved on March 1, 1984. This time period (April 1, 1991 to July 1, 2011) roughly coincides with the period of Method 115 Testing (August 1990 to August 2011).

The average downwind radon concentrations (downwind of the facility and the tailings impoundment) are less than the upwind concentrations and not by just a small fraction but by approximately 18%, in spite of the fact that the detector is approximately 0.54 miles downwind of the impoundment. If radon emissions from tailings impoundments constituted a major risk then it should be possible to measure the contribution to radon in air from the impoundment, which it is not possible to do at the Sweetwater Uranium Project.

Please note that the upwind and downwind Radon-222 data for the facility is provided in Appendix 11. The statistics provided in Appendix 11 include all of the data and not just RadTrak data collected beginning on April 1, 1991, as is shown in this section. A wind rose and monitoring site location map are included in this appendix as well.

UR Energy is in the licensing phase of their Lost Creek Project the southern edge of which lies approximately three (3) miles north of the Sweetwater Uranium Project. Appendix 10 contains data for the Lost Creek Project. This data was provided by UR Energy. Based upon the project's wind rose, locations URPA-7 and URPA-10 would constitute the project's upwind and downwind sampling points respectively. No production has begun at this project so the readings from these stations are true background readings. The data for their monitoring locations is shown in the table below:

Lost Creek Project

Ambient Radon Monitoring Data

Monitoring Period	**URPA-7 West of Project** (picoCuries per liter)	**URPA-8 Southeast of Project** (picoCuries per liter)	**URPA-9 Center of Project** (picoCuries per liter)	**URPA-10 Northeast of Project** (picoCuries per liter)	**URPA-13 Southeast of Project** (picoCuries per liter)	**URPA-1 Baroil** (picoCuries per liter)
Q1	1.5	2.7	3.8	2.1	N/A	0.5
Q2	0.7	1.3	0.8	1.2	2.0	0.3
Q3	1.6	2.1	1.5	1.8	1.5	0.9
Q4	2.8	3.2	2.8	1.0	2.5	0.6
Q5	N/A	N/A	1.7	2.0	2.7	0.8
Average:	1.7	2.3	2.1	1.6	2.2	0.6
Median:	1.6	2.4	1.7	1.8	2.3	0.6
Maximum:	2.8	3.2	3.8	2.1	2.7	0.9
Minimum:	0.7	1.3	0.8	1.0	1.5	0.3
Standard Deviation:	0.9	0.8	1.2	0.5	0.5	0.2

Source: UR Energy – Lost Creek Project – NRC Technical Report Revision 2 – April 2010

This data supports the data for the Sweetwater Uranium Project to the south. The upwind station (URPA-7) averages 1.7 picoCuries per liter while the station on the project's border on the upwind (northeast) side averages 1.6 picoCuries per liter which is slightly less. A distant location to the northeast (the Town of Bairoil) averages far less than the background (upwind) sample. It averages 0.6 picoCuries per liter.

These long term elevated background radon concentrations in ambient air are probably due to the presence of a series of playa lakes in an area known as Battle Spring Flat approximately nine (9) to ten (10) miles southwest (upwind) of the facility. This area and its relationship to the facility are shown on the image provided in Appendix 20. This area contains numerous springs and seeps of groundwater that create shallow playa lakes with associated deposits of salts left behind by evaporation of the groundwater. These salts contain among other elements Radium-226 which are a Radon-222 source. The water in these playa lakes (depending on the level of evaporation) can have high concentrations of Radium-226. The August 28, 1975 sample of Hansen Lake had a Radium-226 activity of 33.6 picoCuries per liter. (Annual Report – Permit to Mine #481 – October 27, 2004). In addition, this general area is underlain with known uranium mineralization, some as shallow as 100 to 200 feet below surface.

The proposed rule states:

> *Although the amount of radiation dose that most people receive as a result of these emissions is lower than their natural background dose, the resulting risk can still be significant. A source does not present an acceptable risk simply by being less than natural background. It is important to note that total background radiation from all sources. Including naturally occurring radon, results in a calculated maximum lifetime risk of fatal cancer of approximately 1 Xl0- 2• In most cases, little can be done to reduce most of this radiation exposure which people receive from natural background.*

In the case of the Sweetwater Uranium Project not only is the radon dose from the facility less than natural background it is indistinguishable from background, as it is lost in background's natural variability. Given the above radon concentration data no dose can be assigned to radon from the facility since average downwind radon concentrations are less than the upwind/background concentrations.

The issue of dose to the nearest resident/member of the general public arises from this discussion. 10 CFR part 20.1301 states:

> ***§ 20.1301 Dose limits for individual members of the public.***
>
> *(a) Each licensee shall conduct operations so that —*
>
> *(1) The total effective dose equivalent to individual members of the public from the licensed operation does not exceed 0.1 rem (1 mSv) in a year, exclusive of the dose contributions from background radiation, from any administration the individual has received, from exposure to individuals administered radioactive material and released under § 35.75, from voluntary participation in medical research programs, and from the licensee's disposal of radioactive material into sanitary sewerage in accordance with § 20.2003,*

This 100 millirem dose limit includes internal and external doses and doses from radon. The preamble to 10 CFR part 20 et al. Standards for Protection Against Radiation; Final rule (Federal Register Volume 56, Number 98 Tuesday, May 21, 1991 states:

> *For uranium mills, it will be necessary to show that the dose from radon and its daughters when added to the dose calculated for 40 CFR Part 190 compliance dose not exceed 0.1 rem.*

10 CFR 40.65 contains reporting requirement for uranium mills. 10 CFR 40.65 states:

> ***§ 40.65 Effluent monitoring reporting requirements.***
>
> *(a) Each licensee authorized to possess and use source material in uranium milling, in production of uranium hexafluoride, or in uranium enrichment facility shall:*
>
> *(1) Within 60 days after January 1, 1976 and July 1, 1976, and within 60 days after January 1 and July 1 of each year thereafter, submit a report to the Director, Office of Federal and State Materials and Environmental Management Programs, using an appropriate method listed in § 40.5, with a copy to the appropriate NRC Regional Office shown in appendix D to part 20 of this chapter; the report must specify the quantity of each of the principal radionuclides released to unrestricted areas in liquid and in gaseous effluents during the previous six months of operation, and such other information as the Commission may require to estimate maximum potential annual radiation doses to the public resulting from effluent releases. If quantities of radioactive materials released during the reporting period are significantly above the licensee's design objectives previously reviewed as part of the licensing action, the report shall cover this specifically. On the basis of such reports and any additional information the Commission may obtain from the licensee or others, the Commission may from time to time require the licensee to take such action as the Commission deems appropriate.*

The Nuclear Regulatory Commission (NRC) recently published *NRC STAFF INTERIM GUIDANCE EVALUATIONS OF URANIUM RECOVERY FACILITY SURVEYS OF RADON AND RADON PROGENY IN AIR AND DEMONSTRATIONS OF COMPLIANCE WITH 10 CFR 20.1301 - Draft Report for Comment* (Docket ID: [NRC-2011-0266 – (Federal Register / Volume 76, Number 224 / Monday, November 21, 2011 / Notices)). This document discusses in detail methodologies for calculating dose from Radon-222 and its decay products to the nearest residents/members of the public from uranium recovery facilities. Kennecott Uranium Company commented on this draft document and includes its comments (*Kennecott Uranium Company Comments on the Draft Interim Staff Guidance: Evaluations of Uranium Recovery Facility Surveys of Radon and Radon Progeny in Air and Demonstrations of Compliance with 10 CFR 20.1301 Docket ID: [NRC-2011-0266 – (Federal Register / Volume 76, Number 224 / Monday, November 21, 2011 / Notices)*) by reference.

The Sweetwater Uranium Project submits an effluent monitoring report semiannually as required by 10 CFR Part 40.65 covering the first and second halves of the year respectively. This report includes an estimate of dose to the nearest resident. The site employs a contract security officer who provides security during the time others are not on site and who resides immediately outside the site fence in a trailer when on site. The trailer is located 0.32 miles from the edge of the tailings impoundment. The trailer interior is monitored for radon using two (2) Radtrak detectors (one in the kitchen and one in the bedroom) that are changed quarterly. In this way the officer's radon exposure can be measured. For purposes of dose calculation, the officer is considered to be a member of the general public at all times in spite of the fact that he is trained, badged and bioassayed as a radiation worker and considered such when on duty. No occupancy factor is used in the calculation of his dose as he is considered to be a resident adjoining the site twenty-four (24) hours each day 365 days per year.

A table is included in Appendix 7 shows doses to the nearest resident, background radon concentration, background radon dose, radon concentration in the Security Trailer and radon dose to the nearest resident (security Officer) from the second half of 1994 to the first half of 2011 a period of over sixteen (16) years.

The table below summarizes this data:

Measured Doses to the Nearest Resident (Security Officer)

	Measured Dose Above Background (millirems)	**Background Radon Concentration** (pCi/L)	**Background Radon Dose** (millirems)	**Radon Concentration in Security Trailer** (pCi/L)	**Radon Dose in Security Trailer** (millirems)
Average:	0.61	3.26	347.73	2.38	251.64
Median:	0.00	3.28	332.65	2.22	234.30
Maximum:	14.80	5.70	702.24	3.75	491.04
Minimum:	0.00	1.35	98.60	0.95	69.40
Standard Deviation:	2.74	0.88	129.82	0.65	86.52

Source: Semiannual 40.65 Reports submitted to the Nuclear Regulatory Commission 1994 to 2011

This average dose is very low.

The average dose above background is lost in the variability of background, in spite of the fact that the Security Trailer is immediately outside the facility fence and 0.32 miles from the impoundment. The doses and radon concentrations shown in the above table are from the facility's semiannual 40.65 Reports and are available through the Nuclear Regulatory Commission's (NRC's) web based ADAMs system for review. These low doses equate to low risk. These doses and associated low risks support the discussion of the risks from Radon-222 related to tailings impoundments in the citation below:

> *Similarly, the National Academy of Science (NAS) (NRC, 1986a) concluded that "persons living at distances greater than a kilometre (about 0.6 miles) from most uncontrolled uranium mill tailings piles, and perhaps somewhat closer to some piles, will experience no significant increase in a lifetime radon lung cancer risk from the pile…".*
>
> Source: Generic Environmental Report in Support of the Nuclear Regulatory Commission's Generic Environmental Impact Statement for In Situ Uranium Recovery Facilities **–** National Mining Association (NMA) – November 30, 2007

The above quotation is supported by the document included in Appendix 21 entitled *Evaluation of Radon-222 Near Uranium Tailings Piles* which was published by the U.S. Public Health Service in March 1969. This document contains the results of 892 air samples collected at the following four (4) study areas (uranium mill tailings impoundments); Grand Junction, Colorado, Salt Lake City, Utah, Monticello, Utah and Durango, Colorado. The report concludes that:

> *The tailings at the four study sites are not significantly affecting the atmospheric radon concentrations beyond a distance of one-half mile in the prevailing wind directions.*

This supports the conclusions from the National Academy of Sciences cited by the National Mining Association (NMA).

The Sweetwater Uranium Project's security officer falls within the category of a person living "perhaps somewhat closer to some piles". When calculating these doses, a site specific equilibrium factor for Radon-222 was used. This was determined by analyzing the air in the Security Trailer semiannually at two (2) locations using the modified Kusnetz Method. A table listing the equilibrium factor is included in Appendix 8. The average equilibrium factor based upon readings collected since 1993 is 0.161.

This raises another issue, that being the equilibrium factor used by the Agency to calculate the radon dose. In the case of indoor air, the Agency uses a 4 pCi/L action level. This action level is based upon an equilibrium factor of 0.5. In modeling radon risk and determining radon dose a realistic equilibrium factor should be used. In the case of the Sweetwater Uranium Project that equilibrium factor is 0.161 determined over sixteen (16) years of testing.

The subject of radiometric equilibrium for Radon-222 is discussed in Generic Environmental Report in Support of the Nuclear Regulatory Commission's Generic Environmental Impact Statement for In Situ Uranium Recovery Facilities **-** National Mining Association (NMA) – November 30, 2007, when it states:

> *When released from a source (mining activity or processing), the radon gas is free from daughters (radioactive decay products). The concentrations of short-lived radon daughters increase with time and hence with distance from the source. On the other hand, the concentrations of radon (and daughters) decrease with increasing distance due to dispersion in the atmosphere. This pattern of ingrowth varies according to the relative length of the half-lives of the original radionuclide and its decay products. Radioactive equilibrium occurs when each radionuclide decays at the same rate at which it is produced. Evans (Evan, 1969) has developed an approximate method for estimating the ingrowth of radon decay products (referred to as fractional ingrowth Feq here), namely that:*
>
> ***Feq = 0.023 t 0.85** where t is in minutes.*
>
> *For a windspeed of 5 mph, the fractional ingrowth at 1 mile (approximately 12 minutes downwind) will be about 0.18. EPA has noted that while secular (i.e., complete) equilibrium is a theoretical upper limit; it is difficult to attain due to the differences in half life (the time required for the disintegration of one-half of the original radioactive atoms) between the original radionuclide and its decay products.*

This recent (November 30, 2007) information conflicts with the basis for the risk assessment for 40 CFR Part 61 Subpart W, which used an equilibrium factor of 0.70. The use of this equilibrium factor in promulgating 40 CFR Part 61 Subpart 40 is discussed in the document entitled Final Report – History and Basis of NESHAPs and Subpart W, which states:

> *For Rn-222, the CAP88 computer codes were used to established ambient concentrations (pCi/m3) in each of the sectors in a 0-80 km radius of the source. The concentration within each sector was then converted to working level months (WLMs), based on a 0.70 equilibrium fraction between Rn-222 and its decay products, and a respiration rate appropriate to members of the general public. Using risk factors derived from human epidemiological studies, the WLM exposure data were converted to risks.*

Uranium recovery sites often have high background Radium-226 activities in soils. Radium-226 is Radon-222's precursor. These high naturally occurring Radium-226 activities can create high naturally occurring soil Radon-222 fluxes that contribute to high ambient background Radon-222 concentrations in air. At the Sweetwater Uranium Project soil sampling in the area has demonstrated high background radium-226 concentrations and radon flux measurements have shown high naturally occurring radon flux readings in undisturbed soils. At the Sweetwater Uranium Project the background (upwind) radon-222 concentrations have been historically higher than those downwind of the tailings impoundment. In addition to the Radon-222 contribution from site soils, elevated upwind Radon-222 concentrations can also be attributed to Radon-222 derived from playa lake deposits southwest of the facility. Doses to the nearest resident (the site's Security Officer) have historically been very low and with two exceptions at or below calculated background over the last fifteen (15) years. At the Sweetwater Uranium Project, not only are ambient Radon-222 concentrations derived from the tailings impoundment are not just *less than natural background,* they are indistinguishable for natural background, being lost in the normal variability of background.

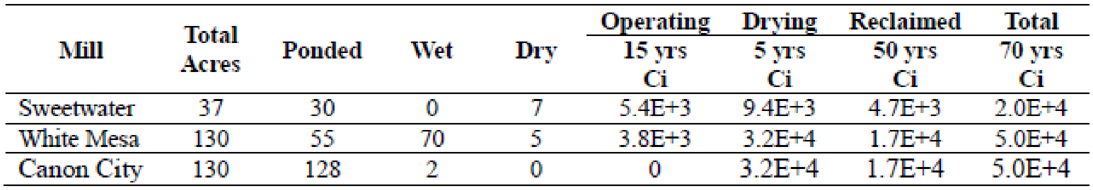
Radon Emissions from Tailings Impoundments Compared to Natural and Other Anthropogenic Sources Other than Uranium Mining and Processing

Contained in Appendix 28 is a spreadsheet entitled *Natural and Man Induced (Excluding Uranium Mining and Processing) Radon Emissions (Estimate Does Not Include Indoor Radon Emissions in Homes, Offices etc).* This spreadsheet based upon data from *NUREG/CR-0573 A Radiological Assessment of Radon-222 Released from Uranium Mills and Other Natural and Technologically Enhanced Sources,* updated with current values for coal, natural gas an phosphate fertilizer consumption, shows Radon-222 emissions from natural sources (soils and evapotranspiration) and anthropogenic sources including tilling of fields, burning of natural gas and coal and the use (from 1900 to 1977) of phosphate fertilizer.

This spreadsheet clearly shows that Radon-222 emissions from uranium processing (mill tailings impoundments and fluid retention impoundments) are miniscule when compared to these other sources.

Table 3 of the *Final Report – Review of Existing and Proposed Tailings Impoundment Technologies* prepared by S. Cohen & Associates shown below shows a total Radon-222 emission for fifteen (15) years of operation for the three listed impoundments is 9.2E+03 Curies.

Table 3. Comparative Rn-222 Emissions over 70 Years
(Assuming 400 pCi/g Ra-226)



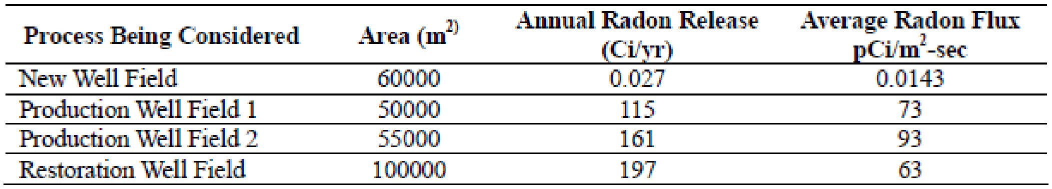
Mill	Total Acres	Ponded	Wet	Dry	Operating 15 yrs Ci	Drying 5 yrs Ci	Reclaimed 50 yrs Ci	Total 70 yrs Ci
Sweetwater	37	30	0	7	5.4E+3	9.4E+3	4.7E+3	2.0E+4
White Mesa	130	55	70	5	3.8E+3	3.2E+4	1.7E+4	5.0E+4
Canon City	130	128	2	0	0	3.2E+4	1.7E+4	5.0E+4

This is 613 Curies per year. This value is dwarfed by the 3,120,000 Curies per year released by tilling of soils, the 12,900 Curies per year released by the combustion of natural gas, or the 115,000 Curies per year released by the use of phosphate fertilizer since 1900.

This activity is 0.02% of the total activity of Radon-222 released by the combination of agricultural tillage, phosphate fertilizer use, and natural gas combustion.

The *Final Report – Review of Existing and Proposed Tailings Impoundment Technologies* includes Table 6 which is shown below:

Table 6. Estimated Rn-222 Releases from an ISL Facility



Process Being Considered	Area (m^2)	Annual Radon Release (Ci/yr)	Average Radon Flux pCi/m^2-sec
New Well Field	60000	0.027	0.0143
Production Well Field 1	50000	115	73
Production Well Field 2	55000	161	93
Restoration Well Field	100000	197	63

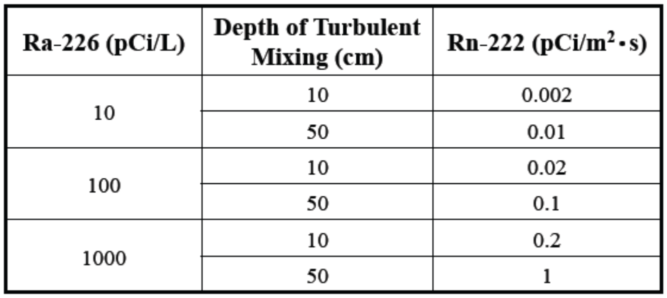
Each in-situ uranium recovery operation is estimated to release 473.027 Curies of Radon-222 per year. There are three (3) currently operating in-situ uranium recovery facilities (Smith Ranch/Highland, Crow Butte and Alta Mesa) and three (3) with license applications currently in process (Draft Supplemental Environmental Impact Statements (SEISs) issued) which are Lost Creek, Moore Ranch and Nichols Ranch. Six (6) operations using S. Cohen and Associates estimates would release 2838.162 Curies of

Radon-222 per year. This is still only 0.09% of the total activity of Radon-222 released by the combination of agricultural tillage, phosphate fertilizer use, and natural gas combustion.

A real solution to reducing anthropogenic Radon-222 would be to displace the use of natural gas for electric power generation with nuclear power. The total annual activity of Radon-222 released by the combustion of natural gas is 12,900 Curies per year.

Emissions of Radon-222 from Fluid Retention Impoundments

In the case of the Sweetwater Uranium Project the quantity Radon-222 emitted from the tailings impoundment is so small that it cannot be distinguished for naturally occurring Radon-222 in ambient air. It is generally accepted that emissions from fluid retention impoundments should be less than that from uranium mill tailings impoundment. Emissions of Radon-222 from ponds has been studied and discussed at the 2009 National Mining Association (NMA)/Nuclear Regulatory Commission (NRC) Uranium Recovery Workshop in Denver, Colorado in 2009. The presentation entitled *Radon Emissions from Tailings Ponds* was given by Doug Chambers of SENES Consultants Limited. He stated that *Rn-222 gas exchange via diffusion from surface of small lake has been measured (Experimental lakes, Ontario).* The data is presented below:



Ra-226 (pCi/L)	Depth of Turbulent Mixing (cm)	Rn-222 (pCi/$m^2 \cdot s$)
10	10	0.002
	50	0.01
100	10	0.02
	50	0.1
1000	10	0.2
	50	1

These fluxes are very low. Given the worst case regarding turbulent mixing (50 centimeters) with a Radium-226 activity of the water of 1000 pCi/L the flux is only 1 pCi/m2-sec. Fluid retention ponds do not present a substantial risk regarding radon release of dose to a member of the general public. Based on the above flux rates, Radon-222 emanating from fluid retention ponds would be lost in the natural variability of background. The entire presentation is included in Appendix 9 for reference.

In a second presentation entitled *Radon Emissions from Tailings and Evaporation Ponds* dated January 2011 Doug Chambers also discussed Radon-222 emissions stating, *"The basic physics, historical and recent studies of radon emissions from water surfaces suggests it is "trivial…"*. The presentation is included in Appendix 36.

In a letter (November 2010) prior to this presentation Steven Brown, also of SENES Consultants Limited, concluded that:

> *Radon emission rates (flux) from water impoundments (evaporation ponds) at licensed conventional mills and ISRs are not expected to be significantly different than that from typical background radon emission associated with land surfaces almost anywhere due to the very poor diffusion of radon through water."*

and that:

> *The possibility of health effects in populations living near uranium mines and mills over 50 years have been well studied by national scientific bodies of the highest professional standing. No additional effects have been observed when compared to the health status of other similar populations not living nearby."*

This letter is included in Appendix 35.

On Wednesday, May 26, 2010 at the National Mining Association (NMA)/Nuclear Regulatory Commission (NRC) Uranium Recovery Workshop, Dr. Kenneth Baker gave a presentation entitled “Radon Flux from Evaporation Ponds”. This presentation is included in its entirety in Appendix 22. This paper provides actual measured fluxes from an evaporation pond containing fluid with a known Radium-226 activity.

The presentation discussed a stagnant film model for the transport of a gas across an air-water interface presented in *Environmental Organic Chemistry,* (Schwarzenbach, Rene P., Philip M. Gschwend, and Dieter M. Imboden. 2nd Edition. 2002) This model predicts that:

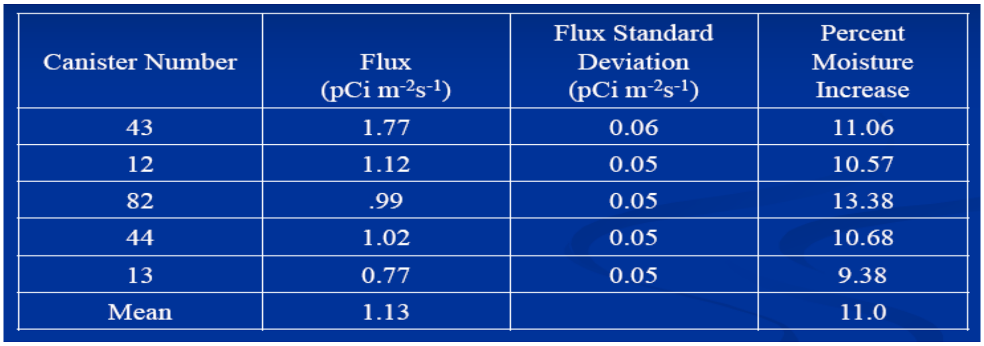
Radon Flux = 0.01 pCi m-2 s-1 per pCi L-1 of dissolved radon in the water.

Assuming that the Radon-222 is in secular equilibrium with the dissolved Radium-226 in the water it means that:

Radon Flux = 0.01 pCi m-2 s-1 per pCi L-1 of dissolved Radium-226 in the water.

A detailed discussion of the *Stagnant Film Model* prepared by Dr. Kenneth Baker is included in Appendix 10.

The fluid retention impoundment described in the presentation contained 165 picoCuries per liter of Radium-226, thus the Radon-222 flux should be approximately 1.65 picoCuries per meter squared second. The measured fluxes were as follows:



Canister Number	Flux ($pCi\ m^{-2}s^{-1}$)	Flux Standard Deviation ($pCi\ m^{-2}s^{-1}$)	Percent Moisture Increase
43	1.77	0.06	11.06
12	1.12	0.05	10.57
82	.99	0.05	13.38
44	1.02	0.05	10.68
13	0.77	0.05	9.38
Mean	1.13		11.0

The mean flux was 1.13 picoCuries per meter squared second. In addition, ten (10) canisters were exposed for twenty-four (24) hours to water only and yielded a mean Flux = 0.13 ± 0.10 picoCuries per meter squared second.

A flux rate of 1.65 picoCuries per meter squared-second is very low and is comparable to natural background flux rates. (Steve Brown – Comments on the presentation – May 26, 2010)

Preoperational soil sampling at the Sweetwater Uranium Project yielded a mean surface soil Radium-226 activity of 1.44 picoCuries per gram. Using the Agency’s estimate that *that 1 pCi/g of radium-226 in the tailings produces 1 pCi/*m^2 *-sec of radon.* A mean Radon-222 flux for the area would be 1.44 picoCuries per meter squared second. This is very close to the calculated/modeled flux rate of 1.65 picoCuries per meter squared second for the pond and greater than the measured flux rate of 1.13 picoCuries per meter squared second for the pond. This soil sampling data is included in Appendix 25.

The table below is from *NUREG-1910 - Generic Environmental Impact Statement for In-Situ Leach Uranium Milling Facilities – May -2009:*

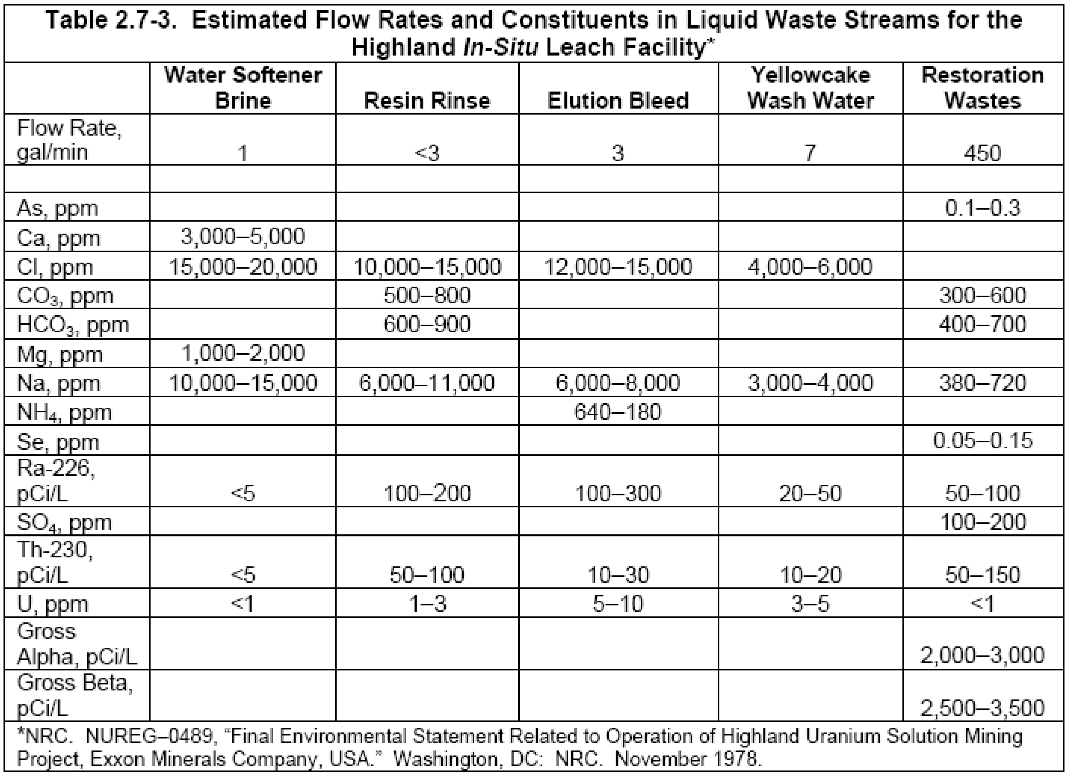


Table 2.7-3. Estimated Flow Rates and Constituents in Liquid Waste Streams for the Highland *In-Situ* Leach Facility*

	Water Softener Brine	Resin Rinse	Elution Bleed	Yellowcake Wash Water	Restoration Wastes
Flow Rate, gal/min	1	<3	3	7	450
As, ppm					0.1–0.3
Ca, ppm	3,000–5,000				
Cl, ppm	15,000–20,000	10,000–15,000	12,000–15,000	4,000–6,000	
CO_3, ppm		500–800			300–600
HCO_3, ppm		600–900			400–700
Mg, ppm	1,000–2,000				
Na, ppm	10,000–15,000	6,000–11,000	6,000–8,000	3,000–4,000	380–720
NH_4, ppm			640–180		
Se, ppm					0.05–0.15
Ra-226, pCi/L	<5	100–200	100–300	20–50	50–100
SO_4, ppm					100–200
Th-230, pCi/L	<5	50–100	10–30	10–20	50–150
U, ppm	<1	1–3	5–10	3–5	<1
Gross Alpha, pCi/L					2,000–3,000
Gross Beta, pCi/L					2,500–3,500

*NRC. NUREG–0489, "Final Environmental Statement Related to Operation of Highland Uranium Solution Mining Project, Exxon Minerals Company, USA." Washington, DC: NRC. November 1978.

It shows based upon flow rates that over 96.9% of the liquid wastes at in-situ leach uranium recovery operations are restoration wastes with Radium-226 activities of 50 to 100 picoCuries per liter which should yield radon fluxes of 0.5 to 1.0 picoCuries per meter squared second using the previously discussed activity to flux relationships (Stagnant Film Model (SFM)) which is below background radon fluxes. Liquid effluents from in-situ uranium recovery operations do not pose a radon risk above existing background since the radon emissions from the ponds are less than the soil background emissions that they displace upon construction over the ground surface.

The tailings fluid at the Sweetwater Uranium Project contained in the pools of free fluid in the have varied from 1.5 to 567 picoCuries per liter averaging 86.45 picoCuries per liter. Please see the spreadsheet entitled "Sweetwater Tailings Cell" in Appendix 27. This average Radium-226 activity of 86.45 picoCuries per liter would result in an average Radon-222 flux of 0.86 (0.01 times the Radium-226 activity) picoCuries per meter squared second over the life of the impoundment (1980 to 2011) using the previously discussed activity to flux relationships (Stagnant Film Model (SFM)).

This average value is lower than the estimated Radium-226 concentration of 250 picoCuries per liter for mill effluent sent to the tailings impoundment in Table 6.3 of *NUREG-0706 – Final Generic Environmental Impact Statement on Uranium Milling – September 1980.* Using the approximation and test data provided by Dr. Baker this value in NUREG-0706 would only yield a radon flux rate of 2.5 picoCuries per meters-squared second.

Fluid retention impoundments do not pose a substantial radon risk above background. When a lined impoundment is constructed, the liner blocks natural Radon-222 flux from the ground surface. This natural flux is then replaced with whatever flux comes from the fluids contained in the impoundment. This new flux generally is comparable to the natural flux it displaces. Thus these fluid retention impoundments do not contribute in any meaningful way to airborne radon concentrations.

Legal Basis for the Regulation of Fluid Retention Impoundments under 40 CFR part 61 Subpart W.

Appendix 12 contains a document entitled *Application of United States Environmental Protection Agency 40 CFR Part 61, Subpart W Regulations to Uranium Recovery Facilities***.** This document was prepared for the National Mining Association (NMA) by the law firm of Thompson and Pugsley and has been submitted previously to the Environmental Protection Agency (EPA). This document reviews the history of 40 CFR Part 61 Subpart W and concludes by stating:

> *Therefore, based on the foregoing discussion, it appears that EPA's 40 CFR Part 61, Subpart W work practice standards do not apply to evaporation ponds at uranium recovery facilities.*

Kennecott Uranium Company concurs with this interpretation.

Conflicts with Pre-Existing Approvals

The Sweetwater Uranium Project is licensed by the Nuclear Regulatory Commission (NRC) under Source Material License SUA-1350. The most current version of the license is included in its entirety in Appendix 13.

License Condition 10.3 states:

> *10.3 The licensee shall construct and operate the proposed tailings impoundment, liner system, evaporation ponds, and tailings disposal system in compliance with Volumes III, IV, and VII of the Final Design application submitted by cover dated June 11, July 23, and September 18, 1997, including page changes submitted April 13, June 10, July 1, and July 20, 1998, and March 25, and June 21,1999.*
>
> *The licensee is currently authorized to construct up to eight evaporation ponds and one new impoundment. An additional two evaporation ponds and an additional five impoundments, as described in the above documents, may be constructed after: 1) notification of NRC; 2) submittal of data confirming the proposed design; and 3) an increase in the surety amount, based on the NRC-approved cost estimate for reclaiming the additional structures.*

These approved plans for the new tailings impoundments and evaporation ponds underwent a required National Environmental Policy Act (NEPA) Review. The plans for the new impoundments were submitted in the following documents:

- Final Design Volume III – Embankment Design Report – June 12, 1997
- Final design Volume IV – Liner Design Report – July 28, 1997
- Final design Volume VII - Operations Plan – September 26, 1997

These three (3) volumes were part of a comprehensive seven (7) volume submittal to the U.S. Nuclear Regulatory Commission (NRC) to relicense the Sweetwater Uranium Project for resumed operation.

An Environmental Assessment (EA) entitled *Environmental Assessment for Source Material License SUA-1350, Renewal for Operations and Amendment for the Reclamation Plan* dated July 1999 was prepared and made available for public comment and review. This document is included in Appendix 24.

This document states in part:

> *This EA has been prepared under 10 CFR Part 51, "Licensing and Regulatory Policy and Procedures for Environmental Protection," which implements NRC's environmental protection program under the National Environmental Policy Act (NEPA) of 1969. In accordance with 10 CFR Part 51, an EA serves to: (a) briefly provide sufficient evidence and analysis for determining whether to prepare an environmental impact statement (EIS) or a finding of no significant impact (FONSI); (b) facilitate preparation of an EIS when one is necessary; and (c) aid the NRC's compliance with NEPA when an EIS is not necessary.*

> *Impacts from the commercial scale operation of the site were previously evaluated in the Final Environmental Statement (FES) (NRC, 1978). Should the NRC issue a FONSI based on this EA, a renewed commercial source material license would be issued to KUC.*
>
> *Other Federal agencies are involved with certain aspects of the Site activities. For example, KUC consulted the U.S. Environmental Protection Agency (EPA) concerning modification of an existing source (tailings impoundment) and construction of a new source under authorization of 40 CFR Part 61. Also, the State of Wyoming Department of Environmental Quality (DEQ) administers and implements the State's environmental protection rules and regulations. The licensee has committed to comply with all applicable Federal regulations, as well as State regulations.*

The State of Wyoming was consulted in the preparation of this Environmental Assessment. In the section entitled References, the document states:

- *Telephone conversation with R. Hoy, Wyoming Department of Environmental Quality, May 20, 1999, no comments.*
- *Telephone conversation with Mark Theisse, Wyoming Department of Environmental Quality, May 26, 1999, no comments.*

The assessment addresses tailings disposal in full, stating:

> *Mill tailings are deposited within a tailings cell/impoundment located at the facility. The tailings, along with liquid waste, are slurried by pipeline to the impoundment system, which consists of a series of synthetically lined cells that are designed for phase construction and reclamation. The 300-acre impoundment area may contain up to six cells to provide the required adequate disposal capacity for the estimated 20-year project life. The impoundment area will be fenced to keep game animals and livestock out of the tailings impoundment.*
>
> *Each of the tailings impoundments is designed to accept approximately 3,000 tons of waste per day, but only two impoundments should be in operation at a time. Each new cell will be constructed by excavating 15.2 m (50 feet) deep, and will be surrounded by 15.2-m (50-feet) high engineered embankments. Double liners with clay and composite layers, along with attendant leak-detection/recovery systems will be constructed to retard and collect seepage. A process water recovery system will be constructed on the cell bottom and on the embankment face opposite the discharge lines, at the location of the decant pool. Drains along the cell bottom and side will reduce the seepage potential. Water from the process water recovery system or the surface pump will be sent to a geomembrane-lined surge pond constructed on regraded tailings in the existing cell for recirculating to the mill and/or evaporation. Discharge into the tailings impoundment will occur from a common center cell wall which will create a gently sloped tailings surface and a drainage divide. As each cell is filled, an additional cell will be constructed. The cover surface and side slope rock is designed to provide erosion protection for the Probable Maximum Precipitation event.*
>
> *Prior to construction of any new tailings impoundments, the topsoil will be removed from the area and stockpiled for use in future reclamation activities. A diversion ditch for Battle Spring Draw will be constructed around the east edge of the impoundment area. Additionally, a new diversion ditch, lined with riprap, will be constructed to divert storm waters when a new cell is built.*
>
> *KUC has committed, in its license renewal application, to returning all liquid effluents from the mill process buildings, with the exception of sanitary wastes, to the mill circuit or discharging them to the tailings impoundment. This is currently required by license condition and will continue to be so required. Non-salvageable solid wastes (e.g., filters, pumps) contaminated in the mill process, and which cannot be decontaminated below NRC unrestricted release limits, will be placed in the tailings impoundment. KUC states that void space in such material will be minimized prior to its emplacement in the impoundment.*

The assessment also addressed the evaporation ponds stating:

> *The evaporation ponds will also have a dual synthetic liner with leak detection and recovery system, which will be installed on prepared base. Monitoring wells will be located immediately down gradient, and monitored monthly for the first year then, quarterly after the first year for indicator parameters. This sampling schedule conforms to regulatory requirements, and establishes baseline data for each well in the first year of monthly monitoring. When site operations cease, evaporation ponds will be decommissioned by evaporating all liquid, then disposing of liners and any accumulated solids in the tailings cell.*
>
> *As discussed in the SER for this licensing action, the staff determined that the operational plan and liner system for both the new impoundments and the new evaporation ponds would be protective and that leakage of contaminants into ground water is unlikely. In the event of any leakage, monitoring would detect the problem so that corrective actions could be taken quickly. In evaluating the operational plan (inspections, monitoring, design), the staff determined that it would comply with NRC ground water regulations.*

Following this assessment, a Finding of No Significant Impact (FONSI) dated August 6, 1999 was published in the Federal Register. It is attached in Appendix 14 for your reference.

Clearly, the already approved plans for additional tailings impoundments and evaporation ponds underwent a thorough NEPA review and were approved. With this approval, the Sweetwater Uranium Project is permitted to have up to two (2) operating tailings impoundments (as per 40 Part 61.252(b)(1)) plus eight (8) evaporation ponds at ten (10) acres each for a total of eighty (80) acres with the potential for two (2) additional ten (10) acre evaporation ponds.

As discussed in the Environmental Assessment (EA), the Environmental Protection Agency (EPA) was also consulted. Part of this consultation regarded the use of the existing impoundment. The Sweetwater Uranium Project's existing impoundment was discussed in a letter dated March 21, 1996. This letter, included in Appendix 12 signed by Milt Lammering, Director Toxics Program, states:

> *Your interpretation of 40 CFR Part 61 Subpart W would retain this unit **(the existing tailings impoundment on site**) under the definition of "Existing impoundment" as referenced by 61.250(d). This interpretation would allow for the construction and use of one additional impoundment per 61.252(b) (1).*
>
> *This office concurs with your interpretation of the referenced regulations.*

Thus the existing sixty (60) acre impoundment on site may be used upon resumption of operations provided that the tailings are leveled and a new liner with a leak detection system is installed. In addition, a second forty (40) acre impoundment may be constructed and operated concurrently with the existing, leveled and relined impoundment, along with at least eight (8) ten (10) acre evaporation ponds. Regulation of evaporation ponds under 40 CFR Part 61 Subpart W and inclusion of their area in the maximum allowable area would interfere with previously reviewed and approved plans.

Epidemiological Considerations

The **Generic Environmental Report in Support of the Nuclear Regulatory Commission's Generic Environmental Impact Statement for In Situ Uranium Recovery Facilities (**National Mining Association (NMA) – November 30, 2007) states:

> *Several epidemiological studies have also been carried out on communities living near by to uranium mining/milling activities. Boice et al. (Boice, 2003) investigated the cancer mortality in Karnes County Texas, a county with a history of uranium mining and milling activities that includes 3 mills and over 40 mines. In brief, this paper concluded that there were no unusual patterns of cancer mortality among people living in Karnes County suggesting that uranium activities had not increased the risk of cancer. In a separate paper, Boice et al. (Boice, 2007a) report a geographical correlation study of cancer and non-cancer mortality in people living near*

> *uranium and vanadium mining/milling operations in Montrose County Colorado between 1950 and 2000. These authors found that cancer and non-cancer mortality rates among people who lived in Montrose County were comparable to those counties not affected by uranium mining/milling. The authors report on a number of occupational and environmental factors. In particular, no statistically significant increases in total risk of cancer or non-malignant respiratory diseases were observed. The authors found an increased risk of lung cancer but suggested they could be a result of cigarette smoking. Overall, the authors concluded that there was no evidence that people who lived in Montrose County experienced an increased risk from environmental exposures arising from uranium or vanadium mining/milling. Finally, another paper by Boice et al. (Boice, 2007b) discusses the mortality of people who lived in Uravan, Colorado, a town built around a uranium mill. This study found no increased risk of lung cancer in female residents of the town or in mill workers. Moreover, the authors also report that their study found no evidence that elevated above-background radiation exposures associated with the operations of the Uravan uranium mill increased the risk of cancer to people living in Uravan.*

This paper entitled *Cancer Mortality in a Texas County with Prior Uranium Mining and Milling Activities 1950 to 2001* (Boice, J.D. Jr. et al September 8, 2003) included in Appendix 18 discusses Karnes County, Texas. This county was home to three (3) conventional uranium mills and associated tailings impoundments, the Susquehanna- Western (Deweeseville) Mill), the Conoco (Conquista) Mill and the Chevron (Panna Maria) Mill. The county was host to a number of open pit uranium mines, as well. The paper reaches the following conclusion:

> *Overall, 1223 cancer deaths occurred in the population residing in Karnes County from 1950 to 2001 compared with 1392 expected based on general population rates for the US. There were 3857 cancer deaths in the four control counties during the same 52 year period compared with 4389 expected. There was no difference between the total cancer mortality rates in Karnes County and those in the control counties (RR = 1.0; 95% confidence interval 0.9–1.1). There were no significant increases in Karnes County for any cancer when comparisons were made with either the US population, the State of Texas or the control counties. In particular, deaths due to cancers of the lung, bone, liver and kidney were not more frequent in Karnes County than in the control counties. These are the cancers of a priori interest given that uranium might be expected to concentrate more in these tissues than in others. Further, any radium intake would deposit primarily in the bone and radon progeny primarily in the lung. Deaths from all cancers combined also were not increased in Karnes County and the RRs of cancer mortality in Karnes County before and in the early years of operations (1950–64), shortly after the uranium activities began (1965–79) and in two later time periods (1980–89, 1990–2001) were similar, 1.0, 0.9, 1.1 and 1.0, respectively. No unusual patterns of cancer mortality could be seen in Karnes County over a period of 50 years, suggesting that the uranium mining and milling operations had not increased cancer rates among residents.*

This conclusion was reached for Karnes County in spite of the fact that it hosted three (3) conventional uranium mill and associated tailings impoundments and a number of open pit mines for an extended period of time.

In a second paper included in Appendix 19 entitled Cancer *and Noncancer Mortality in Persons Living near Uranium and Vanadium Mining and Milling Operations in Montrose County, Colorado 1950 – 2000* (Boice, J.D. Jr. et al 2007), Montrose County, Colorado which was home to the Uravan Mill as well as 223 uranium mines. In spite of this high concentration of uranium production activity, the paper states:

> *Between 1950 and 2000 a total of 1,877 cancer deaths occurred in the population residing in Montrose County, compared with 1,903 expected based on general population rates for Colorado (SMR_{CO} 0.99). There were 11,837 cancer deaths in the five comparison counties during the same 51-year period compared with 12,135 expected (SMR_{CO} 0.98). These was no difference between the total cancer mortality rates in Montrose county and those in the comparison counties (RR= 1.01; 95% CI 0.96-1.06).*

Included in the appendix with each paper is an analysis of that paper prepared by Dr. Nancy Standler MD, PhD a board certified pathologist currently practicing in Utah who also possesses a PhD from the Department of Radiation Biology and Biophysics of the University of Rochester.

Dr Boice published a third paper entitled *A cohort study of uranium millers and miners of Grants, New Mexico, 1979–2005* dated August 28, 2008 which is included in Appendix 23. This study was a cohort mortality study of workers engaged in uranium milling and mining activities near Grants, New Mexico, during the period from 1955 to 1990. This is a long term study of a maximally exposed group of workers. The uranium mill workers (as opposed to the miners) in this study should have had the maximum exposure to Radon-222 from tailings impoundments and fluid retention impoundments since they worked closest to these impoundments as opposed to the underground miners who did not. The study concluded:

> *No statistically significant elevation in any cause of death was seen among the 904 non-miners employed at the Grants uranium mill. Among 718 mill workers with the greatest potential for exposure to uranium ore, no statistically significant increase in any cause of death of a priori interest was seen, i.e., cancers of the lung, kidney, liver, or bone, lymphoma, non-malignant respiratory disease, renal disease or liver disease. Although the population studied was relatively small, the follow-up was long (up to 50 yrs) and complete.*

If the maximally exposed mill workers showed no statistically significant elevation in any cause of death then lesser exposed members of the general public should not either.

The only group to show any increase in mortality were underground uranium miners regarding which Dr. Boice concluded:

> *Increased mortality, however, was seen only among the 1735 underground uranium miners and was due to malignant (SMR 2.17; 95% CI 1.75–2.65; n = 95) and non-malignant (SMR 1.64; 95% CI 1.23–2.13; n = 55) respiratory diseases, cirrhosis of the liver (SMR 1.79; n = 18) and external causes (SMR 1.65; n = 58). The lung cancer excess likely is attributable to the historically high levels of radon in uranium mines of the Colorado Plateau, combined with the heavy use of tobacco products.*

This relationship regarding lung cancer and underground uranium miners, especially those that smoked, is well known (Saccomano et al).

Included in Appendix 26 is a paper entitled *Mortality among a cohort of uranium mill workers: an Update* by Lynn Pinkerton et al of the National Institute of Occupational Safety and Health (NIOSH). This paper examined a cohort of 1,484 uranium mill workers who presumably comprise a maximally exposed population to radon and its decay products from uranium mill tailings impoundments and fluid retention impoundments. This paper concluded:

> *Mortality from all causes was less than expected, which is largely accounted for by fewer deaths from heart disease than expected. Mortality from all malignant neoplasms was also less than expected.*

Cancer deaths which are the ones one would expect from exposure to radon and its decay products were less than expected. The paper also states:

> *Overall mortality was highest among those with the shortest duration of employment and lowest among those with the longest duration of employment. Similar trends with duration of employment were observed for mortality from lung cancer, non-malignant respiratory disease, and emphysema.*

One would think that the longer the exposure the higher the mortality rate, but rather the reverse is true. Long term exposure to radioactive materials associated with uranium milling including radon and its decay products seem to result in a lower mortality rate. This runs counter to the argument that longer residence times near uranium recovery operations result in higher mortality rates.

Two (2) of the above referenced studies involved counties with extensive uranium production and a long period of time (fifty-one (51) years). In neither case were excess cancer deaths detected in spite of the long term presence of uranium mill tailings in these areas. These studies indicate that the perceived risks to the public driving the promulgation of 40 CFR part 61 Subpart W are over estimated.

The third above referenced study describes a cohort that includes maximally exposed uranium mill workers who would have had a maximum exposure to radon and its decay products from tailings impoundments and fluid retention impoundments. It shows no increase in mortality in this group.

The National Institute for Occupational Safety and Health (NIOSH) study describes a cohort that includes 1,484 maximally exposed uranium mill workers who would have had a maximum exposure to radon and its decay products from tailings impoundments and fluid retention impoundments. It shows no increase in mortality in this group and no increase in mortality from cancer.

In *Risk Assessments Methodology Environments Impact Statement NESHAPS for Radionuclides – Background Information Document Volume 1*, the Agency discussed its approach to the estimation of radon risk, stating:

> *The Agency's estimates of the risk of lung cancer due to inhaled radon progeny do not use a dosimetric approach, but rather are based on what is sometimes called an epidemiological approach: that is, on the excess human lung cancer in groups known to have been exposed to radon progeny.*

The two (2) epidemiological studies included in Appendices 18 and 19 *(Cancer Mortality in a Texas County with Prior Uranium Mining and Milling Activities, 1950-2001*; Boice, J.D. Jr. et al, and *Cancer and Non-Cancer Mortality in Populations Living Near Uranium and Vanadium Mining and Milling Operations in Montrose County, Colorado, 1950-2000*; Boice, J.D. Jr. et al) show no excess cancers in the populations of these counties over a fifty (50) year period. The third study *A cohort study of uranium millers and miners of Grants, New Mexico, 1979–2005* dated August 28, 2008 shows no increase in mortality in a cohort of uranium mill workers. A fourth study relating to the Canon City Mill will be discussed in text that follows. The Agency should consider these studies in their epidemiological approach.

Comments on the Document Entitled *Final Report Review of Existing and Proposed Tailings Impoundment Technologies*

Final Report Review of Existing and Proposed Tailings Impoundment Technologies was prepared by S. Cohen & Associates of 1608 Spring Hill Road, Suite 400, Vienna, Virginia. The following is a discussion of the document's inaccuracies as well as other problems with it:

- It lists only three (3) extant conventional uranium mills in the United States (Sweetwater, Canon City and White Mesa). It fails to list the Tickaboo Mill and tailings impoundment owned by Uranium One. It incorrectly lists the owner of the White Mesa mill as UMETCO when in fact the current owner is Denison Mines.

- The listed Radium-226 activity of the Sweetwater Uranium Project tailings is 280 picoCuries per gram. This is wrong. The average Radium-226 concentration is 70.9 picoCuries per gram as shown in the data presented in Appendix 1.

- The document states:

  > *In its previous assessments, the EPA has explicitly taken the fact of rapid drying into account by using a Rn-222 flux rate of 1 pCi/m2 –s/pCi/g Ra-226 to estimate the Rn-222 source term from the dry areas of the impoundments (EPA 1984, EPA 1989).*

  The future use of the relationship of 1 pCi per meter2-sec of radon flux per picocurie per gram of Radium-226 is not justified, at least not in the case of the tailings at the Sweetwater Uranium Project.

The average flux rate from exposed tailings over twenty-two (22) years is 8.69picoCuries per meter2-sec within average Radium-226 activity of 70.9 pCi per gram.

- The following table is included in the document:

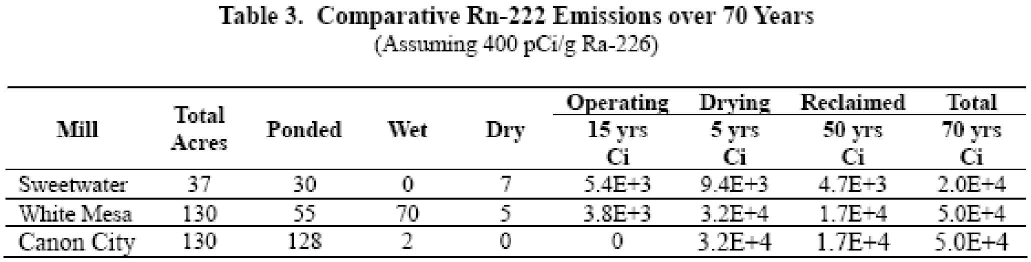


Table 3. Comparative Rn-222 Emissions over 70 Years
(Assuming 400 pCi/g Ra-226)

Mill	Total Acres	Ponded	Wet	Dry	Operating 15 yrs Ci	Drying 5 yrs Ci	Reclaimed 50 yrs Ci	Total 70 yrs Ci
Sweetwater	37	30	0	7	5.4E+3	9.4E+3	4.7E+3	2.0E+4
White Mesa	130	55	70	5	3.8E+3	3.2E+4	1.7E+4	5.0E+4
Canon City	130	128	2	0	0	3.2E+4	1.7E+4	5.0E+4

This table assumes a Radium-226 activity of 400 picoCuries per gram for the Sweetwater Uranium Project when in fact the current average Radium-226 activity is 70.9 picoCuries per gram based upon sample data enclosed in Appendix 1. Activities of the tailings resulting from any future processing activity are unknown and will depend on the nature of the material processed. At a worst case the following Radium-226 activity estimates for the tailings impoundment were used as inputs into the Radiological Assessment and the MILDOS run for the facility for resumed operation (Revised Environmental Report – August 1994 – Appendix H).

- The document entitled *Public Health Assessment for Lincoln Park/Cotter Uranium Mill Cañon City, Fremont County Colorado* discusses exposures to Radon-222 and its decay products in the vicinity of Cotter Corporation's Cañon City Mill and associated tailings impoundment. It states:

> *Outdoor concentrations of radon contributed zero dose to the public, because it is a noble gas and does not stay in the lungs long enough to radioactively decay. On the other hand, the dose from radon decay products (e.g., lead-210) attached to respirable dust held constant year over year accounted for an annual inhalation dose of four to seven millirem annually. Radon decay product concentration off-site did not appear to be related to releases from the site. Radon and its decay products appear to be from natural background and do not represent any health threat at the reported concentrations.*

This citation clearly states that radon decay product concentrations around the Cotter facility did not appear to be related to site emissions, but rather due to natural background despite the fact that the Cotter facility contains a tailings impoundment and associated ponds. This shows that Radon-222 and its decay products from this uranium recovery facility do not pose a public health concern. The document in its entirety is included in Appendix 34.

- The document continues by stating:

> *Using the sizes of the three existing conventional impoundments, and assuming identical grain sizes and a Ra-226 concentration of 400 pCi/g, the effect of impoundment size on Rn-222 emissions can be illustrated for the operational period, the drying period, and the reclamation period as shown in Table 3.*

The document again assumes a Radium-226 activity of 400 pCi/gram. As previously stated, current Radium-226 activity in the impoundment averages 70.9 pCi/gram. Estimated Radium-226 activities of tailings generated should operations resume are 249 pCi/gram (weighted average of slimes and sand) as shown in the table below:

	Activity	**Percentage**
Slimes:	353 picoCuries/gram	29%
Sand:	207 picoCuries/gram	71%
Weighted Average:	249 picoCuries/gram	100%

The tables below show Radon-222 emissions for the Sweetwater Uranium Project tailings impoundment based upon actual measured fluxes. The first table uses measured fluxes from non-water covered (dry) area and the area of the non-water covered areas while the second table uses the average flux from the impoundment as a whole and the area of the entire impoundment:

Using the average flux for the exposed tailings (8.69 picoCuries per meter2-second) and the average exposed tailings area (1990-2011):

Mill	Total Area	Ponded	Dry	Years 15	Years 5	Years 50	Total Years 70
Sweetwater	**161,809.89**	**74,103.72**	**87,704.82**	361	120	1202	1682

Using the average flux for the entire impoundment (4.65 picoCuries per meter2-second) and the average impoundment area (1990-2011):

Mill	Total Area	Ponded	Dry	Years 15	Years 5	Years 50	Total Years 70
Sweetwater	**161,809.89**	**74,103.72**	**87,704.82**	356	119	1186	1661

These calculated values based upon twenty-two (22) years of actual flux measurements are far less than the estimates provided in the document. This spreadsheet is included in Appendix 16.

The document discusses operating uranium in-situ recovery facilities. It lists Hydro Resources, Inc. Crownpoint and Churchrock facilities as operating, which they are not The Lost Creek Project with the listed owner as Lost Creek ISR is not an expansion of an exiting operation but an entirely new project.

The document discusses Radon-222 source terms for in-situ uranium recovery. It discusses Radon-222 releases from mud pits and uses the variable [Ra] which is defined as Ra-226 concentration in the ore zone (pCi/g). The mud pit contains cuttings from the entire bore hole not just from the ore zone. The actual thickness of the ore zone is a fraction of the depth of the entire hole, thus the cuttings from the ore zone would be diluted with cuttings with substantially lower radium-226 activity from above the ore zone. In a typical 500 foot deep bore hole only ten (10) feet of it would be in an actual ore zone. Cuttings from the ore zone would only represent 2% of the total cuttings mass. Use of the Radium-226 activity of the ore zone to describe the activity of the entire drill cuttings mass is incorrect.

The document discusses source terms for in-situ uranium recovery operations including producing wellfields, wellfields in restoration, and ion exchange columns. It provides an estimated radon-222 release for a typical operation of 197 Curies per year of Radon-222, while not discussing actual Radon-222 releases, the Generic Environmental Report in Support of the Nuclear Regulatory Commission's Generic Environmental Impact Statement for In Situ Uranium Recovery Facilities - National Mining Association (NMA) – November 30, 2007) discusses doses from an in-situ uranium recovery operation stating:

> *The HRI Final Environmental Impact Statement to Construct and Operate the Crownpoint Uranium Solution Mining Project, Crownpoint, New Mexico (HRI, 1997a) provides an estimate of population doses due to air effluent releases associated with that ISR project. Analysis was done within a 50-mile radius of the facility, and assumed that releases will come from the resin transfer/process circuit, the process circuit pressure vents, and the land application of restoration water. (Land application values were not presented in the report as, currently, land application of restoration water is problematic). The dryers proposed for the site are vacuum dryers that are assumed to have no radioactive releases. Thirty-eight receptor sites were used, and the estimated TEDE above background determined through the study indicated doses ranging from 0.07 mrem/yr at the nearest school to 0.76 mrem/yr at the nearest residence to the Crownpoint facility (0.6 miles away). Permissible dose limits in 10 CFR Part 20 are 100 mrem/yr TEDE and 2 mrem/hr from any external source. The conclusion was that the estimated doses modeled for babies due to their higher sensitivity to radiation exposure were far below the permissible dose level. The maximum estimated dose was less than 1 percent of the permissible limit and consistent with NCRP's negligible individual risk level (NIRL) (i.e., 1 mrem/yr) defined as "a level*

> *of average annual excess risk of fatal health effects attributable to irradiation, below which further effort to reduce radiation exposure to the individual is unwarranted."*

This Final Environmental Impact Statement (EIS) shows the maximum dose at less than 1% of the permissible limit and being at negligible individual risk level (NIRL). Additional regulation at this low level of risk is unwarranted.

Evaporation Pond Radon Flux Analysis, Piñon Ridge Mill Project Montrose County Colorado / Uranium Mill Tailings Radon Flux Calculations Piñon Ridge Project Montrose County, Colorado

These two (2) documents included in Appendix 37 discuss the planned Piñon Ridge Mill. They conclude that the Radon-222 flux from the site evaporation ponds is equivalent to background Radon-222 fluxes, stating:

> *Conservative estimates of radon flux indicate that the emissions are low and less than or similar to the pre-operational average background radon flux of 1.7 pCi* m^{-2} s^{-1} *observed at various locations within the proposed tailings areas on the site. The estimated radon flux levels from the evaporation ponds is also a small fraction (less than 10%) of the 20 pCi* m^{-2} s^{-1} *limit for pre-1989 uranium tailings that has been assumed here for context. This conservative estimate was based on the Nielson and Rogers model. The model assumes that the emission rates are enhanced by the turbulence at the top layer of the water column where all the radon in the top one-meter of water is assumed to be released to air instantaneously.*

They also concluded that the doses from radon due to all sources (fluid retention impoundments and the tailings impoundment itself) to the nearest residents would be less than 1 mrem/year as stated below:

> *The report "Estimates of Radiation Doses to Members of the Public from the Piñon Ridge Mill" (Two Lines, 2009) also provides insight on the potential radon doses resulting from the ore stockpile, tailings cells and mill emissions. This report is included in EFRC's Radioactive Materials License Application to the Radiation Control Program of CDPHE. This study was conducted using the MILDOS Area model, which includes material properties, emission rates, and site-specific meteorological data as model inputs. The study projected that radon doses at the property's fence line from all sources would range from 1.2 to 9.0 millirems per year (mrem/yr), and the nearest residents to the mill would receive a dose of less than 1 mrem/year. The study conservatively assumed that one tailings cell had reached capacity and a second tailings cell was in the initial stages of operation.*

Comments on the Document Entitled Final Report History and Basis of NESHAPs and Subpart W

This document provides a history of the promulgation of the NESHAPs for Radionuclides and Specifically 40 CFR part 61 Subpart W.

The documents discuses the risk assessment process stating:

> *For Rn-222, the CAP88 computer codes were used to established ambient concentrations (pCi/m3) in each of the sectors in a 0-80 km radius of the source. The concentration within each sector was then converted to working level months (WLMs), based on a 0.70 equilibrium fraction between Rn-222 and its decay products, and a respiration rate appropriate to members of the general public. Using risk factors derived from human epidemiological studies, the WLM exposure data were converted to risks.*

The use of a 0.70 equilibrium factor for Radon-222 and its decay products in the initial rulemaking was unrealistically conservative. The average measured equilibrium factor for the Sweetwater Uranium Project is 0.161 which is much less than 0.70. The Environmental Protection Agency (EPA) uses a lower equilibrium factor itself in establishing the 4 picocurie per liter action level for Radon-222 in homes. It uses an equilibrium factor of 0.50. The use of an equilibrium factor of 0.70 is an initial flaw in the calculation of radon risk. It conflicts with current (November 30, 2007) discussion in the National Mining

Association's Generic Environmental Report in Support of the Nuclear Regulatory Commission's Generic Environmental Impact Statement for In Situ Uranium Recovery Facilities, which states:

> *For a wind speed of 5 mph, the fractional ingrowth at 1 mile (approximately 12 minutes down wind) will be about 0.18.*

The Agency document prepared by S. Cohen and Associates continues by stating:

> *Radon-222 source terms were estimated on the assumption that a Rn-222 flux of 1 pCi/m2 -sec results for each 1 pCi/g Ra-226 in the tailings and the areas of dried tailings at each site. The radon flux rate of 1 pCi/m2-sec per pCi/g Ra-226 was derived based on both theoretical radon diffusion equations and the available radon emissions measurements.*
>
> *For each sector in the 0–80 km grid around each facility, the estimated Rn-222 airborne concentration was converted to cumulative WLMs assuming a 0.70 equilibrium fraction between radon and its decay products, an average respiration rate appropriate for members of the general public, and the assumption of continuous exposure over a 70-year lifetime.*

In following this calculation procedure the excessive ratio of 1 picoCurie per meter2-sec of Radon-222 flux to 1 picoCurie per gram radium-226 is now used in combination with the unrealistically conservative equilibrium factor of 0.70. The use of two (2) overly conservative values in the calculation serves to greatly and unrealistically exaggerate the risk.

The document states,

> *The ingrowth and decay of the Rn-222 decay products is very important to estimating the risks from Rn-222 exposure. When the Rn-222 emanates from the tailings, the fraction of its short-lived decay products is zero, as they are retained in the tailings matrix. However, their ingrowth begins immediately, and theoretically could reach 100% (total equilibrium) at some distance. As a practical matter, 100% ingrowth is unlikely to ever be attained, due to dry deposition and scavenging during plume transport. For the Subpart W assessments, the equilibrium fraction of decay products was set at 0.70. The equilibrium fraction of 0.70 is appropriate for distances beyond approximately 15,000 meters from the impoundments (where the majority of the exposed populations are located) and assumes that an individual spends 75% of their time indoors. For individuals nearer to the impoundments than 15,000 meters, the assumption of a 0.70 equilibrium fractions will over-state their exposure and resulting risk.*

Again the use of an equilibrium factor of 0.70 is discussed. The document states that at distances less than 15,000 meters (9.3 miles) the exposure and risk will be overstated. It is doubtful that Radon-222 from any tailings impoundment could be detected at a distance of 9.3 miles and certainly it is not detectable at a distance of approximately 0.5 miles at the Sweetwater Uranium Project at the downwind monitoring station (Air – 4A)

Required Radon Measurements around Evaporation Ponds

The agency in 2009 required certain uranium recovery licensees to perform radon measurements around fluid retention impoundments at their sites. The agency required that the licensees place fifteen (15) RadTrak detectors in each of five (5) lines extending out from the impoundment. These five (5) lines were North, East, South West and in the predominate downwind direction of the impoundment. Kennecott Uranium Company does not believe that radon fluxes from the surfaces of fluid retention impoundments can be accurately measured in this fashion and that the only current methodology is to use Large Area Activated Charcoal Canisters (LAACCs) floated on the fluid surface. The reason for this belief is that fluid retention impoundments either have embankments of some sort or are below grade meaning that air flow across them is not simple and can only be approximated by the use of computational fluid dynamics (CFD). In addition vegetation and structures complicate air flow. To further explain this issue the following three (3) documents are included in Appendices 29 to 31:

- *A Framework for Fine-Scale Computational Fluid Dynamics Air Quality Modeling and Analysis*
- *Modeling Near-Road Air Quality Using a Computational Fluid Dynamics Model – CFD-VIT-RIT*
- *Using CFD to Study Air Quality in Urban Microenvironments*

Using CFD to Study Air Quality in Urban Microenvironments by J.D. McAlpine and Michael Ruby discusses the influence of terrain and vegetation stating:

> *Upstream objects such as buildings, hills, or vegetation may create large eddies and other flow variations which will have an impact on the incoming flow of our domain.*
>
> *Wind speed variance cannot be estimated so easily, being greatly dependent on the nature of upwind obstacles. The surface layer itself is in a constant rolling turbulence, even without upwind obstacles, due to its viscous nature and the mixing of higher momentum wind down towards the surface.*

This issue is also discussed in **A FRAMEWORK FOR FINE-SCALE COMPUTATIONAL FLUID DYNAMICS AIR QUALITY MODELING AND ANALYSIS** by Alan H. Huber, which states:

> *Unlike currently used regulatory air quality models, fine-scale CFD simulations are able to account rigorously for topographical details such as terrain variations and building structures in urban areas as well as their local aerodynamics and turbulence. Thermal heat fluxes may be added to terrain and building surfaces to simulate the thermal atmospheric boundary layer and their influences on pollution transport and dispersion. The results of these CFD simulations can both be directly used to better understand specific case studies as well as be used to support the development of better simplified algorithms for adoption into other modeling systems.*
>
> *Pollution concentrations potentially contributing to human exposure may be considered composed of a regional background concentration due to long range transport, regional scale mixing, and specific local microenvironmental concentrations …"*
>
> *Fine-scale CFD models can be both interfaced with and applied independent of a larger scale grid model to support the development of human exposure factors and human exposure profiles dominated by local source emissions.*

Alan Huber directly ties the use of computational fluid dynamics to the development of human exposure factors and profiles.

Modeling Near-Road Air Quality Using a Computational Fluid Dynamics Model, CFD-VIT-RIT by Y. Jason Wang and K. Max Zhang specifically discusses embankments stating:

> *An embankment acts as a topographic obstacle which causes a form drag and produces turbulence to compensate for the deformation of the flow field when wind flows over it (35). A recirculation cavity is created downwind of the embankment, containing a well-mixed, and often lower, zone of pollution concentrations (36). The induced turbulence depends on the wind velocity, wind direction, the height and the shape of the embankment (15, 33).*

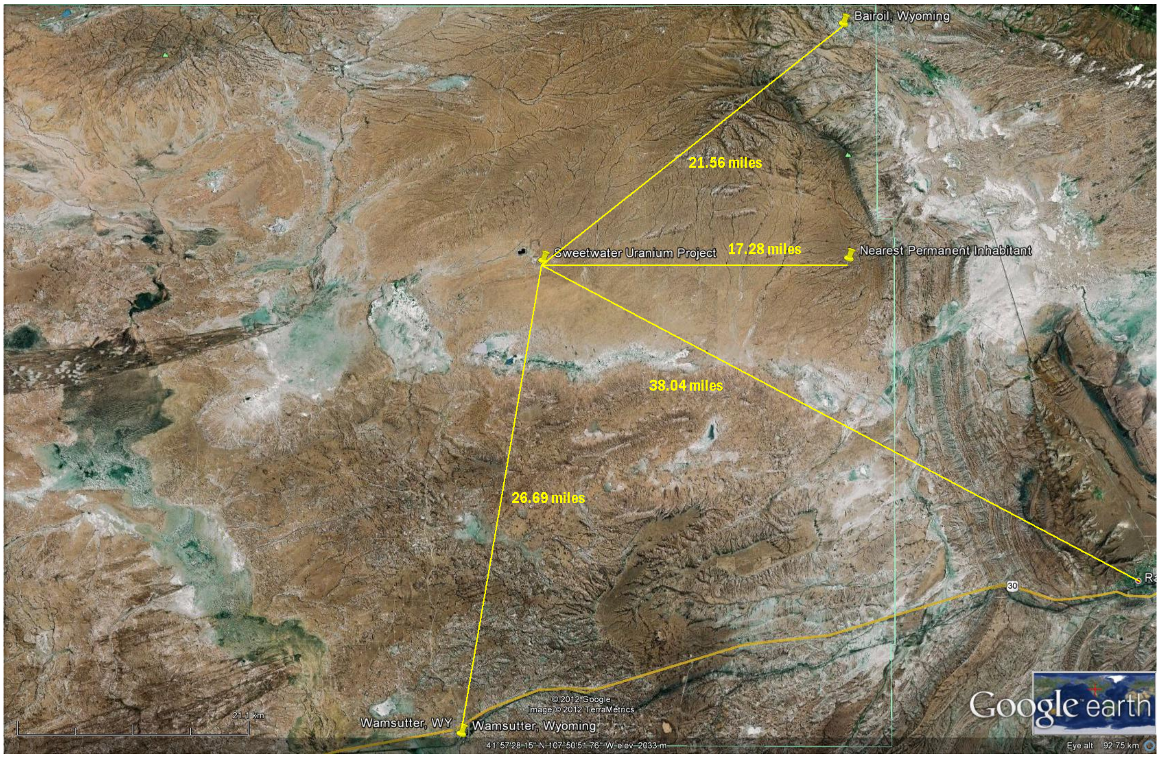
Unless the agency wishes to perform Radon-222 and decay product activity balances across fluid retention impoundments using computational fluid dynamics (CFD), uses of floating Large Area Activated Charcoal Canisters (LAACCs) should be considered as an acceptable method for determining Radon-222 flux from fluid surfaces, especially given the fact that Large Area Activated Charcoal Canisters (LAACCs) are the only currently accepted method for measuring radon flux. The use of computational fluid dynamics to model radon and radon decay product activities in air would require unrealistic commitments of manpower. Use of floating LAACCs is easier and far more direct.

Comments on the *Risk Assessment Revision for 40 CFR Part 61 Subpart W – Radon Emissions from Operating Mill Tailings*

On November 10, 2011, the agency released the document entitled *Risk Assessment Revision for 40 CFR Part 61 Subpart W – Radon Emissions from Operating Mill Tailings.* Kennecott Uranium Company reviewed the document. The document consisted of detailed risk assessments of eight (8) existing uranium recovery sites. One of the sites was Kennecott Uranium Company's Sweetwater Uranium Project. These comments will be confined to the detailed risk assessment of that site since Kennecott Uranium Company is most familiar with that site, having been that site's licensee for approximately twenty (20) years.

The following are Kennecott Uranium Company's comments:

- **Use of SECPOP/Population Distribution**
    - The document states, "*The SECPOP program was used to estimate the population distribution around each site; that population was then modified to account for changes in the population from 2000 to 2010*."
    - Kennecott Uranium Company does not believe that for the purposes of the estimation of radiologic risk; estimates of population based solely on computer models should be used. At the very least, the model's population estimates should be field verified.
    - The program estimated a population of three (3) people ten (10) to twenty (20) kilometers north-northeast of the facility and forty-seven (47) people thirty (30) to forty (40) kilometers south-southwest of the facility. The nearest inhabited locations are approximately 17.28 miles (27.81 kilometers) east of the facility, 26.69 miles (42.95 kilometers) south of the facility (Wamsutter, Wyoming), 21.56 miles (34.70 kilometers) northeast of the facility (Bairoil, Wyoming) and 38.04 miles (61.22 kilometers) to the southeast (Rawlins, Wyoming). The population distribution should not show any inhabitants within twenty-seven (27) kilometers of the facility. Jeffrey City, Wyoming (30.77 miles to the north) is not shown since it lies on the other side of Green Mountain from the facility and probably does not receive wind that has passed over the facility.
    - The image below, modified from a Google Earth image, shows the nearest inhabitants to the facility:



- **Radon Flux Testing Results**
    - The report only used radon flux data for the tailings impoundment from 1990 to 2003. A method 115 test of the impoundment is performed annually, generally in August and a report regarding the flux test is submitted to the agency. As such the agency should present data in the report up to and including the 2009 test data.
- **Use of the Model CAP88**
    - Kennecott Uranium Company disagrees with the use of CAP88 to model exposures to Radon-222 and its decay products. Dr. Jan Johnson of TetraTech stated the following regarding the use of CAP88:
        - "*.. it does not calculate dose from radon decay products just risk. You have to back-calculate dose from the risk. It does calculate dose from radon gas but I suspect SC&A calculated radon decay product dose from risk*." (Dr. Jan Johnson email)
    - For the above reason Kennecott Uranium Company believes that MILDOS should be used.
    - In addition, MILDOS is the standard agency accepted code to evaluate doses including those from Radon-222 and its progeny from uranium recovery facilities.
    - Regarding MILDOS Argonne National Laboratory states:
        - *The MILDOS-AREA computer code calculates the radiological dose commitments received by individuals and the general population within an 80-km radius of an operating uranium recovery facility. In addition, air and ground concentrations of radionuclides are estimated for individual locations, as well as for a generalized population grid. Extra-regional population doses resulting from transport of radon and export of agricultural produce are also estimated.*

          The transport of radiological emissions from point and different area sources is predicted with a sector-averaged Gaussian plume dispersion model. Mechanisms such as radioactive decay, plume depletion by deposition, ingrowth of decay products, and resuspension of deposited radionuclides are included in the transport model. Alterations in operation throughout the facility's lifetime can be accounted for in the input stream. The exposure pathways considered are inhalation; external exposure from groundshine and cloud immersion; and ingestion of vegetables, meat, and milk. Dose commitments are calculated primarily on the basis of the recommendations of the International Commission on Radiological Protection (ICRP). Only airborne releases of radioactive materials are considered in MILDOS-AREA; releases to surface water and to groundwater are not addressed in MILDOS-AREA. MILDOS-AREA is a multi-purpose code that can be used to evaluate population doses for NEPA assessments, maximum individual doses for predictive 40 CFR 190 compliance evaluations, or maximum offsite air concentrations for predictive evaluations of 10 CFR 20 compliance.

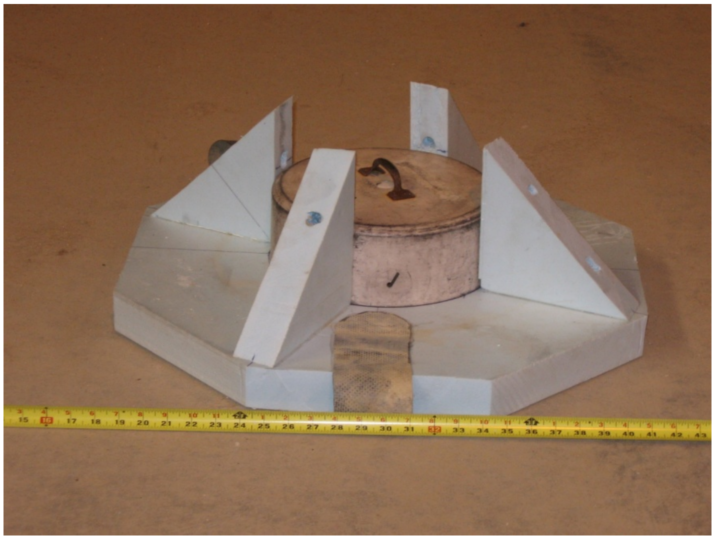
          The MILDOS-AREA computer code was designed as a primary licensing and evaluation tool and is expected to provide basic input to critical licensing, regulatory, and policy decisions. It is used by the staff of the Nuclear Regulatory Commission to perform routine radiological impact and compliance evaluations for various uranium recovery operations.

    - The code designed to calculate doses from uranium recovery operations should be the one that is used.

Determination of Radon-222 Fluxes from Fluid Filled Lagoons

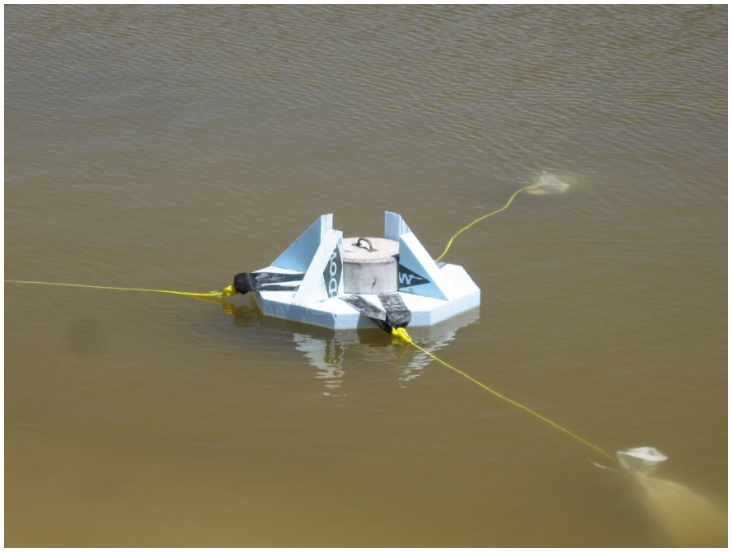
Kennecott Uranium Company conducted tests in August 2010 in fluid filled lagoons in the tailings impoundment at the Sweetwater Uranium Project to determine actual Radon-222 fluxes from fluid filled impoundments. These tests were conducted using Large Area Activated Charcoal Canisters (LAACCs) as described in *Radon Flux Measurements on Gardinier and Royster Phosphogypsum Piles near Tampa and Mulberry, Florida* January 1986) since this is the only currently accepted method to measure Radon-222 flux rates from surfaces.

The Large Area Activated Charcoal Canisters (LAACCs) were mounted on Styrofoam rafts as shown below and floated on the fluid surface in the lagoons. The Large Area Activated Charcoal Canisters (LAACCs) fit tightly over a large hole only slightly smaller than the diameter of the canister to ensure that there was no leakage of air between the lower lip of the canister and the Styrofoam raft. The raft in turn floated on the water surface. The bottom of the raft was slightly below the water surface due to the weight of the canister insuring a seal between the fluid surface and the Styrofoam raft.



Styrofoam float with Large Area Activated Charcoal Canister (LAACC) on Floor

The image below shows a Styrofoam raft floating on the surface of a lagoon.



Styrofoam float with Large Area Activated Charcoal Canister (LAACC) Floating in Lagoon Tied to Anchors

Please note that there is a tight seal between the lagoon surface and the raft and between the raft and the canister.

Large Area Activated Charcoal Canisters (LAACCs) were floated on four (4) different water filled lagoons in the Sweetwater Uranium Project tailings impoundment for twenty-four (24) hour periods beginning on two (2) successive days to collect a total of twenty (20) radon flux readings. The water in each pond was tested for Radon-222 and Radium-226. The pond sediments in each pool were tested for Radium-226 and the radon emanation coefficient for the sediments in each of the four (4) lagoons was also determined. The results are included in Appendix 38 in a spreadsheet entitled "Radon Flux from Tailings Impoundment Pools". Appendix 39 includes the applicable testing procedures used in this study.

The measured fluxes were very low. In a presentation entitled *Radon Flux from Evaporation Ponds* (Kenneth Baker and Al Cox 2010) included in Appendix 22 it was concluded that radon flux from the surface of fluid retention impoundments should obey the stagnant film model and that the Radon-222 flux in picoCuries per meter2-second should equal 0.01 times the Radon-222 activity of the fluid. In the presentation actual Radon-222 activities for the fluid were not provided. The fluids were tested for Radium-226 and the Radon-222 in the fluids was assumed to be in radiometric equilibrium with the Radium-226. Since the measured Radium-226 activity of the fluid was 165 picoCuries per liter it was assumed that the Radon-222 activity of the fluid was also approximately 165 picoCuries per liter. The measured Radon-222 flux was reported at 1.13 picoCuries per liter which roughly agrees with the value calculated using the stagnant film model.

In the tests conducted in the lagoons in the tailings impoundment at the Sweetwater Uranium Project in August 2010 the radon fluxes in picocuries per meter2-second averaged 0.001 times (rounded to three (3) significant figures) the Radon-222 activity of the fluid in picoCuries per liter. This is an order of magnitude lower that that predicted by the Stagnant Film Model.

Testing clearly demonstrates that Radon-222 fluxes from the surface of fluid retention impoundments is very low and does not warrant regulation. These results are in keeping with the Radon-222 fluxes for fifty (50) centimeter turbulent mixing depths reported by Dr. Doug Chambers in his 2009 presentation included in Appendix 9.

Conclusions

Kennecott Uranium Company has been involved in this regulatory process since its inception with the presentation given at the April 28, 2010 meeting of the National Mining Association (NMA)/Nuclear Regulatory Commission (NRC) Uranium Recovery Workshop. Kennecott Uranium Company has examined its own data regarding radon emissions from its tailings impoundment and other related documentation and has reached the following conclusions:

- 40 CFR Part 61 Subpart W does not apply to fluid retention impoundments at licensed uranium recovery facilities as per the legal discussion provided in Appendix 12. Kennecott Uranium Company concurs with the conclusions of this document.

- Expansion of the scope of 40 CFR Part 61 Subpart W to include fluid retention impoundments will conflict with existing approved construction that has not as yet been built. The Sweetwater Uranium Project has existing approval to construct one (1) additional tailings impoundment on site as well as eight (8) evaporation ponds with the potential for two (2) more. In addition in a letter dated March 21, 1996 from the Environmental Protection Agency (EPA), the existing sixty (60) acre evaporation pond was grandfathered and can be used in conjunction with one new forty 940) acre impoundment provided the tailings in the existing impoundment are leveled and the impoundment relined. The approval in Source Material License SUA-1350 was only granted following a NEPA review and a Finding of No Significant Impact (FONSI) which is included in Appendix 14.

- The risks from Radon-222 exposure are not directly due to Radon-222 itself which is a noble gas but rather due to its decay products which affix themselves to airborne particles. Regular measurements taken from 1993 to the present show that the equilibrium factor (ratio between the activity of the Radon-222 and its decay products in air) is, at least for the Sweetwater Uranium Project, quite low (0.161). This low equilibrium factor equates to a lower risk. The Agency used higher equilibrium factors when 40 CFR Part 61 Subpart W was prepared and persists in citing these factors today. Realistic, measured equilibrium factors should be the only ones used.

- Data presented by Doug Chambers at the 2009 Uranium Recovery Workshop in Denver, Colorado, included in Appendix 9, shows that radon emissions from fluid retention impoundments are very low to the point of being insignificant. It does not make sense to expand the scope of 40 CFR part 61 Subpart W to include these non-significant sources, especially in light of the fact that the risks from actual tailings impoundments are low and the risks from fluid retention impoundments are lower still. The data presented was confirmed by field testing at the Sweetwater Uranium Project.

- Kennecott Uranium Company, based upon twenty-two (22) Method 115 tests performed in its tailings impoundment, believes that the risk from radon in uranium mill tailings was vastly overestimated for two (2) reasons:
    - The existing basis for 40 CFR part 61 Subpart W used a relationship of one (1) picocurie per meter2-sec of radon flux per picocurie per gram of radium-226 in the tailings. This is clearly not true in the case of the Sweetwater Uranium Project's tailings impoundment. The relationship is closer to 0.12 picoCuries per meter2-sec to one (1) picoCurie per gram Radium-226 in the tailings.
    - The original studies did not appear to consider emanation coefficients in determining radon releases for tailings impoundments. Only a portion of the total Radon-222 released by the decay of Radium-226 actually enters the pore spaces and can be released into the air. In the case of the Sweetwater Uranium Project only 18.8% of the generated radon-222 actually enters the pore spaces.

  If the magnitude of Radon-222 emissions from tailings was overestimated in 1989, then it is likely that the magnitudes of radon emissions from fluid retention impoundments are being overestimated now, as well.

- None of the documents used as the basis of 40 CFR part 61 Subpart W contained a comprehensive review of background Radon-222 concentrations and their sources. Naturally occurring background Radium-226 activities in soils in uranium producing areas can be very high as discussed in the text. These high Radium-226 activities yield high natural Radon-222 fluxes from soils and high ambient Radon-222 and Radon-222 decay product concentrations in air. At the Sweetwater Uranium Project, average upwind Radon-222 concentrations in ambient air are higher than the average downwind concentrations of Radon-222 in spite of the presence of a tailings impoundment on site. The contribution from radon emissions from the tailings impoundment to radon concentrations in ambient air downwind of the facility cannot be detected. Downwind Radon-222 concentrations are lower than the upwind concentrations. The contribution of Radon-222 from the tailings impoundment to ambient air at the Sweetwater Uranium Project is not measureable. High background Radion-222 concentrations in upwind air as well as high naturally occurring radon fluxes from the ground surface around uranium recovery facilities should be considered in establishing any limits on Radon-222 emissions from tailings impoundments and in designing any Radon-222 measurement, modeling, or monitoring protocols.

- The key issue in regulating Radon-222 emissions from tailings impoundments is dose to the general public and/or nearest resident to the facility. At the Sweetwater Uranium Project, doses to the nearest resident (the Security Guard) have been measured since the second half of 1994. The average dose for the period was 0.61 millirems per year. This is insignificant when compared to the facility's background Radon-222 dose for the same time period of 347.73 millirems. The standard deviation of this average background dose is 129.82 millirems. Any dose from Radon-222 and its decay products for the tailings impoundment is lost in the variability of background.

- Long term (fifty-one (51) year epidemiological studies of two (2) counties (Karnes County, Texas and Montrose County, Colorado) which hosted both uranium processing facilities and uranium mines showed no increase in cancer risk. Both of these studies extend back into the time prior to the enactment of 40 CFR Part 61 Subpart W and its associated restrictions. The preamble to 40 CFR Part 61 Subpart W (final rule) states, "*Since there is such a strong foundation for quantifying the risk of fatal cancer. EPA's consideration of fatal cancers is the principal health consideration in this rulemaking.*" The fact that no excess cancers have been detected in two (2) epidemiological studies calls into the question the need for 40 CFR Part 61 Subpart W, specifically the need for regulating radon emissions to ambient air from uranium mill tailings impoundments and fluid retention impoundments.

- The Agency's calculations in the document entitled *Final Report Review of Existing and Proposed Tailings Impoundment Technologies* prepared by S. Cohen and Associates is unrealistically conservative. In the case of the Sweetwater Uranium Project, it uses incorrect Radium-226 activity values for the tailings.

- 40 CFR Part 61 Subpart W was based upon unrealistically conservative values for radon emanation from tailings (I picocurie per meter2-sec per 1 picoCurie per gram Radium-226) and an unrealistically conservative equilibrium factor of 0.70.

- Kennecott Uranium Company believes that in order for the risk assessment *Risk Assessment Revision or 40 CFR Part 61 Subpart W – Radon Emissions from Operating Mill Tailings* to have any validity accurate population information must be used and MILDOS must be used instead of CAP88 since MILDOS is specifically designed to model doses from uranium recovery facilities.

- Radon flux testing conducted on fluid surfaces in lagoons containing water containing entrained Radon-222 show that the surface flux is insignificant and approximately an order of magnitude less than predicted by the Stagnant Film Model (SFM).

Kennecott Uranium Company believes that:

- 40 CFR part 61 Subpart W was predicated upon unrealistically conservative assumptions that resulted in inflated and unjustified estimates of risk from Radon-222 from uranium mill tailings impoundments and that it failed to account for elevated backgrounds in uraniferous regions, actual as opposed to estimated radon flux rates and actual as opposed to estimated equilibrium factors.

- To extend 40 CFR Subpart W to include fluid retention impoundments is unjustified since they constitute even lower risk impoundments than the tailings impoundments themselves.

Kennecott Uranium Company appreciates the opportunity to comment on these issues. If you have any questions please do not hesitate to contact me.

Sincerely yours,

Oscar A Paulson
Oscar Paulson
Facility Supervisor

cc: Katie Sweeney – National Mining Association (NMA)

List of Appendices

Appendix	Title
18	Cancer mortality in a Texas county with prior uranium and milling activities, 1950 - 2001 with commentary by Dr. Nancy Standler MD, PhD
19	Cancer and Noncancer Mortality in Populations Living Near Uranium and Vanadium Mining and Milling Operations in Montrose County, Colorado 1950-2000 with commentary by Dr. Nancy Standler MD, PhD
20	Areas Around the Sweetwater Uranium Project
21	Evaluation of Radon-222 Near Uranium Tailings Piles
22	Radon Flux from Evaporation Ponds - A presentatioin by Kenneth R. Baker PhD and Alan D. Cox
23	A cohort study of uranium millers and miners of Grants, New Mexico 1979 - 2005
24	Environmental Assessment Regarding License Renewal and the Reclamation Design for the Kennecott Uranium Company's Sweetwater Uranium Mill Site in Wyoming
25	Sweetwater Uranium Project - Preoperatioinal Background Surface Radionuclide Sampling Data
26	Mortality among a cohort of uranium mill workers: an update
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28	Radon Emissions Estimates - Natural and Man Induced
29	A Framework for Fine-Scale Computational Fluid Dynamics Air Quality Modeling and Analysis
30	Modeling Near-Road Air Quality Using a Computational Fluid Dynamics Model, CFD-VIT-RIT
31	Using CFD to Study Air Quality in Urban Microenvironments
32	Five-Hundred Life-Saving Interventions and Their Cost-Effectiveness
33	Commentary by Dr. Nancy Standler MD, PhD, on Five-Hundred Life-Saving Interventions and Their Cost-Effectiveness

Appendix 1

Table A-5 Tailings Radiochemical Testing Results

Sample I.D	Sample Type/Date	Radium Activity (pCi/g)	Emanation Coefficient
1B	Grab - 11/96	27.7	0.188
2B	Grab - 11/96	188	0.258
3B	Grab - 11/96	193	0.070
4B	Grab - 11/96	26.3	0.238
5B	Grab - 11/96	183	0.116
6B	Grab - 11/96	21.6	0.122
7B	Grab - 11/96	11.6	0.089
8B	Grab - 11/96	31.9	0.070
9B	Grab - 11/96	19.5	*
10B	Grab - 11/96	22.0	0.170
TL-1 19'-21'	Split-Spoon - 4/97	42.3	0.271
TL-1 21'-23'	Split-Spoon - 4/97	88.5	0.320
TL-3 2'-4'	Split-Spoon - 4/97	17.8	0.111
TL-3 4'-6'	Split-Spoon - 4/97	17.2	0.195
TL-4 2'-4"	Split-Spoon - 4/97	254	0.140
TL-4 14'-16'	Split-Spoon - 4/97	20.2	0.270
TL-7 2'-4'	Split-Spoon - 4/97	21.7	*
TL-7 12'-14'	Split-Spoon - 4/97	35.0	0.146
TL-9 10'-11.3'	Split-Spoon - 4/97	126	0.333
TL-9 11.3'-15'	Split-Spoon - 4/97	69.7	0.281
Mean Value		**70.9 pCi/g[1]**	**0.188**

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[1] This value was incorrectly reported as 70.4 pCi/g in Volume II, Data Report

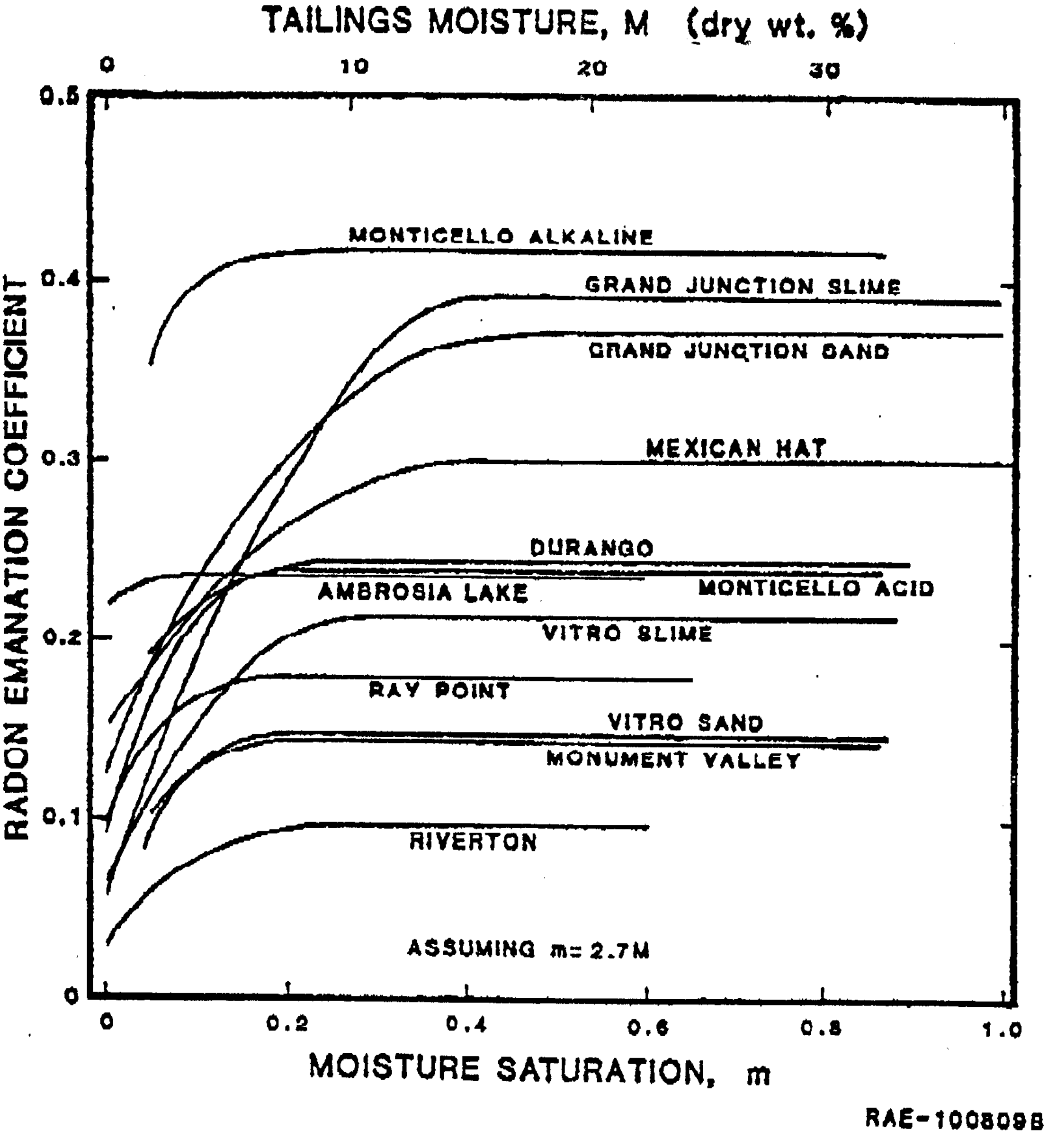

FIGURE 15. RADON EMANATION COEFFICIENTS FOR TAILINGS SAMPLES.

Appendix 2

KENNECOTT URANIUM COMPANY
LOST CREEK TRENCH SAMPLING
Sections 2-7

Source: **Geology of the Lost Creek Schroeckingerite Deposits Sweetwater County, Wyoming**
Geological Survey Bulletin 1087-J

SAMPLE #	SAMPLE AREA	SAMPLE LENGTH	PERCENT EQUIVALENT URANIUM	PERCENT EQUIVALENT URANIUM-238	EQUIVALENT URANIUM-238 ACTIVITY	RADIUM-226 ACTIVITY	PERCENT URANIUM	NATURAL URANIUM ACTIVITY
					(picoCuries per gram)	(picoCuries per gram)		(picoCuries per gram)
DS-52-237	1.9		0.004	0.004	13.5	13.5	0.004	27.1
DS-52-238	4.9		0.005	0.005	16.9	16.9	0.004	27.1
DS-52-239	4.8		0.007	0.007	23.6	23.6	0.012	81.2
DS-52-242	1.2		0.008	0.008	27.0	27.0	0.015	101.6
DS-52-248	0.6		0.021	0.021	70.9	70.9	0.048	325.0
DS-52-249	4.4		0.027	0.027	91.1	91.1	0.06	406.2
DS-52-250	3		0.014	0.014	47.3	47.3	0.024	162.5
DS-52-251	0.8		0.008	0.008	27.0	27.0	0.012	81.2
DS-52-256	1.3		0.008	0.008	27.0	27.0	0.012	81.2
DS-52-257	5.7		0.012	0.012	40.5	40.5	0.018	121.9
DS-52-258	2.6		0.01	0.010	33.8	33.8	0.019	128.6
DS-52-259	2		0.014	0.014	47.3	47.3	0.015	101.6
DS-52-262	0.7		0.021	0.021	70.9	70.9	0.035	237.0
DS-52-263	2.9		0.025	0.025	84.4	84.4	0.049	331.7
DS-52-264	5.5		0.027	0.027	91.1	91.1	0.053	358.8
DS-52-265	3.2		0.015	0.015	50.6	50.6	0.029	196.3
DS-52-265A	4.1		0.029	0.029	97.9	97.9	0.06	406.2
DS-52-266	6.9		0.017	0.017	57.4	57.4	0.034	230.2
DS-52-267	0.4		0.007	0.007	23.6	23.6	0.015	101.6
DS-52-275	6.4		0.039	0.039	131.6	131.6	0.08	541.6
DS-52-207	1.2		0.013	0.013	43.9	43.9	0.021	142.2
DS-52-213	0.8		0.047	0.047	158.7	158.7	0.087	589.0
DS-52-214	3		0.014	0.014	47.3	47.3	0.022	148.9
DS-52-216	1.3		0.012	0.012	40.5	40.5	0.022	148.9
DS-52-218	5.6		0.016	0.016	54.0	54.0	0.035	237.0
DS-52-220	4.9		0.019	0.019	64.1	64.1	0.038	257.3
DS-52-222	3.3		0.012	0.012	40.5	40.5	0.024	162.5
DS-52-227	0.7		0.029	0.029	97.9	97.9	0.065	440.1
DS-52-228	1.3		0.037	0.037	124.9	124.9	0.072	487.4
DS-52-230	1.5		0.016	0.016	54.0	54.0	0.03	203.1
DS-51-199	1.2		0.008	0.008	27.0	27.0	0.013	88.0
DS-52-200	0.3		0.007	0.007	23.6	23.6	0.008	54.2
DS-52-204	1.2		0.012	0.012	40.5	40.5	0.022	148.9
DS-52-224	4		0.016	0.016	54.0	54.0	0.031	209.9
DS-52-233	1.2		0.01	0.010	33.8	33.8	0.012	81.2
DS-52-236	4		0.01	0.010	33.8	33.8	0.016	108.3
DS-52-184	3.5		0.023	0.023	77.6	77.6	0.041	277.6
DS-52-186	1.5		0.011	0.011	37.1	37.1	0.015	101.6
DS-52-190	2		0.02	0.020	67.5	67.5	0.043	291.1
DS-52-193	1		0.011	0.011	37.1	37.1	0.013	88.0
DS-52-194	0.2		0.03	0.030	101.3	101.3	0.062	419.7
DS-52-197	0.5		0.024	0.024	81.0	81.0	0.051	345.3
DS-52-149	4.3		0.015	0.015	50.6	50.6	0.015	101.6
DS-52-150	6.8		0.023	0.023	77.6	77.6	0.037	250.5
DS-52-152	0.3		0.009	0.009	30.4	30.4	0.01	67.7
DS-52-153	7.3		0.013	0.013	43.9	43.9	0.019	128.6
DS-52-155	1.4		0.004	0.004	13.5	13.5	0.004	27.1
DS-52-158	4.1		0.011	0.011	37.1	37.1	0.016	108.3
DS-52-141	20		0.011	0.011	37.1	37.1	0.013	88.0
DS-52-143	1.6		0.01	0.010	33.8	33.8	0.007	47.4
DS-52-145	1.7		0.005	0.005	16.9	16.9	0.003	20.3
DS-52-146	0.2		0.008	0.008	27.0	27.0	0.007	47.4
DS-52-99	2.8		0.034	0.034	114.8	114.8	0.055	372.4
DS-52-100	1.2		0.028	0.028	94.5	94.5	0.05	338.5
DS-52-101	4.5		0.03	0.030	101.3	101.3	0.053	358.8
DS-52-102	0.6		0.018	0.018	60.8	60.8	0.022	148.9
DS-52-103	3.7		0.026	0.026	87.8	87.8	0.036	243.7
DS-52-104	0.2		0.044	0.044	148.5	148.5	0.072	487.4
DS-52-107	7.6		0.037	0.037	124.9	124.9	0.066	446.8
DS-52-109	1		0.024	0.024	81.0	81.0	0.037	250.5
DS-52-110	0.6		0.035	0.035	118.1	118.1	0.055	372.4
DS-52-113	2		0.042	0.042	141.8	141.8	0.051	345.3
DS-52-24	0.5		0.024	0.024	81.0	81.0	0.035	237.0
DS-52-25	1.4		0.032	0.032	108.0	108.0	0.48	3249.6
DS-52-27	9.8		0.019	0.019	64.1	64.1	0.026	176.0
DS-52-28	2.8		0.06	0.060	202.5	202.5	0.11	744.7
DS-52-31	4.8		0.025	0.025	84.4	84.4	0.041	277.6
DS-52-32	2		0.05	0.050	168.8	168.8	0.079	534.8
DS-52-33	1.5		0.044	0.044	148.5	148.5	0.071	480.7
DS-52-34	8.7		0.026	0.026	87.8	87.8	0.041	277.6
DS-52-35	4.1		0.014	0.014	47.3	47.3	0.015	101.6
DS-52-45	2		0.024	0.024	81.0	81.0	0.05	338.5
DS-52-46	26.8		0.049	0.049	165.4	165.4	0.097	656.7
DS-52-47	11.8		0.041	0.041	138.4	138.4	0.075	507.8
DS-52-59	5.9		0.028	0.028	94.5	94.5	0.038	257.3
DS-52-60	12.8		0.018	0.018	60.8	60.8	0.023	155.7
DS-52-61	10.7		0.02	0.020	67.5	67.5	0.029	196.3
DS-52-62	12.2		0.034	0.034	114.8	114.8	0.055	372.4
DS-52-63	16		0.06	0.060	202.5	202.5	0.12	812.4
DS-52-64	4		0.013	0.013	43.9	43.9	0.015	101.6
DS-52-65	9.3		0.058	0.058	195.8	195.8	0.11	744.7
DS-52-66	8.8		0.049	0.049	165.4	165.4	0.078	528.1
DS-52-67	0.7		0.016	0.016	54.0	54.0	0.026	176.0
DS-52-79	0.5		0.024	0.024	81.0	81.0	0.031	209.9
DS-52-80	65		0.017	0.017	57.4	57.4	0.021	142.2
DS-52-81	7.5		0.016	0.016	54.0	54.0	0.023	155.7
DS-52-82	7.4		0.032	0.032	108.0	108.0	0.057	385.9
DS-52-53	5.4		0.02	0.020	67.5	67.5	0.031	209.9

DS-52-84	1.3		0.031	0.031	104.6	104.6	0.047	318.2
DS-52-58	4.4		0.021	0.021	70.9	70.9	0.027	182.8
DS-52-86	8.2		0.028	0.028	94.5	94.5	0.037	250.5
DS-52-87	3.1		0.031	0.031	104.6	104.6	0.043	291.1
DS-52-88	1.6		0.049	0.049	165.4	165.4	0.07	473.9
DS-52-2	1.5		0.035	0.035	118.1	118.1	0.079	534.8
DS-52-4	0.3		0.018	0.018	60.8	60.8	0.033	223.4
DS-52-5	0.2		0.011	0.011	37.1	37.1	0.018	121.9
DS-52-22	1.1		0.033	0.033	111.4	111.4	0.045	304.7
DS-52-7	2.2		0.017	0.017	57.4	57.4	0.03	203.1
DS-52-8	3		0.019	0.019	64.1	64.1	0.031	209.9
DS-52-10	6		0.025	0.025	84.4	84.4	0.041	277.6
DS-52-12	0.3		0.022	0.022	74.3	74.3	0.026	176.0
DS-52-13	9.5		0.037	0.037	124.9	124.9	0.063	426.5
DS-52-14	2.4		0.022	0.022	74.3	74.3	0.035	237.0
DS-52-15	2		0.022	0.022	74.3	74.3	0.032	216.6
DS-52-20	0.5		0.096	0.095	324.1	324.1	0.15	1015.5
LRP-28	6.7		0.011	0.011	37.1	37.1	0.017	115.1
LRP-31	5.8		0.008	0.008	27.0	27.0	0.008	54.2
LRP-10	4.5		0.01	0.010	33.8	33.8	0.017	115.1
LRP-7	0.6		0.004	0.004	13.5	13.5	0.002	13.5
LRP-12	2.1		0.017	0.017	57.4	57.4	0.029	196.3
LRP-H-14		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-13	2.5		0.013	0.013	43.9	43.9	0.019	128.6
LRP-14	3		0.012	0.012	40.5	40.5	0.014	94.8
LRP-15	6.4		0.017	0.017	57.4	57.4	0.026	176.0
LRP-16	2.3		0.015	0.015	50.6	50.6	0.019	128.6
LRP-18	1.6		0.01	0.010	33.8	33.8	0.014	94.8
LRP-19	0.7		0.007	0.007	23.6	23.6	0.005	33.9
LRP-20	0.8		0.02	0.020	67.5	67.5	0.029	196.3
LRP-24	1.7		0.019	0.019	64.1	64.1	0.037	250.5
DS-H-407		10	0.007	0.007	23.6	23.6	0.006	40.6
DS-H-406		10	0.006	0.006	20.3	20.3	0.007	47.4
DS-H-405		10	0.002	0.002	6.8	6.8	0.001	6.8
DS-H-404		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-H-260		10	0.005	0.005	16.9	16.9	0.004	27.1
DS-H-259		10	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-258		10	0.005	0.005	16.9	16.9	0.002	13.5
DS-H-257		10	0.004	0.004	13.5	13.5	0.003	20.3
DS-H-256		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-H-255		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-H-254		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-51-261	7.4		0.017	0.017	57.4	57.4	0.035	237.0
DS-51-259	2.4		0.01	0.010	33.8	33.8	0.013	88.0
DS-H-251		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-H-250		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-H-249		10	0.003	0.003	10.1	10.1	0.003	20.3
DS-H-248		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-H-247		10	0.004	0.004	13.5	13.5	0.001	6.8
DS-H-246		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-H-245		10	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-244		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-H-243		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-H-242		10	0.005	0.005	16.9	16.9	0.005	33.9
DS-51244B	0.4		0.004	0.004	13.5	13.5	0.004	27.1
DS-H-241		10	0.004	0.004	13.5	13.5	0.003	20.3
DS-H-240		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-52-161	6.2		0.014	0.014	47.3	47.3	0.02	135.4
DS-52-160	10.3		0.016	0.016	54.0	54.0	0.035	237.0
DS-52-159	4.7		0.019	0.019	64.1	64.1	0.033	223.4
DS-51-266	2		0.006	0.006	20.3	20.3	0.009	60.9
DS-51-264	3.6		0.028	0.028	94.5	94.5	0.05	338.5
DS-51-263	3.1		0.007	0.007	23.6	23.6	0.008	54.2
DS-51-262	1.1		0.008	0.008	27.0	27.0	0.01	67.7
DS-H-253		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-H-252		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-51-258	5.8	Sample missing		0.000	0.0	0.0		0.0
DS-51-252	2.5		0.003	0.003	10.1	10.1	0.003	20.3
DS-51-251	8.8		0.004	0.004	13.5	13.5	0.003	20.3
DS-51-250	8.7		0.004	0.004	13.5	13.5	0.003	20.3
DS-51-246	9		0.007	0.007	23.6	23.6	0.008	54.2
DS-51-245	10		0.017	0.017	57.4	57.4	0.025	169.3
	6.1	Not Sampled		0.000	0.0	0.0		0.0
DS-51-244A	0.6		0.045	0.045	151.9	151.9	0.075	507.8
DS-51-243	1.6		0.005	0.005	16.9	16.9	0.004	27.1
DS-52-164	4.8		0.009	0.009	30.4	30.4	0.013	88.0
DS-52-163	5.1		0.016	0.016	54.0	54.0	0.024	162.5
DS-52-162	7.5		0.018	0.018	60.8	60.8	0.039	264.0
	0.4	Not Sampled		0.000	0.0	0.0		0.0
DS-51-265	6.9		0.021	0.021	70.9	70.9	0.038	257.3
DS-51-260	3.2		0.004	0.004	13.5	13.5	0.006	40.6
DS-51-256	8.4		0.008	0.008	27.0	27.0	0.01	67.7
DS-51-255	2.2		0.004	0.004	13.5	13.5	0.004	27.1
DS-51-254	4.6		0.005	0.005	16.9	16.9	0.008	54.2
DS-51-253	4.4		0.006	0.006	20.3	20.3	0.009	60.9
DS-51-249	8.2		0.008	0.008	27.0	27.0	0.009	60.9
DS-51-248	17.5		0.006	0.006	20.3	20.3	0.008	54.2
DS-51-247	15.5		0.01	0.010	33.8	33.8	0.015	101.6
DS-51-257	4.6		0.008	0.008	27.0	27.0	0.008	54.2
DS-H-431		10	0.003	0.003	10.1	10.1	<.001	
DS-H-428		7	0.009	0.009	30.4	30.4	0.024	162.5
DS-H-427		5	0.006	0.006	20.3	20.3	0.009	60.9
DS-H-426		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-52-172	0.4		0.008	0.008	27.0	27.0	0.011	74.5
DS-H-411		10	0.005	0.005	16.9	16.9	0.002	13.5
DS-52-165	4.9		0.023	0.023	77.6	77.6	0.044	297.9
DS-H-409		10	0.003	0.003	10.1	10.1	0.001	6.8
DS-H-408		10	0.003	0.003	10.1	10.1	<.001	

DS-H-407	continued in E'-F'			0.000	0.0	0.0		0.0
DS-H-430		10	0.003	0.003	10.1	10.1	<.001	
DS-H-429		8	0.004	0.004	13.5	13.5	<.001	
DS-52-179	2.9		0.012	0.012	40.5	40.5	0.027	182.8
DS-52-178	5.6		0.015	0.015	50.6	50.6	0.037	250.5
DS-52-176	2.3		0.012	0.012	40.5	40.5	0.026	176.0
DS-52-175	0.5		0.009	0.009	30.4	30.4	0.021	142.2
DS-H-425		10	0.003	0.003	10.1	10.1	0.001	6.8
DS-H-424		10	0.002	0.002	6.8	6.8	0.001	6.8
DS-H-422		10	0.002	0.002	6.8	6.8	<.001	
DS-H-421		5	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-420		5	0.004	0.004	13.5	13.5	0.005	33.9
DS-H-419		10	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-418		10	0.003	0.003	10.1	10.1	0.001	6.8
DS-H-417		10	0.002	0.002	6.8	6.8	0.001	6.8
DS-H-416		10	0.005	0.005	16.9	16.9	0.004	27.1
DS-H-415		10	0.004	0.004	13.5	13.5	0.003	20.3
DS-H-414		10	0.002	0.002	6.8	6.8	0.001	6.8
DS-H-413		10	0.004	0.004	13.5	13.5	0.001	6.8
DS-H-412		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-52-167	7.6		0.012	0.012	40.5	40.5	0.021	142.2
DS-52-166	6		0.009	0.009	30.4	30.4	0.014	94.8
DS-H-410		10	0.003	0.003	10.1	10.1	0.001	6.8
DS-52-182	3.3		0.014	0.014	47.3	47.3	0.031	209.9
DS-52-181	3.7		0.014	0.014	47.3	47.3	0.03	203.1
DS-52-180	7.4		0.015	0.015	50.6	50.6	0.041	277.6
DS-52-177	2.9		0.015	0.015	50.6	50.6	0.033	223.4
DS-52-174	0.8		0.008	0.008	27.0	27.0	0.017	115.1
DS-52-173	0.9		0.006	0.006	20.3	20.3	0.007	47.4
DS-52-171	5.4		0.022	0.022	74.3	74.3	0.046	311.4
DS-52-170	4		0.01	0.010	33.8	33.8	0.018	121.9
DS-52-169	6		0.011	0.011	37.1	37.1	0.015	101.6
DS-52-168	6.4		0.016	0.016	54.0	54.0	0.022	148.9
	0.7	Not Sampled		0.000	0.0	0.0		0.0
LRP-74	2		0.01	0.010	33.8	33.8	0.017	115.1
LRP-73	8.5		0.006	0.006	20.3	20.3	0.009	60.9
LRP-72	1.8		0.014	0.014	47.3	47.3	0.022	148.9
	0.08	Not Sampled		0.000	0.0	0.0		0.0
LRP-64	6		0.017	0.017	57.4	57.4	0.026	176.0
LRP-63	7.8		0.013	0.013	43.9	43.9	0.014	94.8
LRP-H-106		13.5	0.009	0.009	30.4	30.4	0.011	74.5
LRP-H-105		9	0.002	0.002	6.8	6.8	0	0.0
LRP-39	1		0.014	0.014	47.3	47.3	0.02	135.4
LRP-68	3.4		0.012	0.012	40.5	40.5	0.02	135.4
LRP-78	1.5		0.018	0.018	60.8	60.8	0.028	189.6
LRP-H-67		5	0.005	0.005	16.9	16.9	0.007	47.4
LRP-H-108		14	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-66		13	0.007	0.007	23.6	23.6	0.008	54.2
LRP-70	3		0.017	0.017	57.4	57.4	0.018	121.9
LRP-H-65		4	0.005	0.005	16.9	16.9	0.005	33.9
LRP-69	2.7		0.012	0.012	40.5	40.5	0.015	101.6
LRP-H-64		8	0.003	0.003	10.1	10.1	0.002	13.5
LRP-H-63		10	0.004	0.004	13.5	13.5	0.005	33.9
LRP-67	0.4		0.039	0.039	131.6	131.6	0.061	413.0
LRP-H-62		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-65	2		0.03	0.030	101.3	101.3	0.064	433.3
LRP-H-61		6	0.005	0.005	16.9	16.9	0.006	40.6
LRP-60		10	0.005	0.005	16.9	16.9	0.003	20.3
LRP-59		10	0.003	0.003	10.1	10.1	0.003	20.3
LRP-H-107		10	0.005	0.005	16.9	16.9	0.004	27.1
LRP-H-58		9	0.005	0.005	16.9	16.9	0.004	27.1
LRP-H-57		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-H-56		10	0.004	0.004	13.5	13.5	0.006	40.6
LRP-62	2.2		0.022	0.022	74.3	74.3	0.036	243.7
LRP-60	2		0.025	0.025	84.4	84.4	0.043	291.1
LRP-H-55		4	0.005	0.005	16.9	16.9	0.008	54.2
LRP-58	4.4		0.008	0.008	27.0	27.0	0.009	60.9
LRP-57	11.5		0.012	0.012	40.5	40.5	0.018	121.9
LRP-H-54		10	0.004	0.004	13.5	13.5	0.002	13.5
LRP-55	3.7		0.008	0.008	27.0	27.0	0.007	47.4
LRP-53		7	0.005	0.005	16.9	16.9	0.012	81.2
LRP-49	4.7		0.007	0.007	23.6	23.6	0.008	54.2
LRP-48	10.1		0.014	0.014	47.3	47.3	0.017	115.1
LRP-47	14.6		0.01	0.010	33.8	33.8	0.015	101.6
LRP-H-52		10	0.005	0.005	16.9	16.9	0.001	6.8
LRP-H-51		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-50		6	0.004	0.004	13.5	13.5	0.002	13.5
LRP-46	2.9		0.01	0.010	33.8	33.8	0.013	88.0
LRP-45	8.4		0.016	0.016	54.0	54.0	0.019	128.6
LRP-H-49		4	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-48		10	0.003	0.003	10.1	10.1	0.002	13.5
LRP-41	3.9		0.016	0.016	54.0	54.0	0.02	135.4
LRP-40	6.3		0.012	0.012	40.5	40.5	0.017	115.1
H-47		13	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-46		10	0.003	0.003	10.1	10.1	0.002	13.5
LRP-H-45		11.5	0.004	0.004	13.5	13.5	0.004	27.1
LRP-37	2.1		0.018	0.018	60.8	60.8	0.027	182.8
LRP-36	10.6		0.015	0.015	50.6	50.6	0.024	162.5
LRP-H-44		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-H-43		10	0.004	0.004	13.5	13.5	0.003	20.3
LRP-H-42		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-41		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-H-40		10	0.005	0.005	16.9	16.9	0.004	27.1
LRP-32	7.3		0.008	0.008	27.0	27.0	0.011	74.5
LRP-H-39		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-H-38		10	0.004	0.004	13.5	13.5	0.003	20.3
LRP-77	4.2		0.012	0.012	40.5	40.5	0.019	128.6
LRP-76	2.6		0.007	0.007	23.6	23.6	0.011	74.5

LRP-75	4.8		0.015	0.015	50.6	50.6	0.03	203.1
LRP-71	7.2		0.021	0.021	70.9	70.9	0.034	230.2
LRP-66	3.8		0.033	0.033	111.4	111.4	0.06	406.2
LRP-61	3.3		0.026	0.026	87.8	87.8	0.041	277.6
LRP-59	0.5		0.017	0.017	57.4	57.4	0.023	155.7
LRP-56	2.9		0.018	0.018	60.8	60.8	0.028	189.6
LRP-53	3.6		0.007	0.007	23.6	23.6	0.007	47.4
LRP-52	9.7		0.012	0.012	40.5	40.5	0.016	108.3
LRP-51	13.7		0.012	0.012	40.5	40.5	0.017	115.1
LRP-50	9		0.013	0.013	43.9	43.9	0.012	81.2
LRP-44	7.2		0.017	0.017	57.4	57.4	0.027	182.8
LRP-43	9.2		0.013	0.013	43.9	43.9	0.021	142.2
LRP-42	6.1		0.01	0.010	33.8	33.8	0.012	81.2
LRP-38	9.4		0.014	0.014	47.3	47.3	0.021	142.2
LRP-35	9.4		0.025	0.025	84.4	84.4	0.051	345.3
LRP-34	4		0.012	0.012	40.5	40.5	0.019	128.6
LRP-33	5.5		0.009	0.009	30.4	30.4	0.012	81.2
LRP-168	2.6		0.007	0.007	23.6	23.6	0.008	54.2
LRP-H-104		5.5	0.004	0.004	13.5	13.5	0.002	13.5
LRP-162	1.2		0.037	0.037	124.9	124.9	0.078	528.1
LRP-161	2.8		0.014	0.014	47.3	47.3	0.022	148.9
	0.6	Not Sampled		0.000	0.0	0.0		0.0
LRP-H-127		6	0.003	0.003	10.1	10.1	0	0.0
LRP-H-126		10	0.003	0.003	10.1	10.1	0	0.0
LRP-H-125		10.5	0.003	0.003	10.1	10.1	0	0.0
LRP-H-124		10	0.007	0.007	23.6	23.6	0.009	60.9
LRP-H-123		10	0.006	0.006	20.3	20.3	0.004	27.1
LRP-H-122		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-121		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-120		10	0.004	0.004	13.5	13.5	0	0.0
LRP-H-119		10	0.004	0.004	13.5	13.5	0	0.0
LRP-H-118		10	0.004	0.004	13.5	13.5	0	0.0
LRP-H-117		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-116		10	0.008	0.008	27.0	27.0	0.008	54.2
LRP-112	9.2		0.022	0.022	74.3	74.3	0.04	270.8
LRP-111	9.6		0.021	0.021	70.9	70.9	0.039	264.0
LRP-H-114		7	0.004	0.004	13.5	13.5	0	0.0
LRP-H-113		5	0.005	0.005	16.9	16.9	0.003	20.3
LRP-H-112		10	0.005	0.005	16.9	16.9	0.004	27.1
LRP-H-111		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-110		10	0.005	0.005	16.9	16.9	0.007	47.4
LRP-85	4.6		0.016	0.016	54.0	54.0	0.027	182.8
LRP-81	2.8		0.021	0.021	70.9	70.9	0.038	257.3
LRP-79	1.7		0.045	0.045	151.9	151.9	0.085	575.5
LRP-H-103		20	0.005	0.005	16.9	16.9	0.003	20.3
LRP-H-102		10	0.003	0.003	10.1	10.1	0.002	13.5
LRP-167	0.4		0.006	0.006	20.3	20.3	0.006	40.6
LRP-H-101		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-100		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-99		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-98		10.5	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-97		11.5	0.006	0.006	20.3	20.3	0.002	13.5
LRP-H-96		10	0.006	0.006	20.3	20.3	0.003	20.3
LRP-H-95		10	0.005	0.005	16.9	16.9	0.003	20.3
LRP-H-94		10	0.009	0.009	30.4	30.4	0.011	74.5
LP-H-128		7	0.006	0.006	20.3	20.3	0.008	54.2
LRP-H-93		7	0.005	0.005	16.9	16.9	0.002	13.5
LRP-H-92		10	0.004	0.004	13.5	13.5	0.002	13.5
LRP-H-91		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-90		10	0.003	0.003	10.1	10.1	<.001	
LRP-H-89		9.5	0.004	0.004	13.5	13.5	0.002	13.5
LRP-H-88		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-156	1.6		0.014	0.014	47.3	47.3	0.024	162.5
LRP-155	12.3		0.008	0.008	27.0	27.0	0.012	81.2
LRP-154	12.6		0.009	0.009	30.4	30.4	0.012	81.2
LRP-H-87		12.5	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-86		10	0.004	0.004	13.5	13.5	<.001	
LRP-149	9.4		0.013	0.013	43.9	43.9	0.026	176.0
LRP-148	7.8		0.01	0.010	33.8	33.8	0.019	128.6
LRP-147	9.5		0.009	0.009	30.4	30.4	0.011	74.5
LRP-146	11.2		0.007	0.007	23.6	23.6	0.009	60.9
LRP-145	12.3		0.007	0.007	23.6	23.6	0.008	54.2
LRP-144	4.2		0.007	0.007	23.6	23.6	0.006	40.6
LRP-143	7.5		0.012	0.012	40.5	40.5	0.021	142.2
LRP-142	3.6	Sample Missing		0.000	0.0	0.0		0.0
LRP-135	3.4		0.011	0.011	37.1	37.1	0.02	135.4
LRP-134	7.3		0.015	0.015	50.6	50.6	0.025	169.3
LRP-133	8.9		0.017	0.017	57.4	57.4	0.031	209.9
LRP-132	6		0.011	0.011	37.1	37.1	0.022	148.9
LRP-H-85		4	0.001	0.001	3.4	3.4	0.001	6.8
LRP-126	8		0.011	0.011	37.1	37.1	0.019	128.6
LRP-125	6.4		0.013	0.013	43.9	43.9	0.022	148.9
LRP-124	8.7		0.007	0.007	23.6	23.6	0.01	67.7
LRP-H-84		2	0.004	0.004	13.5	13.5	0.003	20.3
LRP-H-83		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-123	1.4		0.013	0.013	43.9	43.9	0.024	162.5
LRP-H-82		4	0.004	0.004	13.5	13.5	0.001	6.8
LRP-122	1		0.012	0.012	40.5	40.5	0.009	60.9
LRP-121	3.2		0.027	0.027	91.1	91.1	0.045	304.7
LRP-H-81		1.5	0.004	0.004	13.5	13.5	0.001	6.8
LRP-113	7.1		0.025	0.025	84.4	84.4	0.04	270.8
LRP-H-80		11	0.005	0.005	16.9	16.9	0.007	47.4
LRP-H-79		10	0.004	0.004	13.5	13.5	0.002	13.5
LRP-H-78		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-106	1.3		0.018	0.018	60.8	60.8	0.031	209.9
LRP-105	11.7		0.019	0.019	64.1	64.1	0.028	189.6
LRP-H-77		6	0.004	0.004	13.5	13.5	<.001	
LRP-H-76		10	0.006	0.006	20.3	20.3	0.006	40.6

LRP-101	4.6		0.01	0.010	33.8	33.8	0.016	108.3
LRP-100	8		0.009	0.009	30.4	30.4	0.011	74.5
LRP-H-75	2.2	Sample Missing		0.000	0.0	0.0		0.0
LRP-94	3.7		0.009	0.009	30.4	30.4	0.011	74.5
LRP-93	6.8		0.012	0.012	40.5	40.5	0.014	94.8
LRP-92	4.8		0.009	0.009	30.4	30.4	0.009	60.9
LRP-H-74		2	0.004	0.004	13.5	13.5	0.004	27.1
LRP-88	1.8		0.012	0.012	40.5	40.5	0.018	121.9
LRP-87	7.4		0.035	0.035	118.1	118.1	0.067	453.6
LRP-H-73		5	0.007	0.007	23.6	23.6	0.006	40.6
LRP-H-72		10	0.006	0.006	20.3	20.3	0.008	54.2
LRP-86	4.1		0.018	0.018	60.8	60.8	0.025	169.3
LRP-H-109		11	0.006	0.006	20.3	20.3	0.005	33.9
LRP-H-71		11	0.008	0.008	27.0	27.0	0.007	47.4
LRP-H-70		10	0.006	0.006	20.3	20.3	0.008	54.2
LRP-H-69		10	0.005	0.005	16.9	16.9	0.002	13.5
LRP-H-68		10	0.005	0.005	16.9	16.9	0.005	33.9
LRP-169	3.3		0.007	0.007	23.6	23.6	0.008	54.2
LRP-165	5.3		0.006	0.006	20.3	20.3	0.008	54.2
LRP-164	9.9		0.006	0.006	20.3	20.3	0.008	54.2
LRP-163	2.6		0.009	0.009	30.4	30.4	0.011	74.5
LRP-160	1.2		0.005	0.005	16.9	16.9	0.002	13.5
LRP-159	10.1		0.017	0.017	57.4	57.4	0.024	162.5
LRP-158	11.7		0.008	0.008	27.0	27.0	0.01	67.7
LRP-157	9.7		0.008	0.008	27.0	27.0	0.009	60.9
LRP-153	6		0.016	0.016	54.0	54.0	0.028	189.6
LRP-152	7.7		0.012	0.012	40.5	40.5	0.02	135.4
LRP-151	4.7		0.009	0.009	30.4	30.4	0.013	88.0
LRP-150	7.4		0.01	0.010	33.8	33.8	0.011	74.5
LRP-141	5.8		0.009	0.009	30.4	30.4	0.015	101.6
LRP-140	10.3		0.01	0.010	33.8	33.8	0.013	88.0
LRP-139	7.6		0.007	0.007	23.6	23.6	0.011	74.5
LRP-138	8.4		0.009	0.009	30.4	30.4	0.013	88.0
LRP-137	7.4		0.012	0.012	40.5	40.5	0.021	142.2
LRP-136	5.8		0.009	0.009	30.4	30.4	0.02	135.4
LRP-131	7.4		0.01	0.010	33.8	33.8	0.017	115.1
LRP-130	6.8		0.009	0.009	30.4	30.4	0.016	108.3
LRP-129	10.2		0.011	0.011	37.1	37.1	0.017	115.1
LRP-128	7.7		0.008	0.008	27.0	27.0	0.011	74.5
LRP-127	7.6		0.005	0.005	16.9	16.9	0.006	40.6
LRP-120	2.5		0.027	0.027	91.1	91.1	0.047	318.2
LRP-119	4.6		0.013	0.013	43.9	43.9	0.019	128.6
LRP-118	6.5		0.018	0.018	60.8	60.8	0.012	81.2
LRP-117	4		0.011	0.011	37.1	37.1	0.023	155.7
LRP-116	2.7		0.031	0.031	104.6	104.6	0.053	358.8
LRP-115	13.4		0.02	0.020	67.5	67.5	0.035	237.0
LRP-114	8.5		0.015	0.015	50.6	50.6	0.025	169.3
LRP-110	2.4		0.003	0.003	10.1	10.1	0.005	33.9
LRP-109	3.7		0.006	0.006	20.3	20.3	0.008	54.2
	2	Not Sampled		0.000	0.0	0.0		0.0
LRP-108	10.9		0.01	0.010	33.8	33.8	0.012	81.2
LRP-107	6		0.017	0.017	57.4	57.4	0.023	155.7
LRP-103	1.4		0.005	0.005	16.9	16.9	0.004	27.1
LRP-102	3.9		0.006	0.006	20.3	20.3	0.008	54.2
LRP-99	2		0.007	0.007	23.6	23.6	0.008	54.2
LRP-98	2.4		0.008	0.008	27.0	27.0	0.012	81.2
LRP-97	8.6		0.007	0.007	23.6	23.6	0.009	60.9
LRP-96	7.4		0.009	0.009	30.4	30.4	0.014	94.8
LRP-95	8.1		0.011	0.011	37.1	37.1	0.014	94.8
LRP-91	5.2		0.009	0.009	30.4	30.4	0.009	60.9
LRP-90	5		0.023	0.023	77.6	77.6	0.037	250.5
LRP-89	0.7		0.017	0.017	57.4	57.4	0.027	182.8
LRP-84	4.4		0.021	0.021	70.9	70.9	0.031	209.9
LRP-83	10		0.017	0.017	57.4	57.4	0.025	169.3
LRP-82	6.5		0.023	0.023	77.6	77.6	0.037	250.5
LRP-80	6.3		0.006	0.006	20.3	20.3	0.008	54.2
Mean:			0.013	0.012	42.489	42.489	0.021	139.570
Median:			0.009	0.009	30.381	30.381	0.013	88.010
Standard Deviation:			0.011	0.011	38.248	38.248	0.031	206.938
Maximum:			0.096	0.095	324.060	324.060	0.480	3249.600
Minimum:			0.001	0.000	0.000	0.000	0.000	0.000

🟦 Values computed by Kennecott Uranium Company from data in paper

OAP:02/17/08

KENNECOTT URANIUM COMPANY
LOST CREEK TRENCH SAMPLING
Section 1

Source: Geology of the Lost Creek Schroeckingerite Deposits Sweetwater County, Wyoming
Geological Survey Bulletin 1087-J

SAMPLE #	AREA	LENGTH	PERCENT EQUIVALENT URANIUM	PERCENT EQUIVALENT URANIUM-238	QUIVALENT URANIUM-23 ACTIVITY (picoCuries per gram)	RADIUM-226 ACTIVITY (picoCuries per gram)	PERCENT URANIUM	NATURAL URANIUM ACTIVITY (picoCuries per gram)
DS-H-185		1.3	0.005	0.005	16.9	16.9	0.004	27.1
DS-51-179		0.7	0.006	0.006	20.3	20.3	0.002	13.5
DS-H-187		3.8	0.006	0.006	20.3	20.3	0.007	47.4
DS-H-188		1.9	0.005	0.005	16.9	16.9	0.005	33.9
DS-H-189		4.3	0.01	0.010	33.8	33.8	0.011	74.5
DS-H-190		0.7	0.005	0.005	16.9	16.9	0.006	40.6
DS-H-192		2.7	0.013	0.013	43.9	43.9	0.015	101.6
DS-51-191		0.3	0.008	0.008	27.0	27.0	0.009	60.9
DS-51-192		0.4	0.013	0.013	43.9	43.9	0.018	121.9
DS-51-193		0.7	0.013	0.013	43.9	43.9	0.02	135.4
DS-51-194		0.4	0.03	0.030	101.3	101.3	0.052	352.0
DS-H-198		0.6	0.009	0.009	30.4	30.4	0.01	67.7
DS-H-200		0.4	0.008	0.008	27.0	27.0	0.007	47.4
DS-H-205		3.7	0.007	0.007	23.6	23.6	0.008	54.2
DS-H-207		1	0.008	0.008	27.0	27.0	0.01	67.7
DS-H-208		6.1	0.011	0.011	37.1	37.1	0.015	101.6
DS-H-213		2.5	0.016	0.016	54.0	54.0	0.02	135.4
DS-51-178		0.7	0.003	0.003	10.1	10.1	0.001	6.8
DS-51-180		0.09	0.011	0.011	37.1	37.1	0.01	67.7
DS-51-181		1	0.011	0.011	37.1	37.1	0.011	74.5
DS-51-182		1.4	0.007	0.007	23.6	23.6	0.005	33.9
DS-51-183		1.2	0.006	0.006	20.3	20.3	0.004	27.1
DS-51-184		0.9	0.013	0.013	43.9	43.9	0.013	88.0
DS-51-185		1.2	0.008	0.008	27.0	27.0	0.006	40.6
DS-51-186		1.4	0.005	0.005	16.9	16.9	0.003	20.3
DS-51-187		0.7	0.005	0.005	16.9	16.9	0.003	20.3
DS-51-188		1.4	0.01	0.010	33.8	33.8	0.011	74.5
DS-51-189		1.2	0.01	0.010	33.8	33.8	0.012	81.2
DS-51-190		1.1	0.13	0.129	438.8	438.8	0.018	121.9
DS-51-195		0.3	0.011	0.011	37.1	37.1	0.016	108.3
DS-51-196		0.4	0.007	0.007	23.6	23.6	0.006	40.6
DS-51-197		0.7	0.006	0.006	20.3	20.3	0.006	40.6
DS-51-198		0.8	0.018	0.018	60.8	60.8	0.33	2234.1
DS-51-199		0.4	0.007	0.007	23.6	23.6	0.008	54.2
DS-51-200		0.6	0.012	0.012	40.5	40.5	0.018	121.9
DS-51-201		1.1	0.018	0.018	60.8	60.8	0.033	223.4
DS-51-202		2.1	0.008	0.008	27.0	27.0	0.011	74.5
DS-51-203		1.3	0.011	0.011	37.1	37.1	0.015	101.6
DS-51-204		0.9	0.01	0.010	33.8	33.8	0.014	94.8
DS-51-205		1.1	0.016	0.016	54.0	54.0	0.032	216.6
DS-51-206		1.4	0.039	0.039	131.6	131.6	0.096	649.9
DS-51-78		0.5	0.005	0.005	16.9	16.9	0.004	27.1
DS-H-98		5.9	0.031	0.031	104.6	104.6	0.051	345.3
DS-51-81		1	0.016	0.016	54.0	54.0	0.022	148.9
DS-51-84		0.6	0.007	0.007	23.6	23.6	0.004	27.1
DS-H-100		0.9	0.017	0.017	57.4	57.4	0.023	155.7
DS-H-101		2.9	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-102		1.4	0.022	0.022	74.3	74.3	0.039	264.0
DS-51-88		0.6	0.012	0.012	40.5	40.5	0.013	88.0
DS-51-90		0.5	0.014	0.014	47.3	47.3	0.021	142.2
DS-H-104		4	0.029	0.029	97.9	97.9	0.044	297.9
DS-51-96		1.3	0.022	0.022	74.3	74.3	0.039	264.0
DS-H-106		4.4	0.021	0.021	70.9	70.9	0.032	216.6
DS-H-111		2.4	0.026	0.026	87.8	87.8	0.035	237.0
DS-H-112		3.1	0.014	0.014	47.3	47.3	0.014	94.8
DS-H-114		1.3	0.014	0.014	47.3	47.3	0.021	142.2
DS-52-138	2.2		0.01	0.010	33.8	33.8	0.011	74.5
DS-H-122		6	0.027	0.027	91.1	91.1	0.043	291.1
DS-H-149		1.3	0.19	0.189	641.4	641.4	0.035	237.0
DS-51-151		0.8	0.019	0.019	64.1	64.1	0.032	216.6
DS-H-150		3.2	0.048	0.048	162.0	162.0	0.09	609.3
DS-51-153		0.7	0.023	0.023	77.6	77.6	0.032	216.6
DS-51-156		1	0.022	0.022	74.3	74.3	0.049	331.7
DS-H-151		1.9	0.008	0.008	27.0	27.0	0.009	60.9
DS-H-156		0.8	0.011	0.011	37.1	37.1	0.011	74.5
DS-51-158		0.4	0.008	0.008	27.0	27.0	0.007	47.4
DS-H-157		4.3	0.031	0.031	104.6	104.6	0.051	345.3
DS-H-158		1.2	0.011	0.011	37.1	37.1	0.007	47.4
DS-H-164		0.9	0.01	0.010	33.8	33.8	0.014	94.8
DS-H-165		1.3	0.013	0.013	43.9	43.9	0.019	128.6
DS-51-173		0.7	0.008	0.008	27.0	27.0	0.002	13.5
DS-H-166		1.1	0.008	0.008	27.0	27.0	0.007	47.4
DS-51-174		0.8	0.013	0.013	43.9	43.9	0.012	81.2
DS-H-168		1	0.01	0.010	33.8	33.8	0.008	54.2
DS-H-169		0.9	0.009	0.009	30.4	30.4	0.006	40.6
DS-H-170		0.4	0.019	0.019	64.1	64.1	0.021	142.2
DS-H-172		1	0.012	0.012	40.5	40.5	0.012	81.2
DS-51-79		0.3	0.005	0.005	16.9	16.9	0.005	33.9
DS-51-80		0.6	0.017	0.017	57.4	57.4	0.018	121.9
DS-51-82		2.1	0.054	0.054	182.3	182.3	0.096	649.9
DS-51-83		1.4	0.013	0.013	43.9	43.9	0.022	148.9

SAMPLE #	AREA	LENGTH	PERCENT EQUIVALENT URANIUM	PERCENT EQUIVALENT URANIUM-238	QUIVALENT URANIUM-23 ACTIVITY (picoCuries per gram)	RADIUM-226 ACTIVITY (picoCuries per gram)	PERCENT URANIUM	NATURAL URANIUM ACTIVITY (picoCuries per gram)
DS-51-85		0.5	0.016	0.016	54.0	54.0	0.03	203.1
DS-51-86		0.9	0.012	0.012	40.5	40.5	0.016	108.3
DS-51-87		0.6	0.027	0.027	91.1	91.1	0.027	182.8
DS-51-89		1.2	0.004	0.004	13.5	13.5	0.002	13.5
DS-51-91		0.5	0.043	0.043	145.2	145.2	0.083	561.9
DS-51-92		1.4	0.041	0.041	138.4	138.4	0.043	291.1
DS-51-93		1.5	0.03	0.030	101.3	101.3	0.055	372.4
DS-51-94		1.5	0.031	0.031	104.6	104.6	0.05	338.5
DS-51-95		1.7	0.02	0.020	67.5	67.5	0.03	203.1
DS-H-105		3.5	0.005	0.005	16.9	16.9	0.007	47.4
DS-51-97		1.3	0.015	0.015	50.6	50.6	0.026	176.0
DS-51-98		1.3	0.013	0.013	43.9	43.9	0.023	155.7
DS-51-99		0.4	0.009	0.009	30.4	30.4	0.01	67.7
DS-51-100		0.5	0.012	0.012	40.5	40.5	0.02	135.4
DS-51-101		1	0.015	0.015	50.6	50.6	0.019	128.6
DS-51-102		0.8	0.016	0.016	54.0	54.0	0.023	155.7
DS-51-103		0.7	0.007	0.007	23.6	23.6	0.008	54.2
DS-51-104		0.6	0.015	0.015	50.6	50.6	0.018	121.9
DS-51-105		0.5	0.012	0.012	40.5	40.5	0.016	108.3
DS-51-105		0.5	0.012	0.012	40.5	40.5	0.016	108.3
DS-51-106		0.7	0.006	0.006	20.3	20.3	0.006	40.6
DS-51-107		1.3	0.018	0.018	60.8	60.8	0.033	223.4
DS-51-108		1.8	0.018	0.018	60.8	60.8	0.028	189.6
DS-51-109		2.8	0.021	0.021	70.9	70.9	0.032	216.6
DS-51-110		1.5	0.022	0.022	74.3	74.3	0.038	257.3
DS-51-111		1.5	0.034	0.034	114.8	114.8	0.06	406.2
DS-51-112		1	0.039	0.039	131.6	131.6	0.082	555.1
DS-51-152		0.5	0.068	0.068	229.5	229.5	0.07	473.9
DS-51-154		1.4	0.1	0.099	337.6	337.6	0.2	1354.0
DS-51-155		0.7	0.091	0.090	307.2	307.2	0.26	1760.2
DS-51-157		1	0.011	0.011	37.1	37.1	0.017	115.1
DS-51-159		1.2	0.035	0.035	118.1	118.1	0.055	372.4
DS-51-160		1	0.02	0.020	67.5	67.5	0.023	155.7
DS-51-161		1.1	0.019	0.019	64.1	64.1	0.023	155.7
DS-51-162		1	0.011	0.011	37.1	37.1	0.0004	2.7
DS-51-282		0.9	0.008	0.008	27.0	27.0	0.004	27.1
DS-51-172		1.2	0.014	0.014	47.3	47.3	0.018	121.9
DS-51-175.		0.6	0.012	0.012	40.5	40.5	0.011	74.5
DS-51-177		0.8	0.011	0.011	37.1	37.1	0.008	54.2
DS-H-65		2.5	0.009	0.009	30.4	30.4	0.014	94.8
DS-H-66		3.9	0.007	0.007	23.6	23.6	0.012	81.2
DS-H-67		3.9	0.016	0.016	54.0	54.0	0.03	203.1
DS-H-68		3.2	0.003	0.003	10.1	10.1	0.001	6.8
DS-H-69		3.3	0.014	0.014	47.3	47.3	0.024	162.5
DS-H-72		10	0.013	0.013	43.9	43.9	0.027	182.8
DS-H-73		4.4	0.014	0.014	47.3	47.3	0.025	169.3
DS-H-77		1.5	0.008	0.008	27.0	27.0	0.014	94.8
DS-H-78		7.9	0.009	0.009	30.4	30.4	0.016	108.3
DS-H-79		3.5	0.016	0.016	54.0	54.0	0.02	135.4
DS-H-80		9.3	0.004	0.004	13.5	13.5	0.003	20.3
DS-51-42A		0.6	0.004	0.004	13.5	13.5	0.003	20.3
DS-H-81		10.1	0.011	0.011	37.1	37.1	0.017	115.1
DS-H-82		0.6	0.004	0.004	13.5	13.5	0.005	33.9
DS-H-83		6.2	0.013	0.013	43.9	43.9	0.021	142.2
DS-H-84		1.3	0.005	0.005	16.9	16.9	0.005	33.9
DS-H-85		2.1	0.009	0.009	30.4	30.4	0.001	6.8
DS-H-86		2.5	0.008	0.008	27.0	27.0	0.004	27.1
DS-H-87		3.3	0.038	0.038	128.3	128.3	0.071	480.7
DS-H-89		0.7	0.008	0.008	27.0	27.0	0.005	33.9
DS-H-94		10	0.018	0.018	60.8	60.8	0.026	176.0
DS-H-95		1.3	0.006	0.006	20.3	20.3	0.006	40.6
DS-H-96		3.7	0.005	0.005	16.9	16.9	0.004	27.1
DS-H-97		3	0.019	0.019	64.1	64.1	0.039	264.0
DS-51-6		0.8	0.01	0.010	33.8	33.8	0.019	128.6
DS-51-7		0.5	0.009	0.009	30.4	30.4	0.016	108.3
DS-51-8		0.9	0.009	0.009	30.4	30.4	0.019	128.6
DS-51-9		1.9	0.011	0.011	37.1	37.1	0.018	121.9
DS-51-10		0.7	0.02	0.020	67.5	67.5	0.031	209.9
DS-51-11		1	0.006	0.006	20.3	20.3	0.012	81.2
DS-51-12		1.3	0.028	0.028	94.5	94.5	0.057	385.9
DS-51-13		1	0.01	0.010	33.8	33.8	0.015	101.6
DS-51-14		1.7	0.019	0.019	64.1	64.1	0.034	230.2
DS-51-15		0.7	0.017	0.017	57.4	57.4	0.034	230.2
DS-51-16		1	0.009	0.009	30.4	30.4	0.014	94.8
DS-51-17		1	0.012	0.012	40.5	40.5	0.026	176.0
DS-51-18		0.6	0.012	0.012	40.5	40.5	0.02	135.4
DS-51-36		0.4	0.032	0.032	108.0	108.0	0.052	352.0
DS-51-37		0.4	0.01	0.010	33.8	33.8	0.012	81.2
DS-51-38		0.5	0.012	0.012	40.5	40.5	0.013	88.0
DS-51-39		0.4	0.004	0.004	13.5	13.5	0.003	20.3
DS-51-40		0.6	0.006	0.006	20.3	20.3	0.008	54.2
DS-51-41		2.3	0.011	0.011	37.1	37.1	0.022	148.9
DS-51-42B		0.9	0.027	0.027	91.1	91.1	0.04	270.8
DS-51-43		1.4	0.007	0.007	23.6	23.6	0.008	54.2
DS-51-44		1.2	0.019	0.019	64.1	64.1	0.039	264.0
DS-51-45		1	0.007	0.007	23.6	23.6	0.012	81.2
DS-51-46		1	0.01	0.010	33.8	33.8	0.018	121.9
DS-51-47		0.6	0.018	0.018	60.8	60.8	0.037	250.5
DS-51-48		1	0.027	0.027	91.1	91.1	0.035	237.0

SAMPLE #	AREA	LENGTH	PERCENT EQUIVALENT URANIUM	PERCENT EQUIVALENT URANIUM-238	QUIVALENT URANIUM-23 ACTIVITY	RADIUM-226 ACTIVITY	PERCENT URANIUM	NATURAL URANIUM ACTIVITY
					(picoCuries per gram)	(picoCuries per gram)		(picoCuries per gram)
DS-51-49		1	0.033	0.033	111.4	111.4	0.063	426.5
DS-51-50		0.8	0.077	0.076	259.9	259.9	0.007	47.4
DS-51-51		3.5	0.008	0.008	27.0	27.0	0.013	88.0
DS-51-52		1.3	0.025	0.025	84.4	84.4	0.041	277.6
DS-51-53		20	0.028	0.028	94.5	94.5	0.051	345.3
DS-51-54		0.8	0.026	0.026	87.8	87.8	0.047	318.2
DS-51-55		0.8	0.021	0.021	70.9	70.9	0.035	237.0
DS-51-56		1.2	0.009	0.009	30.4	30.4	0.012	81.2
DS-51-77		1.1	0.023	0.023	77.6	77.6	0.048	325.0
DS-52-114	0.8		0.014	0.014	47.3	47.3	0.016	108.3
DS-52-115	12.9		0.013	0.013	43.9	43.9	0.017	115.1
DS-52-116	8.7	.	0.01	0.010	33.8	33.8	0.01	67.7
DS-52-117	7.7		0.005	0.005	16.9	16.9	0.006	40.6
DS-52-118	5		0.012	0.012	40.5	40.5	0.015	101.6
DS-52-119	3.8		0.014	0.014	47.3	47.3	0.018	121.9
DS-52-120	8		0.013	0.013	43.9	43.9	0.014	94.8
DS-52-121	10.7		0.011	0.011	37.1	37.1	0.01	67.7
DS-52-122	1.2		0.006	0.006	20.3	20.3	0.001	6.8
DS-52-123	637		0.009	0.009	30.4	30.4	0.009	60.9
DS-52-124	10.3		0.012	0.012	40.5	40.5	0.013	88.0
DS-52-125	6		0.013	0.013	43.9	43.9	0.02	135.4
DS-52-126	6.2		0.022	0.022	74.3	74.3	0.033	223.4
DS-52-127	6.8		0.013	0.013	43.9	43.9	0.016	108.3
DS-52-131	6		0.015	0.015	50.6	50.6	0.015	101.6
DS-52-129	5.9		0.011	0.011	37.1	37.1	0.012	81.2
DS-52-130	9		0.023	0.023	77.6	77.6	0.045	304.7
DS-52-131	6		0.015	0.015	50.6	50.6	0.015	101.6
DS-52-132	5.3		0.004	0.004	13.5	13.5	0.005	33.9
DS-52-133	4.8		0.008	0.008	27.0	27.0	0.013	88.0
DS-52-134	7.5		0.013	0.013	43.9	43.9	0.024	162.5
DS-52-135	6.5		0.021	0.021	70.9	70.9	0.033	223.4
DS-52-136	5.5		0.013	0.013	43.9	43.9	0.024	162.5
DS-51-19		0.5	0.008	0.008	27.0	27.0	0.009	60.9
DS-51-20		1.2	0.014	0.014	47.3	47.3	0.021	142.2
DS-51-21		0.8	0.009	0.009	30.4	30.4	0.014	94.8
DS-51-22		0.7	0.014	0.014	47.3	47.3	0.019	128.6
DS-51-23		1	0.01	0.010	33.8	33.8	0.014	94.8
DS-51-24		0.7	0.015	0.015	50.6	50.6	0.019	128.6
DS-51-25		1.3	0.013	0.013	43.9	43.9	0.024	162.5
DS-51-26		0.9	0.002	0.002	6.8	6.8	0.002	13.5
DS-51-27		0.5	0.004	0.004	13.5	13.5	0.003	20.3
DS-51-28		1.2	0.008	0.008	27.0	27.0	0.009	60.9
DS-51-29		1.3	0.033	0.033	111.4	111.4	0.062	419.7
DS-51-30		0.3	0.017	0.017	57.4	57.4	0.025	169.3
DS-51-31		1	0.024	0.024	81.0	81.0	0.04	270.8
DS-51-32		0.5	0.01	0.010	33.8	33.8	0.015	101.6
DS-51-33		0.7	0.011	0.011	37.1	37.1	0.02	135.4
DS-51-34		0.4	0.009	0.009	30.4	30.4	0.013	88.0
DS-51-35		0.8	0.01	0.010	33.8	33.8	0.019	128.6
DS-51-57		0.6	0.016	0.016	54.0	54.0	0.021	142.2
DS-51-58	0.06	Sample missing		0.000	0.0	0.0		0.0
DS-51-59		0.5	0.03	0.030	101.3	101.3	0.052	352.0
DS-51-60		2	0.021	0.021	70.9	70.9	0.024	162.5
DS-51-61		1.6	0.017	0.017	57.4	57.4	0.028	189.6
DS-51-62		1.5	0.003	0.003	10.1	10.1	0.002	13.5
DS-51-63		1.5	0.009	0.009	30.4	30.4	0.012	81.2
DS-51-64		1	0.011	0.011	37.1	37.1	0.012	81.2
DS-51-65		2	0.013	0.013	43.9	43.9	0.022	148.9
DS-51-66		1.4	0.016	0.016	54.0	54.0	0.027	182.8
DS-51-67		1.3	0.01	0.010	33.8	33.8	0.014	94.8
DS-51-69		1.6	0.012	0.012	40.5	40.5	0.016	108.3
DS-51-69		3	0.008	0.008	27.0	27.0	0.011	74.5
DS-51-72		1.9	0.011	0.011	37.1	37.1	0.015	101.6
DS-51-73		1.3	0.026	0.026	87.8	87.8	0.042	284.3
DS-51-74		1.6	0.025	0.025	84.4	84.4	0.036	243.7
DS-51-75		1.7	0.02	0.020	67.5	67.5	0.028	189.6
DS-51-76		2.8	0.006	0.006	20.3	20.3	0.004	27.1
Mean:			0.017	0.017	56.2	56.2	0.024	165.1
Median:			0.012	0.012	40.5	40.5	0.016	108.3
Standard Deviation:			0.019	0.018	62.5	62.5	0.033	223.0
Maximum:			0.190	0.189	641.4	641.4	0.330	2234.1
Minimum:			0.002	0.000	0.0	0.0	0.000	0.0

🟦 Values computed by Kennecott Uranium Company from data in paper

OAP:02/17/08

KENNECOTT URANIUM COMPANY
LOST CREEK TRENCH SAMPLING
Sections 2-7

Source: **Geology of the Lost Creek Schroeckingerite Deposits Sweetwater County, Wyoming**
Geological Survey Bulletin 1087-J

SAMPLE #	SAMPLE AREA	SAMPLE LENGTH	PERCENT EQUIVALENT URANIUM	PERCENT EQUIVALENT URANIUM-238	EQUIVALENT URANIUM-238 ACTIVITY (picoCuries per gram)	RADIUM-226 ACTIVITY (picoCuries per gram)	PERCENT URANIUM	NATURAL URANIUM ACTIVITY (picoCuries per gram)
DS-52-237	1.9		0.004	0.004	13.5	13.5	0.004	27.1
DS-52-238	4.9		0.005	0.005	16.9	16.9	0.004	27.1
DS-52-239	4.8		0.007	0.007	23.6	23.6	0.012	81.2
DS-52-242	1.2		0.008	0.008	27.0	27.0	0.015	101.6
DS-52-248	0.6		0.021	0.021	70.9	70.9	0.048	325.0
DS-52-249	4.4		0.027	0.027	91.1	91.1	0.06	406.2
DS-52-250	3		0.014	0.014	47.3	47.3	0.024	162.5
DS-52-251	0.8		0.008	0.008	27.0	27.0	0.012	81.2
DS-52-256	1.3		0.008	0.008	27.0	27.0	0.012	81.2
DS-52-257	5.7		0.012	0.012	40.5	40.5	0.018	121.9
DS-52-258	2.6		0.01	0.010	33.8	33.8	0.019	128.6
DS-52-259	2		0.014	0.014	47.3	47.3	0.015	101.6
DS-52-262	0.7		0.021	0.021	70.9	70.9	0.035	237.0
DS-52-263	2.9		0.025	0.025	84.4	84.4	0.049	331.7
DS-52-264	5.5		0.027	0.027	91.1	91.1	0.053	358.8
DS-52-265	3.2		0.015	0.015	50.6	50.6	0.029	196.3
DS-52-265A	4.1		0.029	0.029	97.9	97.9	0.06	406.2
DS-52-266	6.9		0.017	0.017	57.4	57.4	0.034	230.2
DS-52-267	0.4		0.007	0.007	23.6	23.6	0.015	101.6
DS-52-275	6.4		0.039	0.039	131.6	131.6	0.08	541.6
DS-52-207	1.2		0.013	0.013	43.9	43.9	0.021	142.2
DS-52-213	0.8		0.047	0.047	158.7	158.7	0.087	589.0
DS-52-214	3		0.014	0.014	47.3	47.3	0.022	148.9
DS-52-216	1.3		0.012	0.012	40.5	40.5	0.022	148.9
DS-52-218	5.6		0.016	0.016	54.0	54.0	0.035	237.0
DS-52-220	4.9		0.019	0.019	64.1	64.1	0.038	257.3
DS-52-222	3.3		0.012	0.012	40.5	40.5	0.024	162.5
DS-52-227	0.7		0.029	0.029	97.9	97.9	0.065	440.1
DS-52-228	1.3		0.037	0.037	124.9	124.9	0.072	487.4
DS-52-230	1.5		0.016	0.016	54.0	54.0	0.03	203.1
DS-51-199	1.2		0.008	0.008	27.0	27.0	0.013	88.0
DS-52-200	0.3		0.007	0.007	23.6	23.6	0.008	54.2
DS-52-204	1.2		0.012	0.012	40.5	40.5	0.022	148.9
DS-52-224	4		0.016	0.016	54.0	54.0	0.031	209.9
DS-52-233	1.2		0.01	0.010	33.8	33.8	0.012	81.2
DS-52-236	4		0.01	0.010	33.8	33.8	0.016	108.3
DS-52-184	3.5		0.023	0.023	77.6	77.6	0.041	277.6
DS-52-186	1.5		0.011	0.011	37.1	37.1	0.015	101.6
DS-52-190	2		0.02	0.020	67.5	67.5	0.043	291.1
DS-52-193	1		0.011	0.011	37.1	37.1	0.013	88.0
DS-52-194	0.2		0.03	0.030	101.3	101.3	0.062	419.7
DS-52-197	0.5		0.024	0.024	81.0	81.0	0.051	345.3
DS-52-149	4.3		0.015	0.015	50.6	50.6	0.015	101.6
DS-52-150	6.8		0.023	0.023	77.6	77.6	0.037	250.5
DS-52-152	0.3		0.009	0.009	30.4	30.4	0.01	67.7
DS-52-153	7.3		0.013	0.013	43.9	43.9	0.019	128.6
DS-52-155	1.4		0.004	0.004	13.5	13.5	4	27080.0
DS-52-158	4.1		0.011	0.011	37.1	37.1	0.016	108.3
DS-52-141	20		0.011	0.011	37.1	37.1	0.013	88.0
DS-52-143	1.6		0.01	0.010	33.8	33.8	0.007	47.4
DS-52-145	1.7		0.005	0.005	16.9	16.9	0.003	20.3
DS-52-146	0.2		0.008	0.008	27.0	27.0	0.007	47.4
DS-52-99	2.8		0.034	0.034	114.8	114.8	0.055	372.4
DS-52-100	1.2		0.028	0.028	94.5	94.5	0.05	338.5
DS-52-101	4.5		0.03	0.030	101.3	101.3	0.053	358.8
DS-52-102	0.6		0.018	0.018	60.8	60.8	0.022	148.9
DS-52-103	3.7		0.026	0.026	87.8	87.8	0.036	243.7
DS-52-104	0.2		0.044	0.044	148.5	148.5	0.072	487.4
DS-52-107	7.6		0.037	0.037	124.9	124.9	0.066	446.8
DS-52-109	1		3.024	3.002	10207.9	10207.9	0.037	250.5
DS-52-110	0.6		0.035	0.035	118.1	118.1	0.055	372.4
DS-52-113	2		0.042	0.042	141.8	141.8	0.051	345.3
DS-52-24	0.5		0.024	0.024	81.0	81.0	0.035	237.0
DS-52-25	1.4		0.032	0.032	108.0	108.0	0.48	3249.6
DS-52-27	9.8		0.019	0.019	64.1	64.1	0.026	176.0
DS-52-28	2.8		0.06	0.060	202.5	202.5	0.11	744.7
DS-52-31	4.8		0.025	0.025	84.4	84.4	0.041	277.6
DS-52-32	2		0.05	0.050	168.8	168.8	0.079	534.8
DS-52-33	1.5		0.044	0.044	148.5	148.5	0.071	480.7
DS-52-34	8.7		0.026	0.026	87.8	87.8	0.041	277.6
DS-52-35	4.1		0.014	0.014	47.3	47.3	0.015	101.6
DS-52-45	2		0.024	0.024	81.0	81.0	0.05	338.5
DS-52-46	26.8		0.049	0.049	165.4	165.4	0.097	656.7
DS-52-47	11.8		0.041	0.041	138.4	138.4	0.075	507.8
DS-52-59	5.9		0.028	0.028	94.5	94.5	0.038	257.3
DS-52-60	12.8		0.018	0.018	60.8	60.8	0.023	155.7
DS-52-61	10.7		0.02	0.020	67.5	67.5	0.029	196.3
DS-52-62	12.2		0.034	0.034	114.8	114.8	0.055	372.4
DS-52-63	16		0.06	0.060	202.5	202.5	0.12	812.4
DS-52-64	4		0.013	0.013	43.9	43.9	0.015	101.6
DS-52-65	9.3		0.058	0.058	195.8	195.8	0.11	744.7
DS-52-66	8.8		0.049	0.049	165.4	165.4	0.078	528.1
DS-52-67	0.7		0.016	0.016	54.0	54.0	0.026	176.0
DS-52-79	0.5		0.024	0.024	81.0	81.0	0.031	209.9
DS-52-80	65		0.017	0.017	57.4	57.4	0.021	142.2
DS-52-81	7.5		0.016	0.016	54.0	54.0	0.023	155.7
DS-52-82	7.4		0.032	0.032	108.0	108.0	0.057	385.9
DS-52-53	5.4		0.02	0.020	67.5	67.5	0.031	209.9
DS-52-84	1.3		0.031	0.031	104.6	104.6	0.047	318.2

DS-52-58	4.4		0.021	0.021	70.9	70.9	0.027	182.8
DS-52-86	8.2		0.028	0.028	94.5	94.5	0.037	250.5
DS-52-87	3.1		0.031	0.031	104.6	104.6	0.043	291.1
DS-52-88	1.6		0.049	0.049	165.4	165.4	0.07	473.9
DS-52-2	1.5		0.035	0.035	118.1	118.1	0.079	534.8
DS-52-4	0.3		0.018	0.018	60.8	60.8	0.033	223.4
DS-52-5	0.2		0.011	0.011	37.1	37.1	0.018	121.9
DS-52-22	1.1		0.033	0.033	111.4	111.4	0.045	304.7
DS-52-7	2.2		0.017	0.017	57.4	57.4	0.03	203.1
DS-52-8	3		0.019	0.019	64.1	64.1	0.031	209.9
DS-52-10	6		0.025	0.025	84.4	84.4	0.041	277.6
DS-52-12	0.3		0.022	0.022	74.3	74.3	0.026	176.0
DS-52-13	9.5		0.037	0.037	124.9	124.9	0.063	426.5
DS-52-14	2.4		0.022	0.022	74.3	74.3	0.035	237.0
DS-52-15	2		0.022	0.022	74.3	74.3	0.032	216.6
DS-52-20	0.5		0.096	0.095	324.1	324.1	0.15	1015.5
LRP-28	6.7		0.011	0.011	37.1	37.1	0.017	115.1
LRP-31	5.8		0.008	0.008	27.0	27.0	0.008	54.2
LRP-10	4.5		0.01	0.010	33.8	33.8	0.017	115.1
LRP-7	0.6		0.004	0.004	13.5	13.5	0.002	13.5
LRP-12	2.1		0.017	0.017	57.4	57.4	0.029	196.3
LRP-H-14		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-13	2.5		0.013	0.013	43.9	43.9	0.019	128.6
LRP-14	3		0.012	0.012	40.5	40.5	0.014	94.8
LRP-15	6.4		0.017	0.017	57.4	57.4	0.026	176.0
LRP-16	2.3		0.015	0.015	50.6	50.6	0.019	128.6
LRP-18	1.6		0.01	0.010	33.8	33.8	0.014	94.8
LRP-19	0.7		0.007	0.007	23.6	23.6	0.005	33.9
LRP-20	0.8		0.02	0.020	67.5	67.5	0.029	196.3
LRP-24	1.7		0.019	0.019	64.1	64.1	0.037	250.5
DS-H-407		10	0.007	0.007	23.6	23.6	0.006	40.6
DS-H-406		10	0.006	0.006	20.3	20.3	0.007	47.4
DS-H-405		10	0.002	0.002	6.8	6.8	0.001	6.8
DS-H-404		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-H-260		10	0.005	0.005	16.9	16.9	0.004	27.1
DS-H-259		10	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-258		10	0.005	0.005	16.9	16.9	0.002	13.5
DS-H-257		10	0.004	0.004	13.5	13.5	0.003	20.3
DS-H-256		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-H-255		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-H-254		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-51-261	7.4		0.017	0.017	57.4	57.4	0.035	237.0
DS-51-259	2.4		0.01	0.010	33.8	33.8	0.013	88.0
DS-H-251		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-H-250		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-H-249		10	0.003	0.003	10.1	10.1	0.003	20.3
DS-H-248		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-H-247		10	0.004	0.004	13.5	13.5	0.001	6.8
DS-H-246		10	0.005	0.005	16.9	16.9	0.003	20.3
DS-H-245		10	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-244		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-H-243		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-H-242		10	0.005	0.005	16.9	16.9	0.005	33.9
DS-51244B	0.4		0.004	0.004	13.5	13.5	0.004	27.1
DS-H-241		10	0.004	0.004	13.5	13.5	0.003	20.3
DS-H-240		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-52-161	6.2		0.014	0.014	47.3	47.3	0.02	135.4
DS-52-160	10.3		0.016	0.016	54.0	54.0	0.035	237.0
DS-52-159	4.7		0.019	0.019	64.1	64.1	0.033	223.4
DS-51-266	2		0.006	0.006	20.3	20.3	0.009	60.9
DS-51-264	3.6		0.028	0.028	94.5	94.5	0.05	338.5
DS-51-263	3.1		0.007	0.007	23.6	23.6	0.008	54.2
DS-51-262	1.1		0.008	0.008	27.0	27.0	0.01	67.7
DS-H-253		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-H-252		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-51-258	5.8	Sample missing		0.000	0.0	0.0		0.0
DS-51-252	2.5		0.003	0.003	10.1	10.1	0.003	20.3
DS-51-251	8.8		0.004	0.004	13.5	13.5	0.003	20.3
DS-51-250	8.7		0.004	0.004	13.5	13.5	0.003	20.3
DS-51-246	9		0.007	0.007	23.6	23.6	0.008	54.2
DS-51-245	10		0.017	0.017	57.4	57.4	0.025	169.3
	6.1	Not Sampled		0.000	0.0	0.0		0.0
DS-51-244A	0.6		0.045	0.045	151.9	151.9	0.075	507.8
DS-51-243	1.6		0.005	0.005	16.9	16.9	0.004	27.1
DS-52-164	4.8		0.009	0.009	30.4	30.4	0.013	88.0
DS-52-163	5.1		0.016	0.016	54.0	54.0	0.024	162.5
DS-52-162	7.5		0.018	0.018	60.8	60.8	0.039	264.0
	0.4	Not Sampled		0.000	0.0	0.0		0.0
DS-51-265	6.9		0.021	0.021	70.9	70.9	0.038	257.3
DS-51-260	3.2		0.004	0.004	13.5	13.5	0.006	40.6
DS-51-256	8.4		0.008	0.008	27.0	27.0	0.01	67.7
DS-51-255	2.2		0.004	0.004	13.5	13.5	0.004	27.1
DS-51-254	4.6		0.005	0.005	16.9	16.9	0.008	54.2
DS-51-253	4.4		0.006	0.006	20.3	20.3	0.009	60.9
DS-51-249	8.2		0.008	0.008	27.0	27.0	0.009	60.9
DS-51-248	17.5		0.006	0.006	20.3	20.3	0.008	54.2
DS-51-247	15.5		0.01	0.010	33.8	33.8	0.015	101.6
DS-51-257	4.6		0.008	0.008	27.0	27.0	0.008	54.2
DS-H-431		10	0.003	0.003	10.1	10.1	<.001	
DS-H-428		7	0.009	0.009	30.4	30.4	0.024	162.5
DS-H-427		5	0.006	0.006	20.3	20.3	0.009	60.9
DS-H-426		10	0.003	0.003	10.1	10.1	0.002	13.5
DS-52-172	0.4		0.008	0.008	27.0	27.0	0.011	74.5
DS-H-411		10	0.005	0.005	16.9	16.9	0.002	13.5
DS-52-165	4.9		0.023	0.023	77.6	77.6	0.044	297.9
DS-H-409		10	0.003	0.003	10.1	10.1	0.001	6.8
DS-H-408		10	0.003	0.003	10.1	10.1	<.001	
DS-H-407	continued in E'-F'			0.000	0.0	0.0		0.0
DS-H-430		10	0.003	0.003	10.1	10.1	<.001	
DS-H-429		8	0.004	0.004	13.5	13.5	<.001	
DS-52-179	2.9		0.012	0.012	40.5	40.5	0.027	182.8
DS-52-178	5.6		0.015	0.015	50.6	50.6	0.037	250.5
DS-52-176	2.3		0.012	0.012	40.5	40.5	0.026	176.0
DS-52-175	0.5		0.009	0.009	30.4	30.4	0.021	142.2
DS-H-425		10	0.003	0.003	10.1	10.1	0.001	6.8
DS-H-424		10	0.002	0.002	6.8	6.8	0.001	6.8
DS-H-422		10	0.002	0.002	6.8	6.8	<.001	

DS-H-421		5	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-420		5	0.004	0.004	13.5	13.5	0.005	33.9
DS-H-419		10	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-418		10	0.003	0.003	10.1	10.1	0.001	6.8
DS-H-417		10	0.002	0.002	6.8	6.8	0.001	6.8
DS-H-416		10	0.005	0.005	16.9	16.9	0.004	27.1
DS-H-415		10	0.004	0.004	13.5	13.5	0.003	20.3
DS-H-414		10	0.002	0.002	6.8	6.8	0.001	6.8
DS-H-413		10	0.004	0.004	13.5	13.5	0.001	6.8
DS-H-412		10	0.004	0.004	13.5	13.5	0.002	13.5
DS-52-167	7.6		0.012	0.012	40.5	40.5	0.021	142.2
DS-52-166	6		0.009	0.009	30.4	30.4	0.014	94.8
DS-H-410		10	0.003	0.003	10.1	10.1	0.001	6.8
DS-52-182	3.3		0.014	0.014	47.3	47.3	0.031	209.9
DS-52-181	3.7		0.014	0.014	47.3	47.3	0.03	203.1
DS-52-180	7.4		0.015	0.015	50.6	50.6	0.041	277.6
DS-52-177	2.9		0.015	0.015	50.6	50.6	0.033	223.4
DS-52-174	0.8		0.008	0.008	27.0	27.0	0.017	115.1
DS-52-173	0.9		0.006	0.006	20.3	20.3	0.007	47.4
DS-52-171	5.4		0.022	0.022	74.3	74.3	0.046	311.4
DS-52-170	4		0.01	0.010	33.8	33.8	0.018	121.9
DS-52-169	6		0.011	0.011	37.1	37.1	0.015	101.6
DS-52-168	6.4		0.016	0.016	54.0	54.0	0.022	148.9
	0.7	Not Sampled		0.000	0.0	0.0		0.0
LRP-74	2		0.01	0.010	33.8	33.8	0.017	115.1
LRP-73	8.5		0.006	0.006	20.3	20.3	0.009	60.9
LRP-72	1.8		0.014	0.014	47.3	47.3	0.022	148.9
	0.08	Not Sampled		0.000	0.0	0.0		0.0
LRP-64	6		0.017	0.017	57.4	57.4	0.026	176.0
LRP-63	7.8		0.013	0.013	43.9	43.9	0.014	94.8
LRP-H-106		13.5	0.009	0.009	30.4	30.4	0.011	74.5
LRP-H-105		9	0.002	0.002	6.8	6.8	0	0.0
LRP-39	1		0.014	0.014	47.3	47.3	0.02	135.4
LRP-68	3.4		0.012	0.012	40.5	40.5	0.02	135.4
LRP-78	1.5		0.018	0.018	60.8	60.8	0.028	189.6
LRP-H-67		5	0.005	0.005	16.9	16.9	0.007	47.4
LRP-H-108		14	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-66		13	0.007	0.007	23.6	23.6	0.008	54.2
LRP-70	3		0.017	0.017	57.4	57.4	0.018	121.9
LRP-H-65		4	0.005	0.005	16.9	16.9	0.005	33.9
LRP-69	2.7		0.012	0.012	40.5	40.5	0.015	101.6
LRP-H-64		8	0.003	0.003	10.1	10.1	0.002	13.5
LRP-H-63		10	0.004	0.004	13.5	13.5	0.005	33.9
LRP-67	0.4		0.039	0.039	131.6	131.6	0.061	413.0
LRP-H-62		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-65	2		0.03	0.030	101.3	101.3	0.064	433.3
LRP-H-61		6	0.005	0.005	16.9	16.9	0.006	40.6
LRP-60		10	0.005	0.005	16.9	16.9	0.003	20.3
LRP-59		10	0.003	0.003	10.1	10.1	0.003	20.3
LRP-H-107		10	0.005	0.005	16.9	16.9	0.004	27.1
LRP-H-58		9	0.005	0.005	16.9	16.9	0.004	27.1
LRP-H-57		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-H-56		10	0.004	0.004	13.5	13.5	0.006	40.6
LRP-62	2.2		0.022	0.022	74.3	74.3	0.036	243.7
LRP-60	2		0.025	0.025	84.4	84.4	0.043	291.1
LRP-H-55		4	0.005	0.005	16.9	16.9	0.008	54.2
LRP-58	4.4		0.008	0.008	27.0	27.0	0.009	60.9
LRP-57	11.5		0.012	0.012	40.5	40.5	0.018	121.9
LRP-H-54		10	0.004	0.004	13.5	13.5	0.002	13.5
LRP-55	3.7		0.008	0.008	27.0	27.0	0.007	47.4
LRP-53		7	0.005	0.005	16.9	16.9	0.012	81.2
LRP-49	4.7		0.007	0.007	23.6	23.6	0.008	54.2
LRP-48	10.1		0.014	0.014	47.3	47.3	0.017	115.1
LRP-47	14.6		0.01	0.010	33.8	33.8	0.015	101.6
LRP-H-52		10	0.005	0.005	16.9	16.9	0.001	6.8
LRP-H-51		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-50		6	0.004	0.004	13.5	13.5	0.002	13.5
LRP-46	2.9		0.01	0.010	33.8	33.8	0.013	88.0
LRP-45	8.4		0.016	0.016	54.0	54.0	0.019	128.6
LRP-H-49		4	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-48		10	0.003	0.003	10.1	10.1	0.002	13.5
LRP-41	3.9		0.016	0.016	54.0	54.0	0.02	135.4
LRP-40	6.3		0.012	0.012	40.5	40.5	0.017	115.1
H-47		13	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-46		10	0.003	0.003	10.1	10.1	0.002	13.5
LRP-H-45		11.5	0.004	0.004	13.5	13.5	0.004	27.1
LRP-37	2.1		0.018	0.018	60.8	60.8	0.027	182.8
LRP-36	10.6		0.015	0.015	50.6	50.6	0.024	162.5
LRP-H-44		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-H-43		10	0.004	0.004	13.5	13.5	0.003	20.3
LRP-H-42		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-41		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-H-40		10	0.005	0.005	16.9	16.9	0.004	27.1
LRP-32	7.3		0.008	0.008	27.0	27.0	0.011	74.5
LRP-H-39		10	0.004	0.004	13.5	13.5	0.004	27.1
LRP-H-38		10	0.004	0.004	13.5	13.5	0.003	20.3
LRP-77	4.2		0.012	0.012	40.5	40.5	0.019	128.6
LRP-76	2.6		0.007	0.007	23.6	23.6	0.011	74.5
LRP-75	4.8		0.015	0.015	50.6	50.6	0.03	203.1
LRP-71	7.2		0.021	0.021	70.9	70.9	0.034	230.2
LRP-66	3.8		0.033	0.033	111.4	111.4	0.06	406.2
LRP-61	3.3		0.026	0.026	87.8	87.8	0.041	277.6
LRP-59	0.5		0.017	0.017	57.4	57.4	0.023	155.7
LRP-56	2.9		0.018	0.018	60.8	60.8	0.028	189.6
LRP-53	3.6		0.007	0.007	23.6	23.6	0.007	47.4
LRP-52	9.7		0.012	0.012	40.5	40.5	0.016	108.3
LRP-51	13.7		0.012	0.012	40.5	40.5	0.017	115.1
LRP-50	9		0.013	0.013	43.9	43.9	0.012	81.2
LRP-44	7.2		0.017	0.017	57.4	57.4	0.027	182.8
LRP-43	9.2		0.013	0.013	43.9	43.9	0.021	142.2
LRP-42	6.1		0.01	0.010	33.8	33.8	0.012	81.2
LRP-38	9.4		0.014	0.014	47.3	47.3	0.021	142.2
LRP-35	9.4		0.025	0.025	84.4	84.4	0.051	345.3
LRP-34	4		0.012	0.012	40.5	40.5	0.019	128.6
LRP-33	5.5		0.009	0.009	30.4	30.4	0.012	81.2
LRP-168	2.6		0.007	0.007	23.6	23.6	0.008	54.2
LRP-H-104		5.5	0.004	0.004	13.5	13.5	0.002	13.5

LRP-162	1.2		0.037	0.037	124.9	124.9	0.078	528.1
LRP-161	2.8		0.014	0.014	47.3	47.3	0.022	148.9
	0.6	Not Sampled		0.000	0.0	0.0		0.0
LRP-H-127		6	0.003	0.003	10.1	10.1	0	0.0
LRP-H-126		10	0.003	0.003	10.1	10.1	0	0.0
LRP-H-125		10.5	0.003	0.003	10.1	10.1	0	0.0
LRP-H-124		10	0.007	0.007	23.6	23.6	0.009	60.9
LRP-H-123		10	0.006	0.006	20.3	20.3	0.004	27.1
LRP-H-122		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-121		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-120		10	0.004	0.004	13.5	13.5	0	0.0
LRP-H-119		10	0.004	0.004	13.5	13.5	0	0.0
LRP-H-118		10	0.004	0.004	13.5	13.5	0	0.0
LRP-H-117		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-116		10	0.008	0.008	27.0	27.0	0.008	54.2
LRP-112	9.2		0.022	0.022	74.3	74.3	0.04	270.8
LRP-111	9.6		0.021	0.021	70.9	70.9	0.039	264.0
LRP-H-114		7	0.004	0.004	13.5	13.5	0	0.0
LRP-H-113		5	0.005	0.005	16.9	16.9	0.003	20.3
LRP-H-112		10	0.005	0.005	16.9	16.9	0.004	27.1
LRP-H-111		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-110		10	0.005	0.005	16.9	16.9	0.007	47.4
LRP-85	4.6		0.016	0.016	54.0	54.0	0.027	182.8
LRP-81	2.8		0.021	0.021	70.9	70.9	0.038	257.3
LRP-79	1.7		0.045	0.045	151.9	151.9	0.085	575.5
LRP-H-103		20	0.005	0.005	16.9	16.9	0.003	20.3
LRP-H-102		10	0.003	0.003	10.1	10.1	0.002	13.5
LRP-167	0.4		0.006	0.006	20.3	20.3	0.006	40.6
LRP-H-101		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-100		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-99		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-98		10.5	0.004	0.004	13.5	13.5	0.001	6.8
LRP-H-97		11.5	0.006	0.006	20.3	20.3	0.002	13.5
LRP-H-96		10	0.006	0.006	20.3	20.3	0.003	20.3
LRP-H-95		10	0.005	0.005	16.9	16.9	0.003	20.3
LRP-H-94		10	0.009	0.009	30.4	30.4	0.011	74.5
LP-H-128		7	0.006	0.006	20.3	20.3	0.008	54.2
LRP-H-93		7	0.005	0.005	16.9	16.9	0.002	13.5
LRP-H-92		10	0.004	0.004	13.5	13.5	0.002	13.5
LRP-H-91		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-90		10	0.003	0.003	10.1	10.1	<.001	
LRP-H-89		9.5	0.004	0.004	13.5	13.5	0.002	13.5
LRP-H-88		10	0.004	0.004	13.5	13.5	0.001	6.8
LRP-156	1.6		0.014	0.014	47.3	47.3	0.024	162.5
LRP-155	12.3		0.008	0.008	27.0	27.0	0.012	81.2
LRP-154	12.6		0.009	0.009	30.4	30.4	0.012	81.2
LRP-H-87		12.5	0.003	0.003	10.1	10.1	0.001	6.8
LRP-H-86		10	0.004	0.004	13.5	13.5	<.001	
LRP-149	9.4		0.013	0.013	43.9	43.9	0.026	176.0
LRP-148	7.8		0.01	0.010	33.8	33.8	0.019	128.6
LRP-147	9.5		0.009	0.009	30.4	30.4	0.011	74.5
LRP-146	11.2		0.007	0.007	23.6	23.6	0.009	60.9
LRP-145	12.3		0.007	0.007	23.6	23.6	0.008	54.2
LRP-144	4.2		0.007	0.007	23.6	23.6	0.006	40.6
LRP-143	7.5		0.012	0.012	40.5	40.5	0.021	142.2
LRP-142	3.6	Sample Missing		0.000	0.0	0.0		0.0
LRP-135	3.4		0.011	0.011	37.1	37.1	0.02	135.4
LRP-134	7.3		0.015	0.015	50.6	50.6	0.025	169.3
LRP-133	8.9		0.017	0.017	57.4	57.4	0.031	209.9
LRP-132	6		0.011	0.011	37.1	37.1	0.022	148.9
LRP-H-85		4	0.001	0.001	3.4	3.4	0.001	6.8
LRP-126	8		0.011	0.011	37.1	37.1	0.019	128.6
LRP-125	6.4		0.013	0.013	43.9	43.9	0.022	148.9
LRP-124	8.7		0.007	0.007	23.6	23.6	0.01	67.7
LRP-H-84		2	0.004	0.004	13.5	13.5	0.003	20.3
LRP-H-83		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-123	1.4		0.013	0.013	43.9	43.9	0.024	162.5
LRP-H-82		4	0.004	0.004	13.5	13.5	0.001	6.8
LRP-122	1		0.012	0.012	40.5	40.5	0.009	60.9
LRP-121	3.2		0.027	0.027	91.1	91.1	0.045	304.7
LRP-H-81		1.5	0.004	0.004	13.5	13.5	0.001	6.8
LRP-113	7.1		0.025	0.025	84.4	84.4	0.04	270.8
LRP-H-80		11	0.005	0.005	16.9	16.9	0.007	47.4
LRP-H-79		10	0.004	0.004	13.5	13.5	0.002	13.5
LRP-H-78		10	0.003	0.003	10.1	10.1	0.001	6.8
LRP-106	1.3		0.018	0.018	60.8	60.8	0.031	209.9
LRP-105	11.7		0.019	0.019	64.1	64.1	0.028	189.6
LRP-H-77		6	0.004	0.004	13.5	13.5	<.001	
LRP-H-76		10	0.006	0.006	20.3	20.3	0.006	40.6
LRP-101	4.6		0.01	0.010	33.8	33.8	0.016	108.3
LRP-100	8		0.009	0.009	30.4	30.4	0.011	74.5
LRP-H-75	2.2	Sample Missing		0.000	0.0	0.0		0.0
LRP-94	3.7		0.009	0.009	30.4	30.4	8	54160.0
LRP-93	6.8		0.012	0.012	40.5	40.5	0.014	94.8
LRP-92	4.8		0.009	0.009	30.4	30.4	0.009	60.9
LRP-H-74		2	0.004	0.004	13.5	13.5	0.004	27.1
LRP-88	1.8		0.012	0.012	40.5	40.5	0.018	121.9
LRP-87	7.4		0.035	0.035	118.1	118.1	0.067	453.6
LRP-H-73		5	0.007	0.007	23.6	23.6	0.006	40.6
LRP-H-72		10	0.006	0.006	20.3	20.3	0.008	54.2
LRP-86	4.1		0.018	0.018	60.8	60.8	0.025	169.3
LRP-H-109		11	0.006	0.006	20.3	20.3	0.005	33.9
LRP-H-71		11	0.008	0.008	27.0	27.0	0.007	47.4
LRP-H-70		10	0.006	0.006	20.3	20.3	0.008	54.2
LRP-H-69		10	0.005	0.005	16.9	16.9	0.002	13.5
LRP-H-68		10	0.005	0.005	16.9	16.9	0.005	33.9
LRP-169	3.3		0.007	0.007	23.6	23.6	0.008	54.2
LRP-165	5.3		0.006	0.006	20.3	20.3	0.008	54.2
LRP-164	9.9		0.006	0.006	20.3	20.3	0.008	54.2
LRP-163	2.6		0.009	0.009	30.4	30.4	0.011	74.5
LRP-160	1.2		0.005	0.005	16.9	16.9	0.002	13.5
LRP-159	10.1		0.017	0.017	57.4	57.4	0.024	162.5
LRP-158	11.7		0.008	0.008	27.0	27.0	0.01	67.7
LRP-157	9.7		0.008	0.008	27.0	27.0	0.009	60.9
LRP-153	6		0.016	0.016	54.0	54.0	0.028	189.6
LRP-152	7.7		0.012	0.012	40.5	40.5	0.02	135.4
LRP-151	4.7		0.009	0.009	30.4	30.4	0.013	88.0

LRP-150	7.4		0.01	0.010	33.8	33.8	0.011	74.5
LRP-141	5.8		0.009	0.009	30.4	30.4	0.015	101.6
LRP-140	10.3		0.01	0.010	33.8	33.8	0.013	88.0
LRP-139	7.6		0.007	0.007	23.6	23.6	0.011	74.5
LRP-138	8.4		0.009	0.009	30.4	30.4	0.013	88.0
LRP-137	7.4		0.012	0.012	40.5	40.5	0.021	142.2
LRP-136	5.8		0.009	0.009	30.4	30.4	0.02	135.4
LRP-131	7.4		0.01	0.010	33.8	33.8	0.017	115.1
LRP-130	6.8		0.009	0.009	30.4	30.4	0.016	108.3
LRP-129	10.2		0.011	0.011	37.1	37.1	0.017	115.1
LRP-128	7.7		0.008	0.008	27.0	27.0	0.011	74.5
LRP-127	7.6		0.005	0.005	16.9	16.9	0.006	40.6
LRP-120	2.5		0.027	0.027	91.1	91.1	0.047	318.2
LRP-119	4.6		0.013	0.013	43.9	43.9	0.019	128.6
LRP-118	6.5		0.018	0.018	60.8	60.8	0.012	81.2
LRP-117	4		0.011	0.011	37.1	37.1	0.023	155.7
LRP-116	2.7		0.031	0.031	104.6	104.6	0.053	358.8
LRP-115	13.4		0.02	0.020	67.5	67.5	0.035	237.0
LRP-114	8.5		0.015	0.015	50.6	50.6	0.025	169.3
LRP-110	2.4		0.003	0.003	10.1	10.1	0.005	33.9
LRP-109	3.7		0.006	0.006	20.3	20.3	0.008	54.2
	2	Not Sampled		0.000	0.0	0.0		0.0
LRP-108	10.9		0.01	0.010	33.8	33.8	0.012	81.2
LRP-107	6		0.017	0.017	57.4	57.4	0.023	155.7
LRP-103	1.4		0.005	0.005	16.9	16.9	0.004	27.1
LRP-102	3.9		0.006	0.006	20.3	20.3	0.008	54.2
LRP-99	2		0.007	0.007	23.6	23.6	0.008	54.2
LRP-98	2.4		0.008	0.008	27.0	27.0	0.012	81.2
LRP-97	8.6		0.007	0.007	23.6	23.6	0.009	60.9
LRP-96	7.4		0.009	0.009	30.4	30.4	0.014	94.8
LRP-95	8.1		0.011	0.011	37.1	37.1	0.014	94.8
LRP-91	5.2		0.009	0.009	30.4	30.4	0.009	60.9
LRP-90	5		0.023	0.023	77.6	77.6	0.037	250.5
LRP-89	0.7		0.017	0.017	57.4	57.4	0.027	182.8
LRP-84	4.4		0.021	0.021	70.9	70.9	0.031	209.9
LRP-83	10		0.017	0.017	57.4	57.4	0.025	169.3
LRP-82	6.5		0.023	0.023	77.6	77.6	0.037	250.5
LRP-80	6.3		0.006	0.006	20.3	20.3	0.008	54.2
Mean:			0.020	0.019	65.094	65.094	0.049	323.975
Median:			0.009	0.009	30.381	30.381	0.014	88.010
Standard Deviation:			0.144	0.142	481.791	481.791	0.431	2882.598
Maximum:			3.024	3.002	10207.881	10207.881	8.000	54160.000
Minimum:			0.001	0.000	0.000	0.000	0.000	0.000

▨ Values computed by Kennecott Uranium Company from data in paper

OAP:02/17/08

KENNECOTT URANIUM COMPANY
LOST CREEK TRENCH SAMPLING
Sections 8-13

Source: **Geology of the Lost Creek Schroeckingerite Deposits Sweetwater County, Wyoming**
Geological Survey Bulletin 1087-J

SAMPLE #	SAMPLE AREA	SAMPLE LENGTH	PERCENT EQUIVALENT URANIUM	PERCENT EQUIVALENT URANIUM-238	EQUIVALENT URANIUM-238 ACTIVITY	RADIUM-226 ACTIVITY	PERCENT URANIUM	NATURAL URANIUM ACTIVITY
					(picoCuries per gram)	(picoCuries per gram)		(picoCuries per gram)
DS-52-293	3.4		0.019	0.019	64.1	64.1	0.033	223.4
DS-52-294	3.9		0.008	0.008	27.0	27.0	0.008	54.2
DS-52-295	2.9		0.008	0.008	27.0	27.0	0.007	47.4
DS-52-297	1.7		0.005	0.005	16.9	16.9	0.002	13.5
DS-52-284	5		0.016	0.016	54.0	54.0	0.028	189.6
DS-52-285	5.6		0.014	0.014	47.3	47.3	0.024	162.5
DS-52-286	3.5		0.017	0.017	57.4	57.4	0.033	223.4
DS-52-287	0.06		0.006	0.006	20.3	20.3	0.006	40.6
DS-52-371	5		0.014	0.014	47.3	47.3	0.024	162.5
DS-52-372	3.5		0.014	0.014	47.3	47.3	0.018	121.9
DS-52-373	3.6		0.008	0.008	27.0	27.0	0.008	54.2
DS-52-374	3.4		0.009	0.009	30.4	30.4	0.011	74.5
DS-52-375	5.3		0.008	0.008	27.0	27.0	0.015	101.6
DS-52-376	4.5		0.009	0.009	30.4	30.4	0.009	60.9
DS-52-377	5.7		0.008	0.008	27.0	27.0	0.01	67.7
DS-52-378	4.2		0.013	0.013	43.9	43.9	0.02	135.4
DS-52-379	3.7		0.011	0.011	37.1	37.1	0.019	128.6
DS-52-380	4.7		0.011	0.011	37.1	37.1	0.015	101.6
DS-52-382	3.5		0.031	0.031	104.6	104.6	0.065	440.1
DS-52-390	5.8		0.015	0.015	50.6	50.6	0.026	176.0
DS-52-391	5		0.007	0.007	23.6	23.6	0.01	67.7
DS-52-392	6.5		0.005	0.005	16.9	16.9	0.007	47.4
DS-52-393	5.7		0.008	0.008	27.0	27.0	0.012	81.2
DS-52-394	3.9		0.005	0.005	16.9	16.9	0.005	33.9
DS-52-395	3		0.007	0.007	23.6	23.6	0.007	47.4
DS-52-397	5.6		0.004	0.004	13.5	13.5	0.003	20.3
DS-52-399	3.4		0.006	0.006	20.3	20.3	0.004	27.1
DS-52-299	5.6		0.004	0.004	13.5	13.5	0.003	20.3
DS-52-300	5.6		0.009	0.009	30.4	30.4	0.011	74.5
DS-52-301	6		0.005	0.005	16.9	16.9	0.005	33.9
DS-52-304	3.3		0.006	0.006	20.3	20.3	0.006	40.6
DS-52-305	4.9		0.012	0.012	40.5	40.5	0.015	101.6
DS-52-306	4.4		0.011	0.011	37.1	37.1	0.011	74.5
DS-52-307	3.6		0.021	0.021	70.9	70.9	0.032	216.6
DS-52-311	4.4		0.01	0.010	33.8	33.8	0.012	81.2
DS-52-314	2.6		0.006	0.006	20.3	20.3	0.007	47.4
DS-52-315	1.4		0.009	0.009	30.4	30.4	0.007	47.4
DS-52-317	3.2		0.012	0.012	40.5	40.5	0.014	94.8
DS-52-318	4.3		0.012	0.012	40.5	40.5	0.014	94.8
DS-52-320	2.6		0.008	0.008	27.0	27.0	0.008	54.2
DS-52-321	3.8		0.01	0.010	33.8	33.8	0.014	94.8
DS-52-322	4.5		0.009	0.009	30.4	30.4	0.013	88.0
DS-52-323	4.6		0.009	0.009	30.4	30.4	0.011	74.5
DS-52-324	5.1		0.007	0.007	23.6	23.6	0.007	47.4
DS-52-325	5		0.005	0.005	16.9	16.9	0.004	27.1
DS-52-332	1.5		0.005	0.005	16.9	16.9	0.005	33.9
DS-52-333	1.8		0.003	0.003	10.1	10.1	0.001	6.8
DS-52-340	0.7		0.007	0.007	23.6	23.6	0.009	60.9
DS-52-341	4.7		0.009	0.009	30.4	30.4	0.011	74.5
DS-52-342	5		0.011	0.011	37.1	37.1	0.014	94.8
DS-52-343	5.6		0.008	0.008	27.0	27.0	0.011	74.5
DS-52-344	5.1		0.007	0.007	23.6	23.6	0.008	54.2
DS-52-345	4.6		0.011	0.011	37.1	37.1	0.018	121.9
DS-52-346	5.5		0.011	0.011	37.1	37.1	0.017	115.1
DS-52-347	5.8		0.015	0.015	50.6	50.6	0.022	148.9
DS-52-348	6.1		0.018	0.018	60.8	60.8	0.03	203.1
DS-52-349	6.8		0.015	0.015	50.6	50.6	0.025	169.3
DS-52-312	4.8		0.009	0.009	30.4	30.4	0.012	81.2
DS-52-313	4		0.009	0.009	30.4	30.4	0.016	108.3
DS-52-316	3.3		0.009	0.009	30.4	30.4	0.01	67.7
DS-52-319	2.6		0.01	0.010	33.8	33.8	0.01	67.7
DS-52-326	4.5		0.028	0.028	94.5	94.5	0.019	128.6
DS-52-327	0.8		0.004	0.004	13.5	13.5	0.002	13.5
DS-52-328	3.8		0.004	0.004	13.5	13.5	0.005	33.9
DS-52--329	3.3		0.008	0.008	27.0	27.0	0.011	74.5
DS-52-330	3.5		0.005	0.005	16.9	16.9	0.005	33.9
DS-52-331	2.6		0.005	0.005	16.9	16.9	0.006	40.6

DS-52-352	2.7	0.005	0.005	16.9	16.9	0.004	27.1
DS-52-302	6	0.007	0.007	23.6	23.6	0.007	47.4
DS-52-303	4.9	0.005	0.005	16.9	16.9	0.005	33.9
DS-52-308	3.1	0.008	0.008	27.0	27.0	0.007	47.4
DS-52-309	4.7	0.011	0.011	37.1	37.1	0.013	88.0
DS-52-310	3.9	0.019	0.019	64.1	64.1	0.029	196.3
DS-52-334	3.2	0.005	0.005	16.9	16.9	0.02	135.4
DS-52-335	3	0.004	0.004	13.5	13.5	0.001	6.8
DS-52-336	0.9	0.004	0.004	13.5	13.5	0.002	13.5
DS-52-337	6	0.012	0.012	40.5	40.5	0.017	115.1
DS-52-338	6.1	0.012	0.012	40.5	40.5	0.018	121.9
DS-52-339	6.2	0.012	0.012	40.5	40.5	0.018	121.9
DS-52-350	5.3	0.011	0.011	37.1	37.1	0.018	121.9
DS-52-351	4.8	0.01	0.010	33.8	33.8	0.016	108.3
DS-52-353	3.1	0.01	0.010	33.8	33.8	0.012	81.2
DS-52-354	5.2	0.009	0.009	30.4	30.4	0.012	81.2
DS-52-355	5.7	0.014	0.014	47.3	47.3	0.02	135.4
DS-52-356	6.2	0.01	0.010	33.8	33.8	0.013	88.0
DS-52-357	5.7	0.015	0.015	50.6	50.6	0.024	162.5
DS-52-278	1	0.007	0.007	23.6	23.6	0.009	60.9
DS-52-281	3.1	0.021	0.021	70.9	70.9	0.034	230.2
DS-52-282	2.4	0.006	0.006	20.3	20.3	0.007	47.4
DS-52-283	4.7	0.012	0.012	40.5	40.5	0.021	142.2
DS-52-408	4.3	0.017	0.017	57.4	57.4	0.031	209.9
DS-52-409	3.8	0.017	0.017	57.4	57.4	0.033	223.4
DS-52-410	4	0.018	0.018	60.8	60.8	0.035	237.0
DS-52-411	3.2	0.016	0.016	54.0	54.0	0.035	237.0
DS-52-414	0.9	0.009	0.009	30.4	30.4	0.014	94.8
DS-52-415	2.7	0.008	0.008	27.0	27.0	0.014	94.8
DS-52-418	1.6	0.011	0.011	37.1	37.1	0.023	155.7
DFS-52-403	1.3	0.028	0.028	94.5	94.5	0.051	345.3
Mean:		0.010	0.010	34.962	34.962	0.015	100.376
Median:		0.009	0.009	30.381	30.381	0.012	81.240
Standard Deviation:		0.005	0.005	18.060	18.060	0.011	73.342
Maximum:		0.031	0.031	104.644	104.644	0.065	440.050
Minimum:		0.003	0.003	10.127	10.127	0.001	6.770

▨ Values computed by Kennecott Uranium Company from data in paper

OAP:02/17/08

KENNECOTT URANIUM COMPANY
LOST CREEK TRENCH SAMPLING
Section 1

Source: **Geology of the Lost Creek Schroeckingerite Deposits Sweetwater County, Wyoming**
Geological Survey Bulletin 1087-J

SAMPLE #	AREA	LENGTH	PERCENT EQUIVALENT URANIUM	PERCENT EQUIVALENT URANIUM-238	QUIVALENT URANIUM-23 ACTIVITY (picoCuries per gram)	RADIUM-226 ACTIVITY (picoCuries per gram)	PERCENT URANIUM	NATURAL URANIUM ACTIVITY (picoCuries per gram)
DS-H-185		1.3	0.005	0.005	16.9	16.9	0.004	27.1
DS-51-179		0.7	0.006	0.006	20.3	20.3	0.002	13.5
DS-H-187		3.8	0.006	0.006	20.3	20.3	0.007	47.4
DS-H-188		1.9	0.005	0.005	16.9	16.9	0.005	33.9
DS-H-189		4.3	0.01	0.010	33.8	33.8	0.011	74.5
DS-H-190		0.7	0.005	0.005	16.9	16.9	0.006	40.6
DS-H-192		2.7	0.013	0.013	43.9	43.9	0.015	101.6
DS-51-191		0.3	0.008	0.008	27.0	27.0	0.009	60.9
DS-51-192		0.4	0.013	0.013	43.9	43.9	0.018	121.9
DS-51-193		0.7	0.013	0.013	43.9	43.9	0.02	135.4
DS-51-194		0.4	0.03	0.030	101.3	101.3	0.052	352.0
DS-H-198		0.6	0.009	0.009	30.4	30.4	0.01	67.7
DS-H-200		0.4	0.008	0.008	27.0	27.0	0.007	47.4
DS-H-205		3.7	0.007	0.007	23.6	23.6	0.008	54.2
DS-H-207		1	0.008	0.008	27.0	27.0	0.01	67.7
DS-H-208		6.1	0.011	0.011	37.1	37.1	0.015	101.6
DS-H-213		2.5	0.016	0.016	54.0	54.0	0.02	135.4
DS-51-178		0.7	0.003	0.003	10.1	10.1	0.001	6.8
DS-51-180		0.09	0.011	0.011	37.1	37.1	0.01	67.7
DS-51-181		1	0.011	0.011	37.1	37.1	0.011	74.5
DS-51-182		1.4	0.007	0.007	23.6	23.6	0.005	33.9
DS-51-183		1.2	0.006	0.006	20.3	20.3	0.004	27.1
DS-51-184		0.9	0.013	0.013	43.9	43.9	0.013	88.0
DS-51-185		1.2	0.008	0.008	27.0	27.0	0.006	40.6
DS-51-186		1.4	0.005	0.005	16.9	16.9	0.003	20.3
DS-51-187		0.7	0.005	0.005	16.9	16.9	0.003	20.3
DS-51-188		1.4	0.01	0.010	33.8	33.8	0.011	74.5
DS-51-189		1.2	0.01	0.010	33.8	33.8	0.012	81.2
DS-51-190		1.1	0.13	0.129	438.8	438.8	0.018	121.9
DS-51-195		0.3	0.011	0.011	37.1	37.1	0.016	108.3
DS-51-196		0.4	0.007	0.007	23.6	23.6	0.006	40.6
DS-51-197		0.7	0.006	0.006	20.3	20.3	0.006	40.6
DS-51-198		0.8	0.018	0.018	60.8	60.8	0.33	2234.1
DS-51-199		0.4	0.007	0.007	23.6	23.6	0.008	54.2
DS-51-200		0.6	0.012	0.012	40.5	40.5	0.018	121.9
DS-51-201		1.1	0.018	0.018	60.8	60.8	0.033	223.4
DS-51-202		2.1	0.008	0.008	27.0	27.0	0.011	74.5
DS-51-203		1.3	0.011	0.011	37.1	37.1	0.015	101.6
DS-51-204		0.9	0.01	0.010	33.8	33.8	0.014	94.8
DS-51-205		1.1	0.016	0.016	54.0	54.0	0.032	216.6
DS-51-206		1.4	0.039	0.039	131.6	131.6	0.096	649.9
DS-51-78		0.5	0.005	0.005	16.9	16.9	0.004	27.1
DS-H-98		5.9	0.031	0.031	104.6	104.6	0.051	345.3
DS-51-81		1	0.016	0.016	54.0	54.0	0.022	148.9
DS-51-84		0.6	0.007	0.007	23.6	23.6	0.004	27.1
DS-H-100		0.9	0.017	0.017	57.4	57.4	0.023	155.7
DS-H-101		2.9	0.004	0.004	13.5	13.5	0.004	27.1
DS-H-102		1.4	0.022	0.022	74.3	74.3	0.039	264.0
DS-51-88		0.6	0.012	0.012	40.5	40.5	0.013	88.0
DS-51-90		0.5	0.014	0.014	47.3	47.3	0.021	142.2
DS-H-104		4	0.029	0.029	97.9	97.9	0.044	297.9
DS-51-96		1.3	0.022	0.022	74.3	74.3	0.039	264.0
DS-H-106		4.4	0.021	0.021	70.9	70.9	0.032	216.6
DS-H-111		2.4	0.026	0.026	87.8	87.8	0.035	237.0
DS-H-112		3.1	0.014	0.014	47.3	47.3	0.014	94.8
DS-H-114		1.3	0.014	0.014	47.3	47.3	0.021	142.2
DS-52-138	2.2		0.01	0.010	33.8	33.8	0.011	74.5
DS-H-122		6	0.027	0.027	91.1	91.1	0.043	291.1
DS-H-149		1.3	0.19	0.189	641.4	641.4	0.035	237.0
DS-51-151		0.8	0.019	0.019	64.1	64.1	0.032	216.6
DS-H-150		3.2	0.048	0.048	162.0	162.0	0.09	609.3
DS-51-153		0.7	0.023	0.023	77.6	77.6	0.032	216.6
DS-51-156		1	0.022	0.022	74.3	74.3	0.049	331.7
DS-H-151		1.9	0.008	0.008	27.0	27.0	0.009	60.9
DS-H-156		0.8	0.011	0.011	37.1	37.1	0.011	74.5
DS-51-158		0.4	0.008	0.008	27.0	27.0	0.007	47.4
DS-H-157		4.3	0.031	0.031	104.6	104.6	0.051	345.3
DS-H-158		1.2	0.011	0.011	37.1	37.1	0.007	47.4
DS-H-164		0.9	0.01	0.010	33.8	33.8	0.014	94.8
DS-H-165		1.3	0.013	0.013	43.9	43.9	0.019	128.6
DS-51-173		0.7	0.008	0.008	27.0	27.0	0.002	13.5
DS-H-166		1.1	0.008	0.008	27.0	27.0	0.007	47.4
DS-51-174		0.8	0.013	0.013	43.9	43.9	0.012	81.2
DS-H-168		1	0.01	0.010	33.8	33.8	0.008	54.2
DS-H-169		0.9	0.009	0.009	30.4	30.4	0.006	40.6
DS-H-170		0.4	0.019	0.019	64.1	64.1	0.021	142.2
DS-H-172		1	0.012	0.012	40.5	40.5	0.012	81.2
DS-51-79		0.3	0.005	0.005	16.9	16.9	0.005	33.9
DS-51-80		0.6	0.017	0.017	57.4	57.4	0.018	121.9

DS-51-82	2.1	0.054	0.054	182.3	182.3	0.096	649.9
DS-51-83	1.4	0.013	0.013	43.9	43.9	0.022	148.9
DS-51-85	0.5	0.016	0.016	54.0	54.0	0.03	203.1
DS-51-86	0.9	0.012	0.012	40.5	40.5	0.016	108.3
DS-51-87	0.6	0.027	0.027	91.1	91.1	0.027	182.8
DS-51-89	1.2	0.004	0.004	13.5	13.5	0.002	13.5
DS-51-91	0.5	0.043	0.043	145.2	145.2	0.083	561.9
DS-51-92	1.4	0.041	0.041	138.4	138.4	0.043	291.1
DS-51-93	1.5	0.03	0.030	101.3	101.3	0.055	372.4
DS-51-94	1.5	0.031	0.031	104.6	104.6	0.05	338.5
DS-51-95	1.7	0.02	0.020	67.5	67.5	0.03	203.1
DS-H-105	3.5	0.005	0.005	16.9	16.9	0.007	47.4
DS-51-97	1.3	0.015	0.015	50.6	50.6	0.026	176.0
DS-51-98	1.3	0.013	0.013	43.9	43.9	0.023	155.7
DS-51-99	0.4	0.009	0.009	30.4	30.4	0.01	67.7
DS-51-100	0.5	0.012	0.012	40.5	40.5	0.02	135.4
DS-51-101	1	0.015	0.015	50.6	50.6	0.019	128.6
DS-51-102	0.8	0.016	0.016	54.0	54.0	0.023	155.7
DS-51-103	0.7	0.007	0.007	23.6	23.6	0.008	54.2
DS-51-104	0.6	0.015	0.015	50.6	50.6	0.018	121.9
DS-51-105	0.5	0.012	0.012	40.5	40.5	0.016	108.3
DS-51-105	0.5	0.012	0.012	40.5	40.5	0.016	108.3
DS-51-106	0.7	0.006	0.006	20.3	20.3	0.006	40.6
DS-51-107	1.3	0.018	0.018	60.8	60.8	0.033	223.4
DS-51-108	1.8	0.018	0.018	60.8	60.8	0.028	189.6
DS-51-109	2.8	0.021	0.021	70.9	70.9	0.032	216.6
DS-51-110	1.5	0.022	0.022	74.3	74.3	0.038	257.3
DS-51-111	1.5	0.034	0.034	114.8	114.8	0.06	406.2
DS-51-112	1	0.039	0.039	131.6	131.6	0.082	555.1
DS-51-152	0.5	0.068	0.068	229.5	229.5	0.07	473.9
DS-51-154	1.4	0.1	0.099	337.6	337.6	0.2	1354.0
DS-51-155	0.7	0.091	0.090	307.2	307.2	0.26	1760.2
DS-51-157	1	0.011	0.011	37.1	37.1	0.017	115.1
DS-51-159	1.2	0.035	0.035	118.1	118.1	0.055	372.4
DS-51-160	1	0.02	0.020	67.5	67.5	0.023	155.7
DS-51-161	1.1	0.019	0.019	64.1	64.1	0.023	155.7
DS-51-162	1	0.011	0.011	37.1	37.1	0.0004	2.7
DS-51-282	0.9	0.008	0.008	27.0	27.0	0.004	27.1
DS-51-172	1.2	0.014	0.014	47.3	47.3	0.018	121.9
DS-51-175.	0.6	0.012	0.012	40.5	40.5	0.011	74.5
DS-51-177	0.8	0.011	0.011	37.1	37.1	0.008	54.2
DS-H-65	2.5	0.009	0.009	30.4	30.4	0.014	94.8
DS-H-66	3.9	0.007	0.007	23.6	23.6	0.012	81.2
DS-H-67	3.9	0.016	0.016	54.0	54.0	0.03	203.1
DS-H-68	3.2	0.003	0.003	10.1	10.1	0.001	6.8
DS-H-69	3.3	0.014	0.014	47.3	47.3	0.024	162.5
DS-H-72	10	0.013	0.013	43.9	43.9	0.027	182.8
DS-H-73	4.4	0.014	0.014	47.3	47.3	0.025	169.3
DS-H-77	1.5	0.008	0.008	27.0	27.0	0.014	94.8
DS-H-78	7.9	0.009	0.009	30.4	30.4	0.016	108.3
DS-H-79	3.5	0.016	0.016	54.0	54.0	0.02	135.4
DS-H-80	9.3	0.004	0.004	13.5	13.5	0.003	20.3
DS-51-42A	0.6	0.004	0.004	13.5	13.5	0.003	20.3
DS-H-81	10.1	0.011	0.011	37.1	37.1	0.017	115.1
DS-H-82	0.6	0.004	0.004	13.5	13.5	0.005	33.9
DS-H-83	6.2	0.013	0.013	43.9	43.9	0.021	142.2
DS-H-84	1.3	0.005	0.005	16.9	16.9	0.005	33.9
DS-H-85	2.1	0.009	0.009	30.4	30.4	0.001	6.8
DS-H-86	2.5	0.008	0.008	27.0	27.0	0.004	27.1
DS-H-87	3.3	0.038	0.038	128.3	128.3	0.071	480.7
DS-H-89	0.7	0.008	0.008	27.0	27.0	0.005	33.9
DS-H-94	10	0.018	0.018	60.8	60.8	0.026	176.0
DS-H-95	1.3	0.006	0.006	20.3	20.3	0.006	40.6
DS-H-96	3.7	0.005	0.005	16.9	16.9	0.004	27.1
DS-H-97	3	0.019	0.019	64.1	64.1	0.039	264.0
DS-51-6	0.8	0.01	0.010	33.8	33.8	0.019	128.6
DS-51-7	0.5	0.009	0.009	30.4	30.4	0.016	108.3
DS-51-8	0.9	0.009	0.009	30.4	30.4	0.019	128.6
DS-51-9	1.9	0.011	0.011	37.1	37.1	0.018	121.9
DS-51-10	0.7	0.02	0.020	67.5	67.5	0.031	209.9
DS-51-11	1	0.006	0.006	20.3	20.3	0.012	81.2
DS-51-12	1.3	0.028	0.028	94.5	94.5	0.057	385.9
DS-51-13	1	0.01	0.010	33.8	33.8	0.015	101.6
DS-51-14	1.7	0.019	0.019	64.1	64.1	0.034	230.2
DS-51-15	0.7	0.017	0.017	57.4	57.4	0.034	230.2
DS-51-16	1	0.009	0.009	30.4	30.4	0.014	94.8
DS-51-17	1	0.012	0.012	40.5	40.5	0.026	176.0
DS-51-18	0.6	0.012	0.012	40.5	40.5	0.02	135.4
DS-51-36	0.4	0.032	0.032	108.0	108.0	0.052	352.0
DS-51-37	0.4	0.01	0.010	33.8	33.8	0.012	81.2
DS-51-38	0.5	0.012	0.012	40.5	40.5	0.013	88.0
DS-51-39	0.4	0.004	0.004	13.5	13.5	0.003	20.3
DS-51-40	0.6	0.006	0.006	20.3	20.3	0.008	54.2
DS-51-41	2.3	0.011	0.011	37.1	37.1	0.022	148.9
DS-51-42B	0.9	0.027	0.027	91.1	91.1	0.04	270.8
DS-51-43	1.4	0.007	0.007	23.6	23.6	0.008	54.2
DS-51-44	1.2	0.019	0.019	64.1	64.1	0.039	264.0
DS-51-45	1	0.007	0.007	23.6	23.6	0.012	81.2
DS-51-46	1	0.01	0.010	33.8	33.8	0.018	121.9
DS-51-47	0.6	0.018	0.018	60.8	60.8	0.037	250.5
DS-51-48	1	0.027	0.027	91.1	91.1	0.035	237.0
DS-51-49	1	0.033	0.033	111.4	111.4	0.063	426.5
DS-51-50	0.8	0.077	0.076	259.9	259.9	0.007	47.4
DS-51-51	3.5	0.008	0.008	27.0	27.0	0.013	88.0
DS-51-52	1.3	0.025	0.025	84.4	84.4	0.041	277.6
DS-51-53	20	0.028	0.028	94.5	94.5	0.051	345.3
DS-51-54	0.8	0.026	0.026	87.8	87.8	0.047	318.2
DS-51-55	0.8	0.021	0.021	70.9	70.9	0.035	237.0

DS-51-56		1.2	0.009	0.009	30.4	30.4	0.012	81.2
DS-51-77		1.1	0.023	0.023	77.6	77.6	0.048	325.0
DS-52-114	0.8		0.014	0.014	47.3	47.3	0.016	108.3
DS-52-115	12.9		0.013	0.013	43.9	43.9	0.017	115.1
DS-52-116	8.7	.	0.01	0.010	33.8	33.8	0.01	67.7
DS-52-117	7.7		0.005	0.005	16.9	16.9	0.006	40.6
DS-52-118	5		0.012	0.012	40.5	40.5	0.015	101.6
DS-52-119	3.8		0.014	0.014	47.3	47.3	0.018	121.9
DS-52-120	8		0.013	0.013	43.9	43.9	0.014	94.8
DS-52-121	10.7		0.011	0.011	37.1	37.1	0.01	67.7
DS-52-122	1.2		0.006	0.006	20.3	20.3	0.001	6.8
DS-52-123	637		0.009	0.009	30.4	30.4	0.009	60.9
DS-52-124	10.3		0.012	0.012	40.5	40.5	0.013	88.0
DS-52-125	6		0.013	0.013	43.9	43.9	0.02	135.4
DS-52-126	6.2		0.022	0.022	74.3	74.3	0.033	223.4
DS-52-127	6.8		0.013	0.013	43.9	43.9	0.016	108.3
DS-52-131	6		0.015	0.015	50.6	50.6	0.015	101.6
DS-52-129	5.9		0.011	0.011	37.1	37.1	0.012	81.2
DS-52-130	9		0.023	0.023	77.6	77.6	0.045	304.7
DS-52-131	6		0.015	0.015	50.6	50.6	0.015	101.6
DS-52-132	5.3		0.004	0.004	13.5	13.5	0.005	33.9
DS-52-133	4.8		0.008	0.008	27.0	27.0	0.013	88.0
DS-52-134	7.5		0.013	0.013	43.9	43.9	0.024	162.5
DS-52-135	6.5		0.021	0.021	70.9	70.9	0.033	223.4
DS-52-136	5.5		0.013	0.013	43.9	43.9	0.024	162.5
DS-51-19		0.5	0.008	0.008	27.0	27.0	0.009	60.9
DS-51-20		1.2	0.014	0.014	47.3	47.3	0.021	142.2
DS-51-21		0.8	0.009	0.009	30.4	30.4	0.014	94.8
DS-51-22		0.7	0.014	0.014	47.3	47.3	0.019	128.6
DS-51-23		1	0.01	0.010	33.8	33.8	0.014	94.8
DS-51-24		0.7	0.015	0.015	50.6	50.6	0.019	128.6
DS-51-25		1.3	0.013	0.013	43.9	43.9	0.024	162.5
DS-51-26		0.9	0.002	0.002	6.8	6.8	0.002	13.5
DS-51-27		0.5	0.004	0.004	13.5	13.5	0.003	20.3
DS-51-28		1.2	0.008	0.008	27.0	27.0	0.009	60.9
DS-51-29		1.3	0.033	0.033	111.4	111.4	0.062	419.7
DS-51-30		0.3	0.017	0.017	57.4	57.4	0.025	169.3
DS-51-31		1	0.024	0.024	81.0	81.0	0.04	270.8
DS-51-32		0.5	0.01	0.010	33.8	33.8	0.015	101.6
DS-51-33		0.7	0.011	0.011	37.1	37.1	0.02	135.4
DS-51-34		0.4	0.009	0.009	30.4	30.4	0.013	88.0
DS-51-35		0.8	0.01	0.010	33.8	33.8	0.019	128.6
DS-51-57		0.6	0.016	0.016	54.0	54.0	0.021	142.2
DS-51-58	0.06	Sample missing		0.000	0.0	0.0		0.0
DS-51-59		0.5	0.03	0.030	101.3	101.3	0.052	352.0
DS-51-60		2	0.021	0.021	70.9	70.9	0.024	162.5
DS-51-61		1.6	0.017	0.017	57.4	57.4	0.028	189.6
DS-51-62		1.5	0.003	0.003	10.1	10.1	0.002	13.5
DS-51-63		1.5	0.009	0.009	30.4	30.4	0.012	81.2
DS-51-64		1	0.011	0.011	37.1	37.1	0.012	81.2
DS-51-65		2	0.013	0.013	43.9	43.9	0.022	148.9
DS-51-66		1.4	0.016	0.016	54.0	54.0	0.027	182.8
DS-51-67		1.3	0.01	0.010	33.8	33.8	0.014	94.8
DS-51-69		1.6	0.012	0.012	40.5	40.5	0.016	108.3
DS-51-69		3	0.008	0.008	27.0	27.0	0.011	74.5
DS-51-72		1.9	0.011	0.011	37.1	37.1	0.015	101.6
DS-51-73		1.3	0.026	0.026	87.8	87.8	0.042	284.3
DS-51-74		1.6	0.025	0.025	84.4	84.4	0.036	243.7
DS-51-75		1.7	0.02	0.020	67.5	67.5	0.028	189.6
DS-51-76		2.8	0.006	0.006	20.3	20.3	0.004	27.1
Mean:			0.017	0.017	56.2	56.2	0.024	165.1
Median:			0.012	0.012	40.5	40.5	0.016	108.3
Standard Deviation:			0.019	0.018	62.5	62.5	0.033	223.0
Maximum:			0.190	0.189	641.4	641.4	0.330	2234.1
Minimum:			0.002	0.000	0.0	0.0	0.000	0.0

▨ Values computed by Kennecott Uranium Company from data in paper

OAP:02/17/08

Appendix 3

Kennecott Uranium Company
Soil Radiometric Data
UMETCO Gas Hills Site

Non-Random Background Soil Radiometric Data

	U-Nat	**Ra226**		**Th230**		**Pb210**	
SAMPLE I.D.#	(pCi/g)	pCi/g	Prec. +/-	pCi/g	Pec. +/-	pCi/g	Prec. +/-
SS # 1; 0-6"	0.9	1.6	0.5	< 0.02		0.2	0.2
SS # 1; 6-12"	0.8	1.1	0.3	< 0.02		< 0.10	
SS # 2; 0-6"	0.07	1.3	0.2	2.3	0.7	0.3	0.3
SS # 2; 6-12"	0.06	1.3	0.2	< 0.02		0.5	0.4
SS # 3; Road Bed	37.4	119	0.2	177	5.8	89.3	3.2
SS # 4; 0-6"	0.05	1	1	< 0.02		0.3	0.3
SS # 4; 6-12"	0.6	1.1	0.3	< 0.02		0.3	0.3
SS # 5: 0-6"	1.1	1.4	0.3	< 0.02		< 0.10	
SS # 5; 6-12"	1.2	1.7	0.3	< 0.02		1.1	0.8
SS # 6; 0-6"	1.1	1.6	0.3	< 0.02		< 0.10	
SS # 6; 6-12"	1.4	1.6	0.3	< 0.02		< 0.10	
SS # 7; 0-6"	2.3	1.7	0.3	< 0.02		0.8	0.8
SS # 7; 6-12"	2.9	1.9	0.3	< 0.02		0.3	0.3
SS # 8; 0-6"	1.1	1.5	0.3	< 0.02		0.4	0.4
SS # 8; 6-12"	0.9	0.8	0.1	< 0.02		0.2	0.2
SS # 9; 0-6"	1.65	15.4	1	0.5	0.1	< 0.01	
SS # 9; 6-12"	0.66	7.7	0.8	0.4	0.1	< 0.01	
SS # 10; 0-6"	3.06	38.4	1.6	1.6	0.2	0.4	0.2
SS # 10; 6-12"	2.5	41	1.6	1.9	0.2	1.3	0.2
SS # 11; 0-6"	21.5	268	2.4	50.8	2.2	153	1.1
SS # 11; 6-12"	14.5	504	3.3	58.1	2.1	272	1.2
SS # 12; 0-6"	2.19	2.9	0.3	1	0.1	1.3	0.2
SS # 12; 6-12"	0.8	1.4	0.2	0.4	0.1	10.8	0.4
SS # 13; 0-6"	0.86	1.3	0.2	0.5	0.1	1.25	0.4
SS # 13; 6-12"	0.63	0.9	0.2	0.4	0.1	0.88	0.4
SS # 14; 0-6"	0.84	1	0.2	0.5	0.1	0.86	0.4
SS # 14; 6-12"	0.59	0.9	0.2	0.4	0.1	1.08	0.4
SS # 15; 0-6"	1.88	1.4	0.2	0.6	0.1	0.75	0.4
SS # 15; 6-12"	1.19	1.4	0.2	0.9	0.2	0.42	0.3
SS # 16; 0-6"	1.66	1.1	0.2	0.8	0.2	< 0.01	
SS # 16; 6-12"	2.16	0.9	0.2	0.8	0.2	1.18	0.4
SS # 17; 0-6"	1.23	1.5	0.2	1.7	0.2	1.17	0.4
SS # 17; 6-12"	1.19	1.3	0.2	0.9	0.2	< 0.01	
SS # 18; 0-6"	0.85	0.9	0.2	0.8	0.2	1.01	0.4
SS # 18; 6-12"	0.86	1.1	0.2	0.9	0.2	0.93	0.4
SS # 19; 0-6"	19.7	68.9	1.2	18	1.3	36	0.9
SS # 19; 6-12"	23.8	35.1	0.9	6.5	0.5	21.7	0.8
SS # 20; 0-6"	24.8	7.16	0.22	3.5	0.3	2.2	0.5
SS # 20; 6-12"	8.36	11.4	0.28	6.5	0.5	4.5	0.6
	0.02	0.02		0.02		0.1	
Mean:	4.85	29.58		12.99		19.56	
Median:	1.19	1.50		0.90		1.01	
Standard Deviation:	8.67	91.12		36.52		56.40	
Maximum:	37.40	504.00		177.00		272.00	
Minimum:	0.05	0.80		0.40		0.20	

Notes: This data was collected by UMETCO Minerals Corporation
This data was provided by John Hamrick formerly of UMETCO Minerals Corporatrion now of Cotter Corporation
This data was collected from background soil sampling locations in the Gas Hills of Wyoming.
This data was collected by UMETCO Minerals Corporation to demonstrate the variability of natural background in the Gas Hills.

Appendix 4

Gareth D. Mitchell
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June 13, 2007

Mr. Steve Dobos
Energy Laboratories, Inc.
2393 Salt Creek Hwy.
Casper, WY 82602

RE: **Petrographic Evaluation of Sample #C07051289-001A from P.O. # 1845**

Dear Mr. Dobos,

Work requested in your purchase order of 5-29-07 for sample #C07051289-001A to perform carbon identification using reflected-light optical microscopy has been completed and the final report is attached.

If there are any questions or concerns, please call or e-mail me directly.

Thank you.

Sincerely,

Gareth Mitchell

Enclosure: Report

Final Report

To: Mr. Steve Dobos
From: Gareth D. Mitchell
Date: June 13, 2007
Subject: **Petrographic Evaluation of Sample #C07051289-001A from P.O. # 1845**

Request

A sample identified as **#C07051289-001A** was received 6-7-07 for petrographic evaluation. The sample had been shipped in a cooler containing bags of ice and was still cold when received. Consequently, the specimen was placed under refrigeration until sample preparation was initiated. As established from our email conversation of 5-24-07, optical microscopy was to be employed to determine the nature of the organic matter found in the sample and specifically to determine if "any naturally-occurring organic matter" (such as lignin, kerogen, bitumen, etc. that might have precipitated uranium at this location) was present.

Procedures

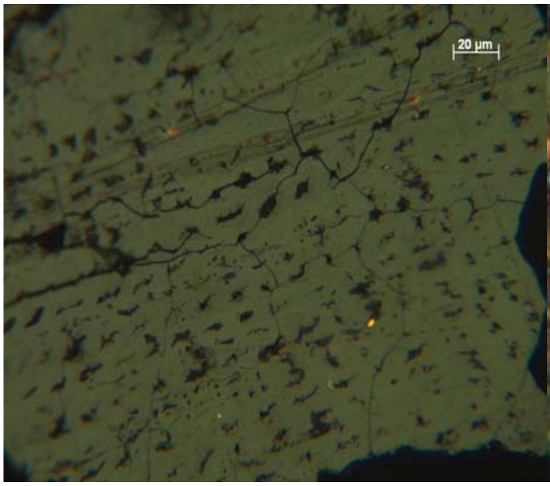
The sample was found to be composed of three fairly large angular particles (~10 g) and a coarse powder (~11 g). These components were separated and allowed to come to room temperature before they were inspected. The largest particle was soft, organic matter which had prominent bedding and considerable surface moisture, whereas the particulate matter ranged in particle size (0.5 – 3.0 mm), appeared to be a mixture of light and dark colored materials and was agglomerated with surface moisture. To prepare an optical mount suitable for reflected-light microscopy, the moisture content had to be reduced. The large particle was placed in a drying pan and a one-quarter split of the particulate sample retrieved by riffling was placed in second pan. Both samples were placed in a vacuum oven between 30-50°C for about 18 hrs with the result that the large particle had become swollen, desiccated and broken into smaller segments, while the particulate sample was composed of individual loose particles.

Remnants of the large particle were glued fast to the bottom of a 28 mm sample mold and embedded under vacuum with a cold-setting epoxy (EL01). The particulate sample (EL02) was vacuum impregnated in epoxy resin and placed in a centrifuge to establish a density/particle-size gradient. After hardening, the sample was cut longitudinally to expose the particle gradation and mounted 25 mm sample mold with additional epoxy. Both specimen surfaces were ground using 400 and 600 grit papers and polished using 0.3 and 0.05 micron alumina slurries on a high-nap cloth and silk, respectively. The sample was examined first in air using blue-light (436 nm) irradiation inspecting the 520 nm emission surface at 500X magnification and then using white light employing an oil immersion objective at 625X magnification using Zeiss research microscopes. In addition, a few reflectance readings were taken from the main organic component identified in EL01. A Leitz MPV2 reflectance photometer system at 625 X magnification in oil immersion and polarized white-light was used to collect maximum reflectance values from 11 different areas and the mean value is provided below. Mean reflectance values are an acceptable procedure for determination of organic maturity.

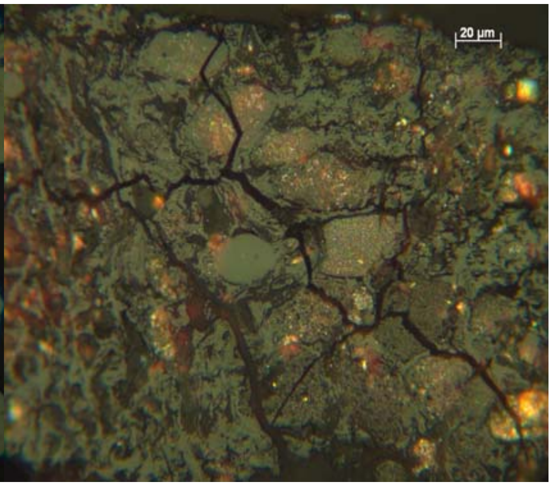
Results

The organic matter observed in both specimens (EL01 and EL02) separated from sample #C07051289-001A is basically humified woody tissue of very low maturity (mean maximum reflectance in oil of 0.18 % ±0.01) that contains fluorescent and presumably resinous material within open cell lumens and along some open fractures. A few fluorescent bodies appearing to be amorphous organic matter were the only other organic matter observed in either sample.

As seen in the photomicrographs below, the regular alignment of cell wall and filled or open lumens taken from EL01 are compared with a fragment of humified and gelified woody tissue found in specimen EL02. The large particle separated as EL01 was composed entirely of woody tissue that had gone through the biochemical stage of coalifiaction in which the cell walls were gelified and converted to humic matter. The tissue observed in the EL01 photograph exhibits little detail within the remnant cell walls and most of the lumens were filled with amorphous humic material or a fluorescing resin (dark areas), suggesting that the tissue has gone beyond the peat stage. However, the very low mean reflectance suggests that it may not have reached the rank of lignite in terms of coal maturity.



EL01



EL02

The photograph of the dominant organic matter in specimen EL02 shows many rounded bodies which in brown coal terminology are referred to as gelinite. As the name implies the humic matter from which they were derived were once gelatinous and have since formed into these amorphous bodies surrounded by the remnants of cell walls. In addition to organic matter, specimen EL02 contained mostly angular fragments of minerals and rocks composed of quartz, other silicates and carbonate. Furthermore, some of the organic material had been infilled and was in the early stage of being replaced by silica.

These observations demonstrate that the organic matter contained in sample #C07051289-001A were derived from terrestrial plants with secondary woody tissues that have gone through at least the initial stage of coalification. Depending upon stratigraphy and sample location in the field, the type and condition of organic matter and mineralization observed suggests that it is naturally occurring.

Appendix 5

Kennecott Uranium Company
Sweetwater Uranium Project
Diesel Contaminated Soil Excavation
South Pit Wall Uranium Study

Depth Above Hole Bottom (feet)	Elevation (Feet above mean sea level)	Gamma Exposure (micro/R/hour)	Density (grams per cubic centimeter)	Moisture (Percent)	Chemical Uranium Concentration (milligrams per kilogram)	Chemical Uranium Concentration (Percent)	Chemical U3O8 Concentration (milligrams per kilogram)	Chemical U3O8 Concentration (Percent)	Radium-226 (picocuries per gram)	Gamma Equivalent Uranium Concentration (milligrams per kilogram)	Gamma Equivalent Uranium Concentration (Percent)	Notes	Sample Sequence Image
7.50	6556.2											Nail Set - Five (5) feet Above Water table	
7.00		156										Dry	
6.75			2.48	10.8	51.7	0.005	61.0	0.006	65	196	0.020	Dry	
6.50		222										Dry	
6.25			2.73	10.6	14	0.001	16.5	0.002	113	340	0.034	Dry	
6.00		351										Dry	
5.75			2.35	12.3	13.1	0.001	15.4	0.002	209	631	0.063	Dry	
5.50		422										Dry	
5.25			2.54	12.6	33.3	0.003	39.2	0.004	301	909	0.091	Dry	
5.00		464										Dry	
4.75			2.62	11.8	14.8	0.001	17.5	0.002	254	766	0.077	Dry	
4.50		524										Dry	
4.25			2.59	14.3	16.1	0.002	19.0	0.002	206	623	0.062	Dry	
4.00		548										Dry	
3.75			2.68	14.8	18.8	0.002	22.2	0.002	332	1000	0.100	Dry	
3.50		634										Dry	
3.25			2.44	16.3	26.3	0.003	31.0	0.003	224	676	0.068	Dry	
3.00		593										Dry	
2.75			2.69	18.5	39.7	0.004	46.9	0.005	379	1150	0.115	Dry	
2.50	6552.4	691										Top of Water Table - Nail Set	
2.25			2.66	17.1	33	0.003	38.9	0.004	265	799	0.080	Wet	
2.00		751										Wet	
1.75			2.76	18.8	18.3	0.002	21.6	0.002	306	923	0.092	Wet	
1.50		655										Wet	
1.25			2.29	20.3	23.7	0.002	28.0	0.003	309	933	0.093	Wet	
1.00		448										Wet	
0.75			2.43	21.6	26.6	0.003	31.3	0.003	44.1	133	0.013	Wet	
0.50		351										Wet	
0.25			2.53	26.7	22	0.002	25.9	0.003	58.7	177	0.018	Wet	
0.00		340										Wet	
Average:		477	2.56	16.2	25.1	0.003	29.6	0.003	219.0	661	0.066		
Median:		464	2.57	15.6	22.9	0.002	27.0	0.003	239.0	721	0.072		
Maximum:		751	2.76	26.7	51.7	0.005	61.0	0.006	379.0	1150	0.115		
Minimum:		156	2.29	10.6	13.1	0.001	15.4	0.002	44.1	133	0.013		
Standard Deviation:		173	0.14	4.7	11.1	0.001	13.1	0.001	109.4	331	0.033		

Coordinates:

	Northing	Easting	Elevation
Nail at 7.5 Feet	149142.0	323018.63	6556.2
Nail at Water Table	149144.1	323019.84	6552.41

Appendix 6

Kennecott Uranium Company
Sweetwater Uranium Project
Background Radon Flux

	Year																									
Location	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**Average**	**Median**	**Maximum**	**Minimum**	**Standard Deviation**
	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)	(pCi/M2-Sec)
S ¼ Cor. Sec. 15	18.2				70.0	60.8	74.3	71.4	55.1	67.7	114.0	56.8	45.1	108.6	102.6	42.7	2.2	68.4	27.7	52.38	59.4	61.0	60.1	114.0	2.2	29.1
Air 2		9.7	15.6	15.4	7.7	12.1	14.3	13.7	15.9	2.2	3.1	18.9	10.9	15.1	15.5	12.8	1.2	14.3	3.4	7.35	10.7	11.0	12.5	18.9	1.2	5.2
BM 4-SDHW					2.2	2.1	2.9	2.8	2.3	13.9	13.5	2.7	2.5	2.3	3.6	2.0	2.0	1.4	0.6	1.44	2.2	3.6	2.3	13.9	0.6	3.9
CLM-1		8.5				7.0	6.0	7.4	15.8	8.4	10.4	13.2	9.3	8.2	9.4	6.0	<0.5	4.5	3.7	3.62	8.6	8.1	8.3	15.8	3.6	3.2
RE-110		2.7			14.1	2.1	2.8	1.9	12.2	3.7	6.8	9.7	6.1	7.7	3.1	2.2	0.9	0.6	1.3	1.40	18.9	5.5	2.9	18.9	0.6	5.2
North Camp Well			9.6																			9.6				
CLM-3		3.5																				3.5				
CLM-17		4.5		13.2																		8.9				
CLM-19		2.0																				2.0				
18 miles from site				2.7																		2.7				
G. Palochak's house				2.7																		2.7				
Overall Average - Site Area:	17.5	pCi/M2-Sec																								
Overall Median - Site Area:	8.3	pCi/M2-Sec																								
Overall Maximum - Site Area:	114.0	pCi/M2-Sec																								
Overall Minimum - Site Area:	0.6	pCi/M2-Sec																								
Overall Standard Deviation - Site Area:	25.6	pCi/M2-Sec																								

Appendix 7

Kennecott Uranium company
Sweetwater Uanium Project

Measured Doses to the Nearest Resident (Security Officer)

Year	Half	Measured Dose Above Background	Background Radon Concentration	Background Radon Dose	Radon Concentration in Security Trailer	Radon Dose in Security Trailer
		(millirems)	(pCi/L	(millirems)	(pCi/L	(millirems)
1994	Second	0.00	3.40	418.90	2.91	358.50
1995	First	0.00	2.75	338.80	1.86	228.90
	Second	0.00	4.60	566.70	2.60	320.30
1996	First	0.00	2.60	364.00	1.60	224.00
	Second	0.00	3.50	431.20	2.20	271.04
1997	First	0.00	2.60	320.30	1.50	187.88
	Second	0.00	3.30	406.60	2.20	271.00
1998	First	0.00	2.30	283.40	1.65	203.30
	Second	0.00	2.90	357.30	1.85	228.20
1999	First	0.00	2.65	326.50	1.90	234.10
	Second	0.00	5.15	634.48	3.25	400.40
2000	First	0.00	2.65	326.48	2.12	261.18
	Second	0.00	5.70	702.24	3.05	375.76
2001	First	0.00	4.35	593.34	3.60	491.04
	Second	0.00	3.60	407.09	2.78	314.36
2002	First	0.00	2.50	290.04	2.48	288.08
	Second	0.00	3.80	421.34	2.80	310.46
2003	First	0.00	3.25	350.35	2.40	258.72
	Second	14.80	3.50	368.06	3.75	394.35
2004	First	0.00	2.60	266.55	2.08	213.24
	Second	0.00	3.80	366.17	3.00	289.08
2005	First	0.00	2.45	225.30	2.55	234.50
	Second	0.00	4.10	368.00	3.22	289.03
2006	First	0.00	3.60	305.70	2.40	203.80
	Second	0.00	3.60	342.10	2.13	202.40
2007	First	0.00	3.00	271.90	1.65	148.80
	Second	0.00	3.65	316.40	2.10	182.00
2008	First	5.90	2.80	231.60	3.33	275.50
	Second	0.00	3.65	290.70	2.83	225.40
2009	First	0.00	2.68	205.00	2.24	171.40
	Second	0.00	3.64	273.90	2.04	153.50
2010	First	0.00	2.50	184.80	2.13	157.50
	Second	0.00	2.31	169.10	1.62	118.70
2011	First	0.00	1.35	98.60	0.95	69.40
	Average:	0.61	3.26	347.73	2.38	251.64
	Median:	0.00	3.28	332.65	2.22	234.30
	Maximum:	14.80	5.70	702.24	3.75	491.04
	Minimum:	0.00	1.35	98.60	0.95	69.40
	Standard Deviation:	2.74	0.88	129.82	0.65	86.52

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security_dose.xls

Appendix 8

Kennecott Uranium Company
Sweetwater Uranium Project
Equilibrium Factor for Nearest Residence
(Security Guard Trailer)

Date	Radon Concentration (pCi/L)	Exposure (WL)	Equilibrium Factor
1/1/93 – 6/30/93	3.20	0.009	0.28
1/1/97 – 6/30/97	1.50	0.003	0.20
7/1/97 – 12/31/97	2.20	0.002	0.09
1/1/98 – 6/30/98	1.65	0.003	0.18
1/1/99 – 6/30/99	1.90	0.009	0.47
7/1/99 – 12/31/99	3.25	0.002	0.06
1/1/00 – 6/30/00	2.12	0.004	0.19
7/1/00 – 12/31/00	3.05	0.009	0.30
1/1/01 – 6/30/01	3.60[1]	0.012	0.33
7/1/01 – 12/31/01	2.78	0.013[2]	0.47
1/1/02 – 6/30/02	2.48	0.009[2]	0.36
7/1/02 – 12/31/02	2.80	0.003[2]	0.11
1/1/03 – 6/30/03	2.40	0.004[2]	0.17
7/1/03 – 12/31/03	3.75[3]	0.006[2]	0.16
1/1/04 – 6/30/04	2.08	0.003[2]	0.14
7/1/04 – 12/31/04	3.00	0.0005	0.017
1/1/05 – 6/30/05	2.55	0.0013	0.051
7/1/05 – 12/31/05	3.22	0.0035	0.109
1/1/06 – 6/30/06	2.40	0	0.00
7/1/06 – 12/31/06	2.13	0.014	0.66
1/1/07 – 6/30/07	1.65	0	0.00
7/1/07 – 12/31/07	2.10[4]	0.0001	0.005
1/1/08 – 6/30/08	3.28	0	0.00
7/1/08 - 12/31/08	2.83	0	0.00
1/1/09 - 6/30/09	2.25	0	0.00
7/1/09 - 12/31/09	2.03	0.002	0.10
1/1/10 - 6/30/10	2.13	0.002	0.09
7/1/10 - 12/31/10	1.63	0.002	0.12
1/1/11 - 6/30/11	0.95	0.0015	0.16
7/1/11 – 12/31/11	1.90	0	0.00
Average			**0.161**

[1] This value is based upon an average of three (3) RadTrak detectors. The second quarter RadTrak detector in the Security Trailer bedroom was lost.

[2] Average of two (2) measurements.

[3] Fourth quarter 2003 concentration only. Landauer, Inc. lost the third quarter 2003 RadTrak units.

[4] This value is based upon an average of three (3) RadTrak detectors. The fourth quarter RadTrak detector in the Security Trailer kitchen was lost.

Calculation Parameters

1. Radon concentrations in the Security Trailer are calculated based upon the results of two (2) RadTrak detectors (one in the kitchen and one in the bedroom) that are changed quarterly. The radon concentration for a given semiannual period is an average of the results of four (4) RadTrak detections, one in the kitchen and one in the bedroom, changed quarterly.

2. Radon exposures (radon daughters concentrations measured in Working Levels) are taken semiannually in the trailer in two (2) locations (kitchen and bedroom) using a Buck Basic 12, Bendix BDX-44, MSA or Sensidyne GilAir II air pump and a filter. The filter is evaluated using the modified Kusnetz Method.

3. The equilibrium factor is calculated.

Radon Dose (rems) = (Radon Concentration (pCi/L)) * (Equilibrium Factor) * (0.44 rem/pCi/L)
An occupancy factor may be added as required.
1 WL ~ 100 pCi/L with daughters present (100% equilibrium)
Equilibrium Factor Formula: Equilibrium Factor = Exposure (WL) * 100 / Concentration (pCi/L)

Source: National Council on Radiation Protection (NCRP) Report #97

Appendix 9

Radon Emissions From Tailings Ponds

Presented To:

National Mining Association (NMA)

/Nuclear Regulatory Commission (NRC)
Uranium Recovery Workshop
Denver – July 2, 2009

Presented By:

Dr. Douglas B. Chambers

Today's Discussion

- Subpart W
- Radon
- Radon diffusion
- Radon flux from tailings
- Radon from water cover
- EPA's proposed method of monitoring
- Summary observations

Subpart W

NESHAP for Radon Emissions from Operating Mill Tailings

- ❑ *Uranium byproduct material or tailings* means waste produced by the extraction or concentration of uranium from any ore processed primarily for its source material content.
- ❑ Rn-222 flux from existing uranium mill tailings pile of less than 20 pCi/$m^2 \cdot s$

Subpart W …(cont'd)

NESHAP for Radon Emissions from Operating Mill Tailings

- New tailings impoundments must meet one of two work practices
  - For phased disposal, no more than two 40 acre cells (including existing impoundments can be in operation at any single time
  - For continuous disposal, tailings are dewatered and immediately disposed with no more than 10 acres in operation at any one time
- Annual radon flux testing required

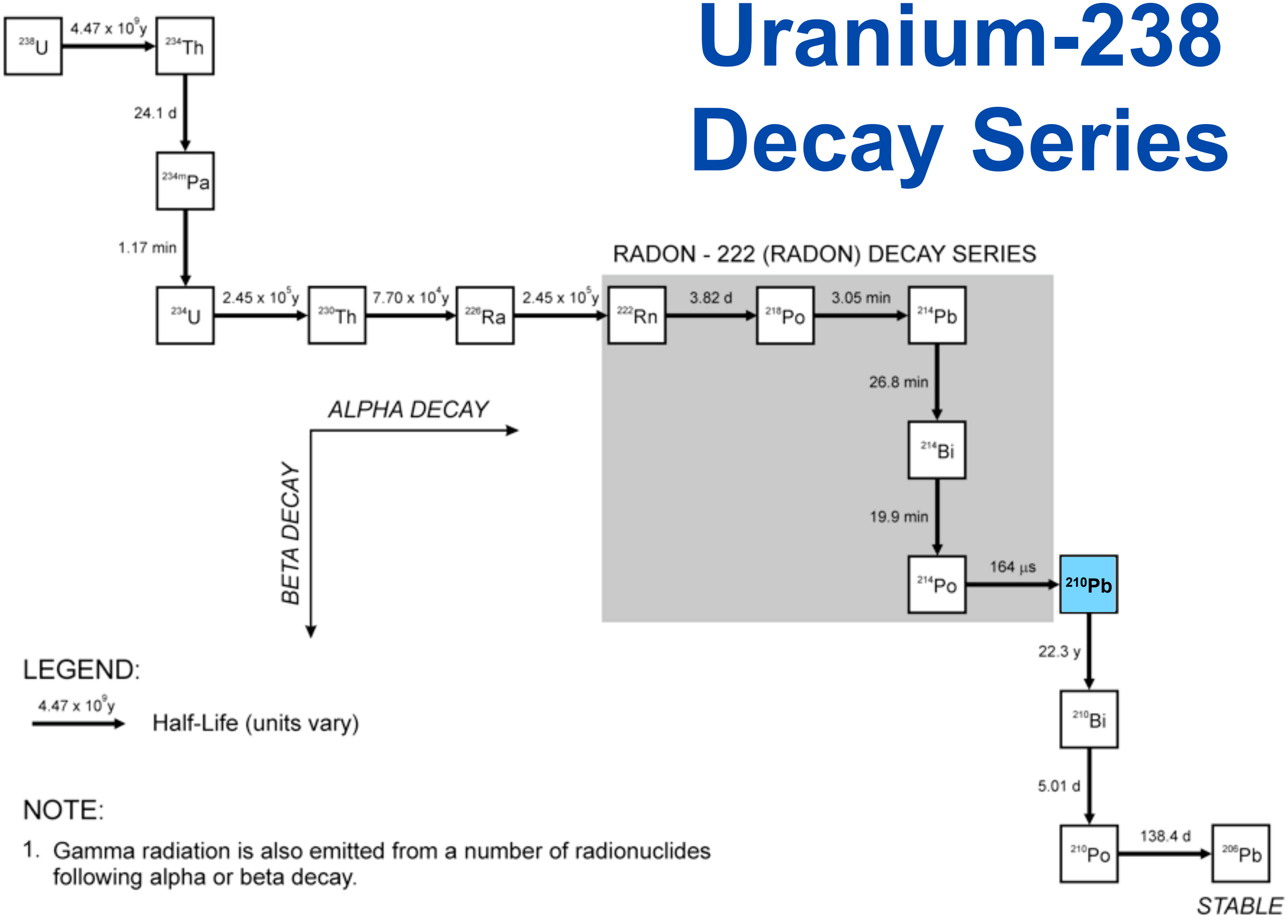
Nominal Radon Flux
(BID – Final Rule for Radon, EPA 1986)

❑ Dry Tailings (soil)	1 pCi Rn-222/m^{2}s per pCi Ra-226/g
❑ Saturated	0.3 pCi Rn-222/m^{2}s per pCi Ra-226/g
❑ Water Cover	0 pCi Rn-222/m^{2}s per pCi Ra-226/g

Radon

- Radon is everywhere
- Produced through radioactive decay of Ra-226
- Half-life of 3.82 days
- EPA has raised issue with ISR evaporation ponds
- EPA has raised issue with Pb-210

Uranium-238 Decay Series



^{238}U

4.47×10^9 y

^{234}Th

24.1 d

^{234m}Pa

1.17 min

^{234}U

2.45×10^5 y

^{230}Th

7.70×10^4 y

^{226}Ra

2.45×10^5 y

RADON - 222 (RADON) DECAY SERIES

^{222}Rn

3.82 d

^{218}Po

3.05 min

^{214}Pb

26.8 min

^{214}Bi

19.9 min

^{214}Po

164 µs

^{210}Pb

22.3 y

^{210}Bi

5.01 d

^{210}Po

138.4 d

^{206}Pb

STABLE

ALPHA DECAY

BETA DECAY

LEGEND:

$\xrightarrow{4.47 \times 10^9 \text{y}}$ Half-Life (units vary)

NOTE:

1. Gamma radiation is also emitted from a number of radionuclides following alpha or beta decay.

Radon Production Rate

The radon production rate (q) in a porous radium-bearing material can be expressed as:

$$q = [Ra] \times \rho \times \frac{E}{P} \times \lambda$$

$$= \frac{\beta \times E}{P} = \frac{\beta}{P}$$

Where:

[Ra] = radium-226 concentration

ρ = bulk density (g/cm^3)

E = emanation coefficient

P = porosity (void fraction)

λ = radon decay constant

β = emanating power (pCi/s-cm^3)

Diffusion Length

$$L = \sqrt{\frac{D}{\lambda P}}$$

Where:

L = diffusion length

= distance to which concentration decreases by factor of e (= 2.718)

D = bulk diffusion coefficient (cm^2/s)

λ = radon decay constant

= 2.1×10^{-6}/s

P = porosity (void volume/total volume)

Diffusion of Radon Across a Medium

In general, when radon is covered by inert material, diffusive flux (J) can be expressed (approximately) as:

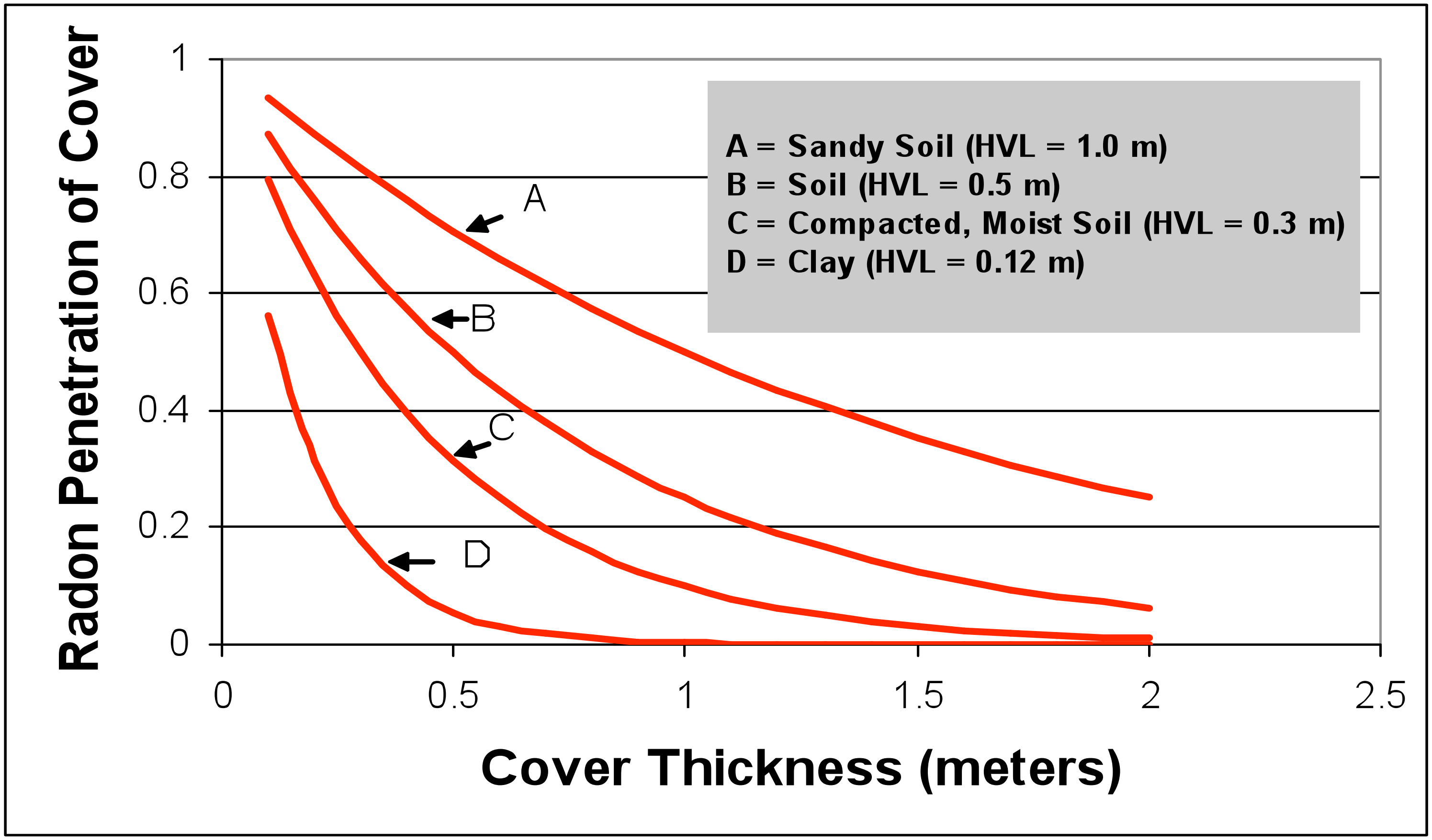
$$J = e^{\frac{-Z}{L}}$$

Where:

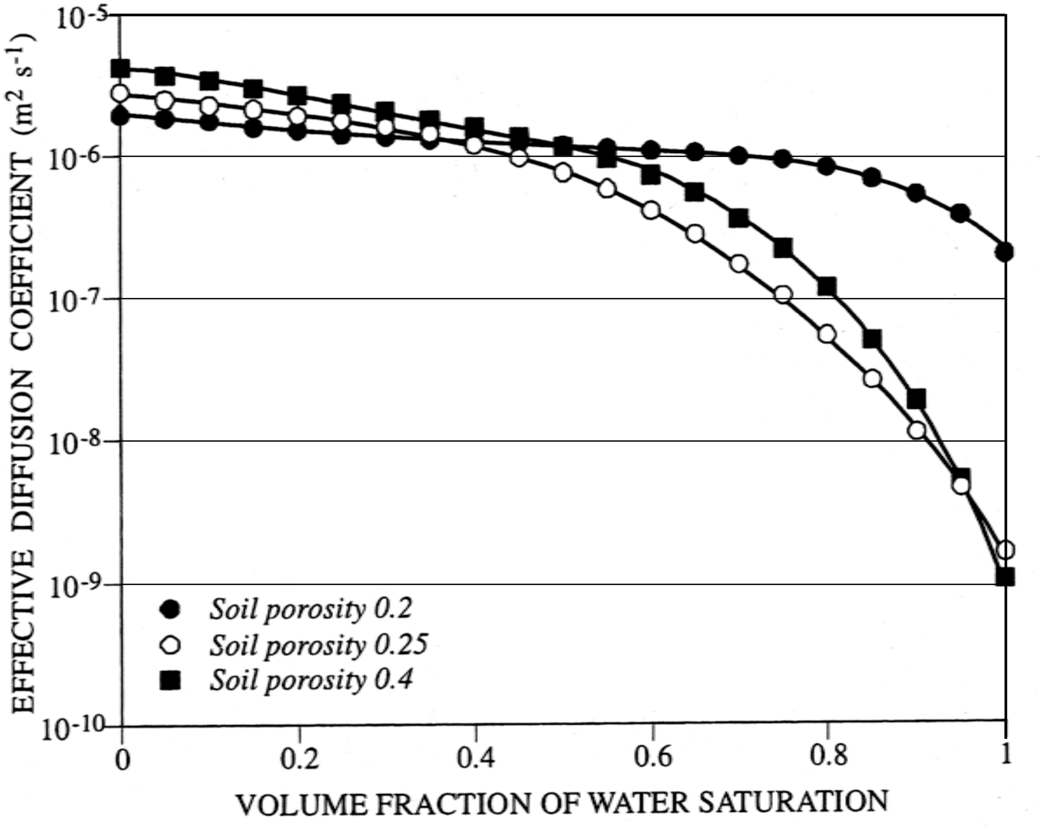
Z = "Cover" thickness

L = diffusion length

Diffusion of Radon Across a Medium

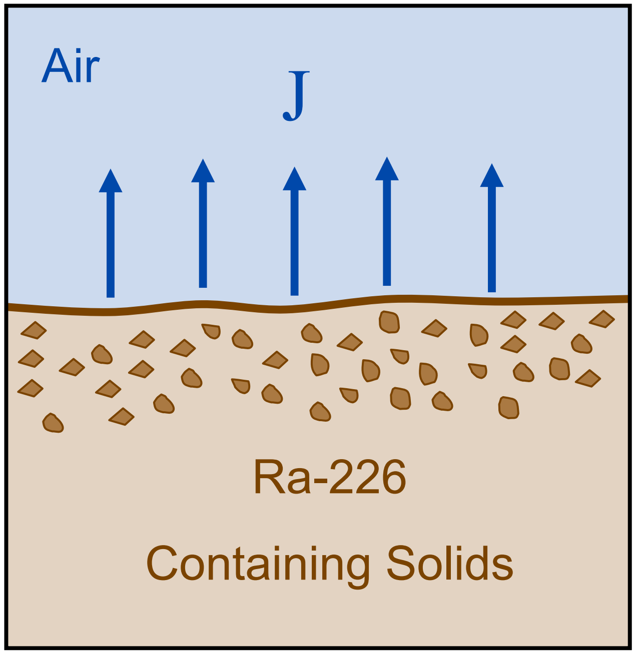


Experimental Diffusion Coefficients (UNSCEAR 2000)



SOURCE: After UNSCEAR 2000

Radon Flux



Based on Fick's Laws:

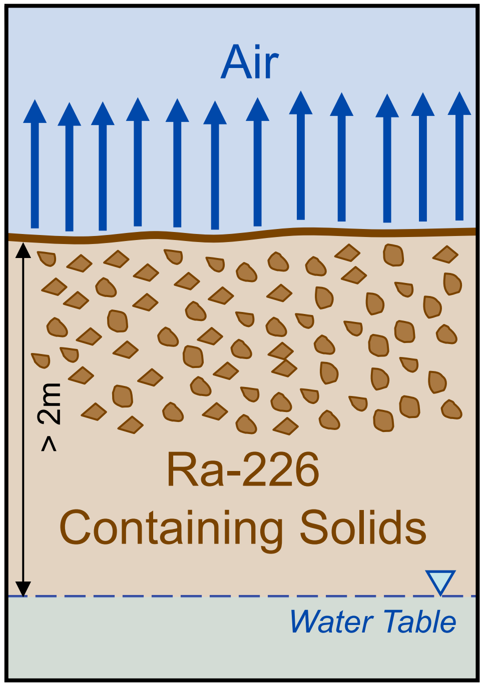
$$J = \beta \times L \quad (\mathrm{pCi/m^2 \cdot s})$$

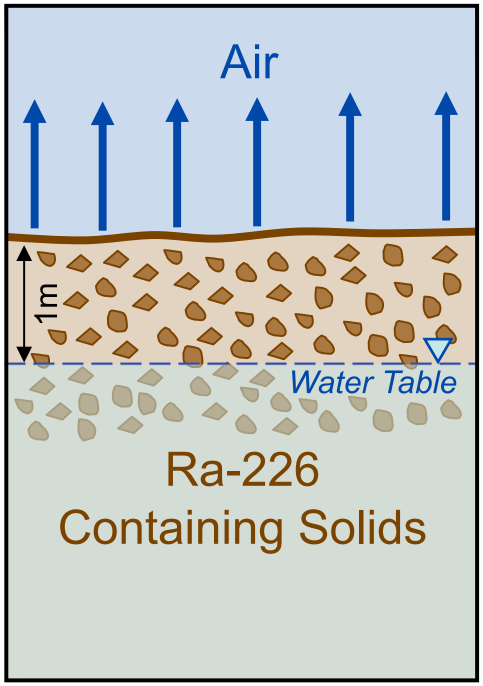
Where:

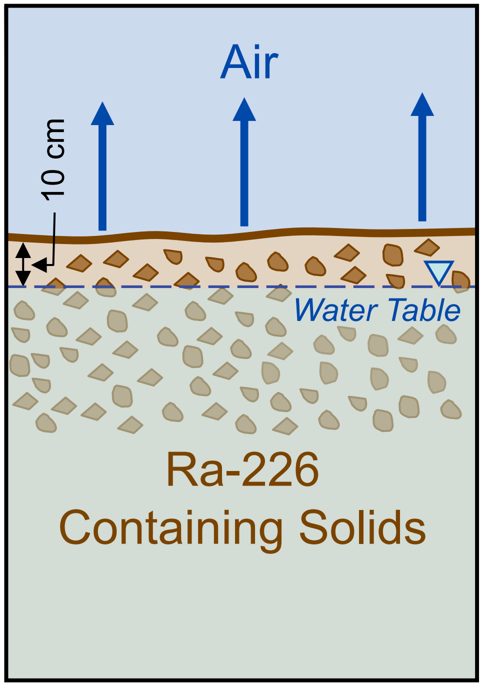
β = emanating power ($\mathrm{pCi/m^3 \cdot s}$)

L = diffusion length

Effects of Depth to Water Table







Radon From Water Cover (1)

- Two Mechanisms
  - Diffusion
  - Turbulent transfer

Radon From Water Cover (2)

Diffusion

- **Diffusion coefficient in water << diffusion coefficient in air (1/100th)**
- **Rn-222 gas exchange via diffusion from surface of small lake has been measured (Experimental lakes, Ontario)**

$$F\ (\mathrm{pCi/m^2 \cdot d}) \cong k_{Rn}\ (\mathrm{m/d}) \times [C - C_o]\ (\mathrm{pCi/m^3})$$

$$\cong k_{Rn} \times C$$

- For $k_{Rn} \sim 0.5$m/d

C (pCi/L)	F (pCi/m²•s)
10	5.8×10^{-5}
100	5.8×10^{-4}
1000	5.8×10^{-3}

Radon From Water Cover (3)

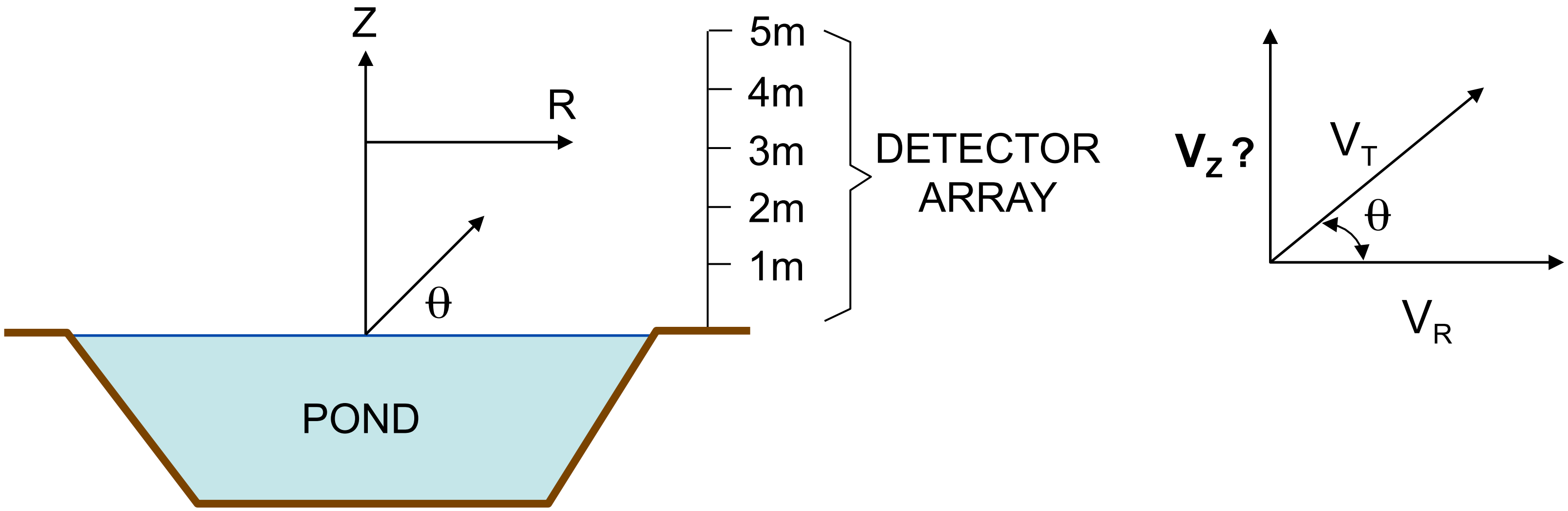
- Turbulence (wave action)
  - Rn-222 is produced at the rate of 2.1 x 10^{-6}/s from Ra-226
  - Assumes radon released at surface as it is produced from Ra-226 within "turbulent" layer

Ra-226 (pCi/L)	Depth of Turbulent Mixing (cm)	Rn-222 ($pCi/m^2 \cdot s$)
10	10	0.002
	50	0.01
100	10	0.02
	50	0.1
1000	10	0.2
	50	1

Can We Measure Radon Flux From Water Covered Tailings ?

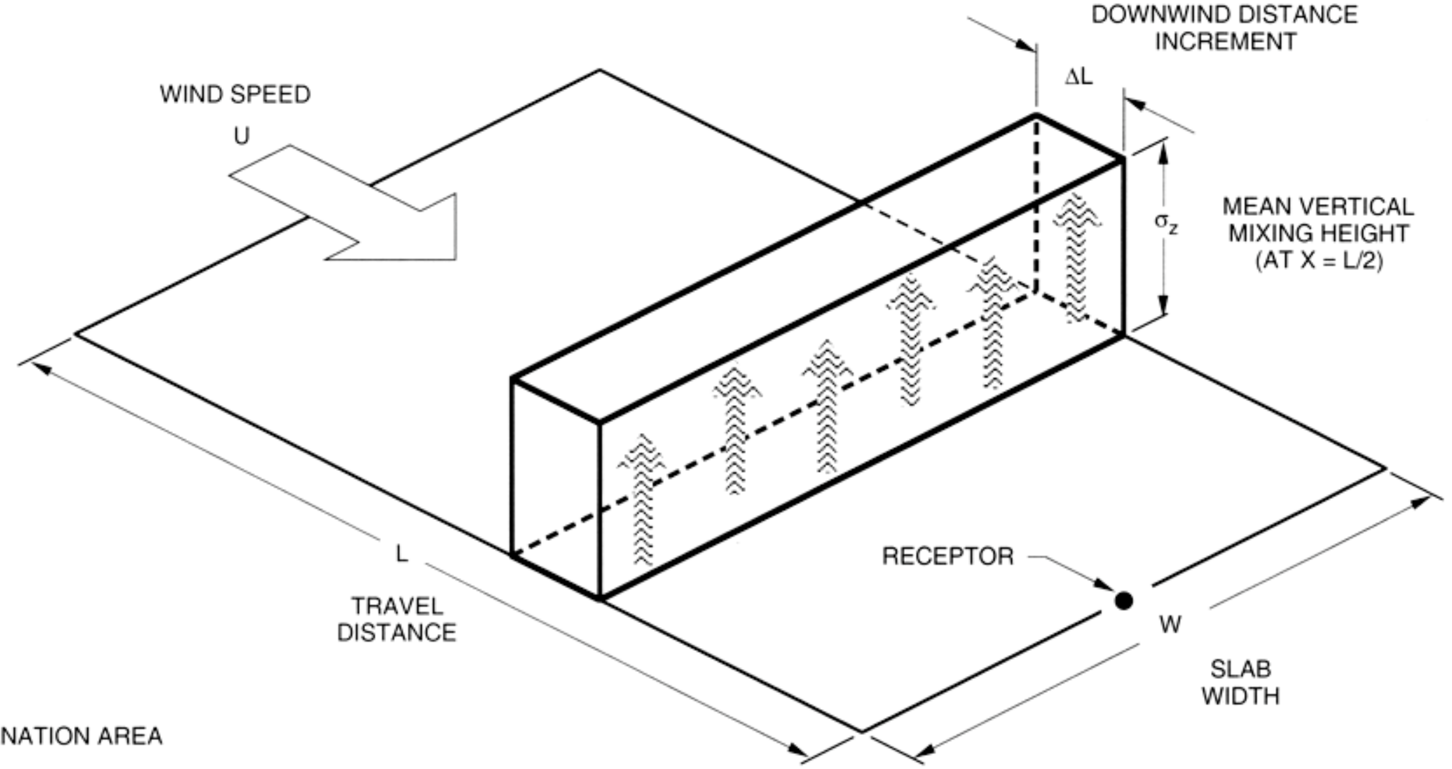
- ☐ **EPA's proposal**
- ☐ **Schiager's method**
- ☐ **Diurnal variation**
- ☐ **Rn-222 with distance**
- ☐ **Pb-210 with distance**

Pond Showing Z & R Directions and Detector Array



SOURCE: After EPA, 2009

Schiager's Box Model



NOTE:

$W\Delta L$ = EMANATION AREA

$\sigma_z W\Delta L$ = DILUTION VOLUME

$$C_X\ (\text{pCi / m}^3) = \frac{[\text{ FLUX, } \Phi\ ]\ [\text{ AREA, } W\Delta L\ ]\ [\text{ TIME, } L/U\ ]}{[\text{ VOLUME, } \sigma_z W\Delta L\ ]} = \frac{\Phi L}{U\sigma_z}$$

σ_z defined by stability class

SOURCE: After Schiager, 1974

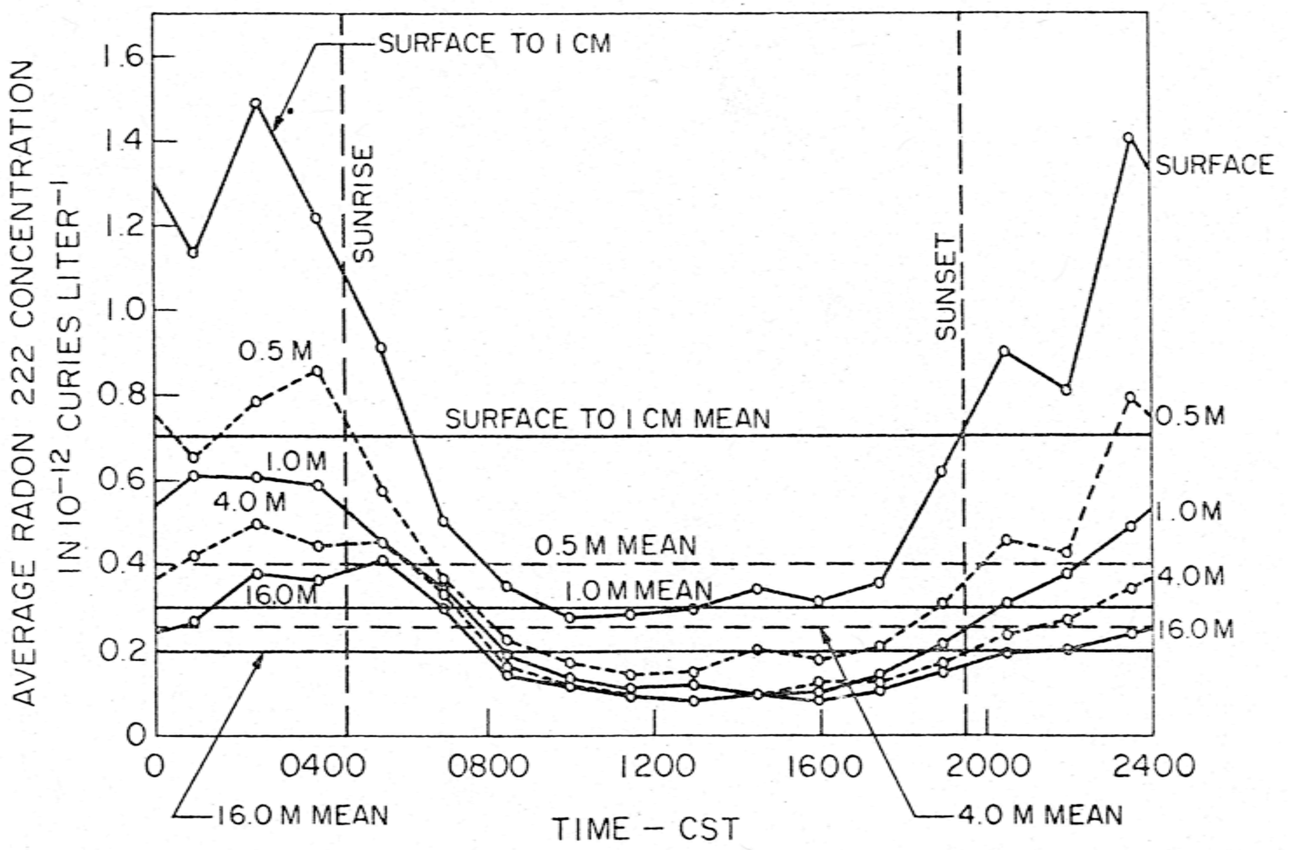
Incremental Radon

- Using Schiager model
  - 80 acres of pond
  - Radon flux of 1 $pCi/m^2 \cdot S$
  - L= 600 m
  - Sigma z from Turner workbook of (about) 24m
  - Assume u = 3 m/s
- Radon concentration at edge of cell

$C = (1 \times 600)/(3 \times 24)\ pCi/m^3 \times 1\ m^3/1000L$

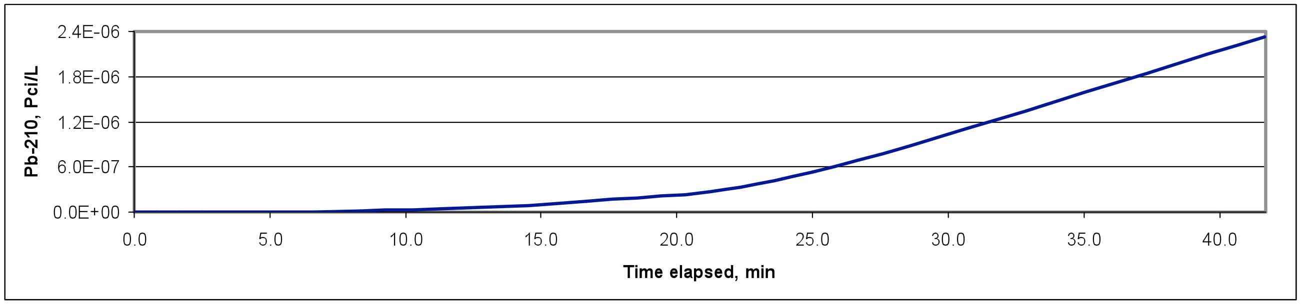
$= 0.08\ pCi/L$

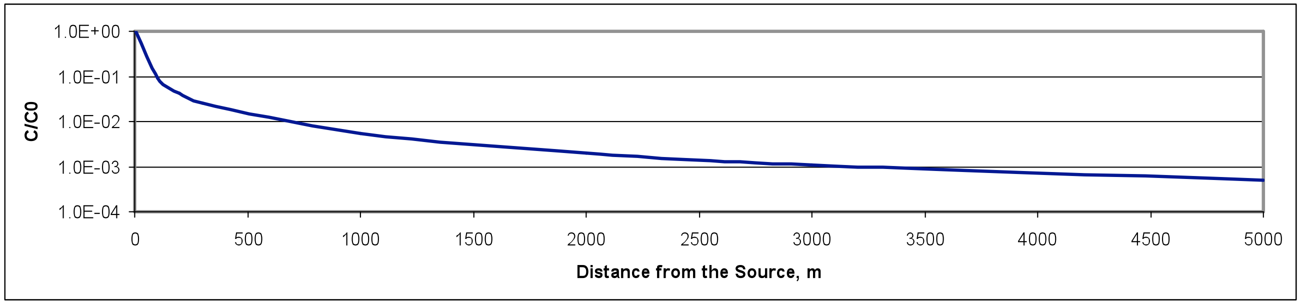
Rn-222 Concentration Diurnal Variation

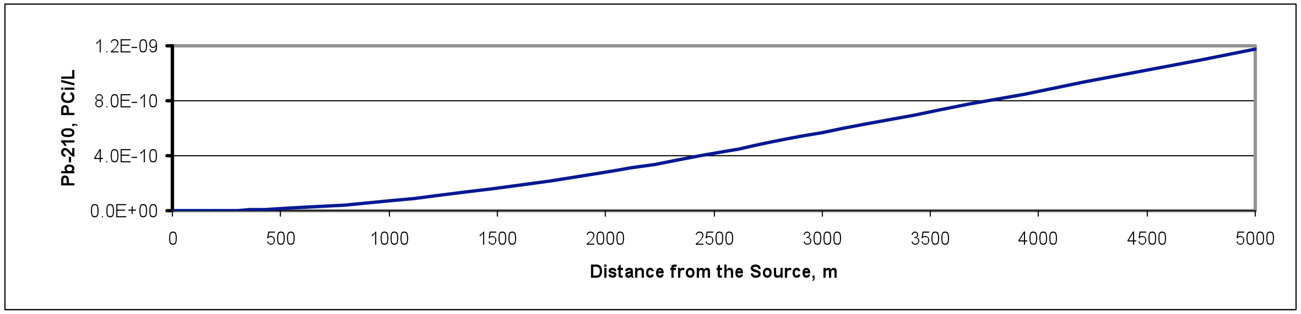


SOURCE: After Pearson, U.S. Department of Health & Welfare, 1967

Pb-210 with Distance*







* Denver Windrose, 80 acre source at 1pCi/m^{2}s, direction of maximum concentration

** Background Pb-210 ranges from 3x10^{-6} pCi/L to 30x10^{-6} pCi/L (UNSCEAR 2000)

Key Observations

- ☐ Rn-222 is everywhere
- ☐ Concentrations of Rn-222 vary with location, time of day, meteorological conditions .....
- ☐ Rn-222 flux from ponded areas << dry areas
- ☐ Practical limits on ability to measure Rn-222 (or Pb-210) from pond areas
- ☐ Suggest feasibility assessment (DQO process) prior to implementation of proposed monitoring practices

Appendix 10

Lost Creek Project
Ambient Radon Monitoring Data

Monitoring Period	**URPA-7** **West of Project** **(picocuries per liter)**	**URPA-8** **Southeast of Project** **(picocuries per liter)**	**URPA-9** **Center of Project** **(picocuries per liter)**	**URPA-10** **Northeast of Project** **(picocuries per liter)**	**URPA-13** **Southeast of Project** **(picocuries per liter)**	**URPA-1** **Baroil** **(picocuries per liter)**
Q1	1.5	2.7	3.8	2.1	N/A	0.5
Q2	0.7	1.3	0.8	1.2	2.0	0.3
Q3	1.6	2.1	1.5	1.8	1.5	0.9
Q4	2.8	3.2	2.8	1.0	2.5	0.6
Q5	N/A	N/A	1.7	2.0	2.7	0.8
Average:	1.7	2.3	2.1	1.6	2.2	0.6
Median:	1.6	2.4	1.7	1.8	2.3	0.6
Maximum:	2.8	3.2	3.8	2.1	2.7	0.9
Minimum:	0.7	1.3	0.8	1.0	1.5	0.3
Standard Deviation:	0.9	0.8	1.2	0.5	0.5	0.2

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UR_Energy_spreadsheet.xls

Table 2.9-3 Analytical Results for Passive Radon and Gamma Sampling

Location	Period [(1)]	Radon Concentration (pCi/l)	Radon Exposure (pCi/l-days)	Gamma Exposure (millirems)	Gamma Exposure Rate (millirems/day)
URPA1 (Bairoil)	Q1	0.5	50.3	11.3	0.12
	Q2	0.3	22.5	16.9	0.20
	Q3	0.9	90.5	18.6	0.19
	Q4	0.6	58.9	44.2	0.43
	Q5	0.8	89.1	23.0	0.20
URPA7 (W of LC)	Q1	1.5	147.6	33.0	0.34
	Q2	0.7	56.3	23.2	0.28
	Q3	1.6	153.7	41.7	0.43
	Q4	2.8	297.6	53.6	0.51
	Q5	NA (2)	NA (2)	NA (2)	NA (2)
URPA8 (SE of LC)	Q1	2.7	258.4	13.6	0.14
	Q2	1.3	108.1	23.4	0.28
	Q3	2.1	203.1	38.2	0.39
	Q4	3.2	331.3	69.6	0.66
	Q5	NA (2)	NA (2)	NA (2)	NA (2)
URPA9 (Central LC)	Q1	3.8	370.6	23.7	0.24
	Q2	0.8	67.5	18.0	0.21
	Q3	1.5	148.8	42.1	0.43
	Q4	2.8	295.2	67.4	0.64
	Q5	1.7	184.8	20.7	0.18
URPA10 (NE of LC)	Q1	2.1	201.7	24.4	0.25
	Q2	1.2	100.7	NA (3)	NA (3)
	Q3	1.8	173.2	50.4	0.52
	Q4	1.0	100.4	55.3	0.53
	Q5	2.0	206.9	32.6	0.29
URPA13 (SE of new LC)	Q1	NA (4)	NA (4)	NA (4)	NA (4)
	Q2	2.0	167.2	25.6	0.30
	Q3	1.5	146.8	24.8	0.26
	Q4	2.5	259.2	42.6	0.41
	Q5	2.7	290.9	37.7	0.37

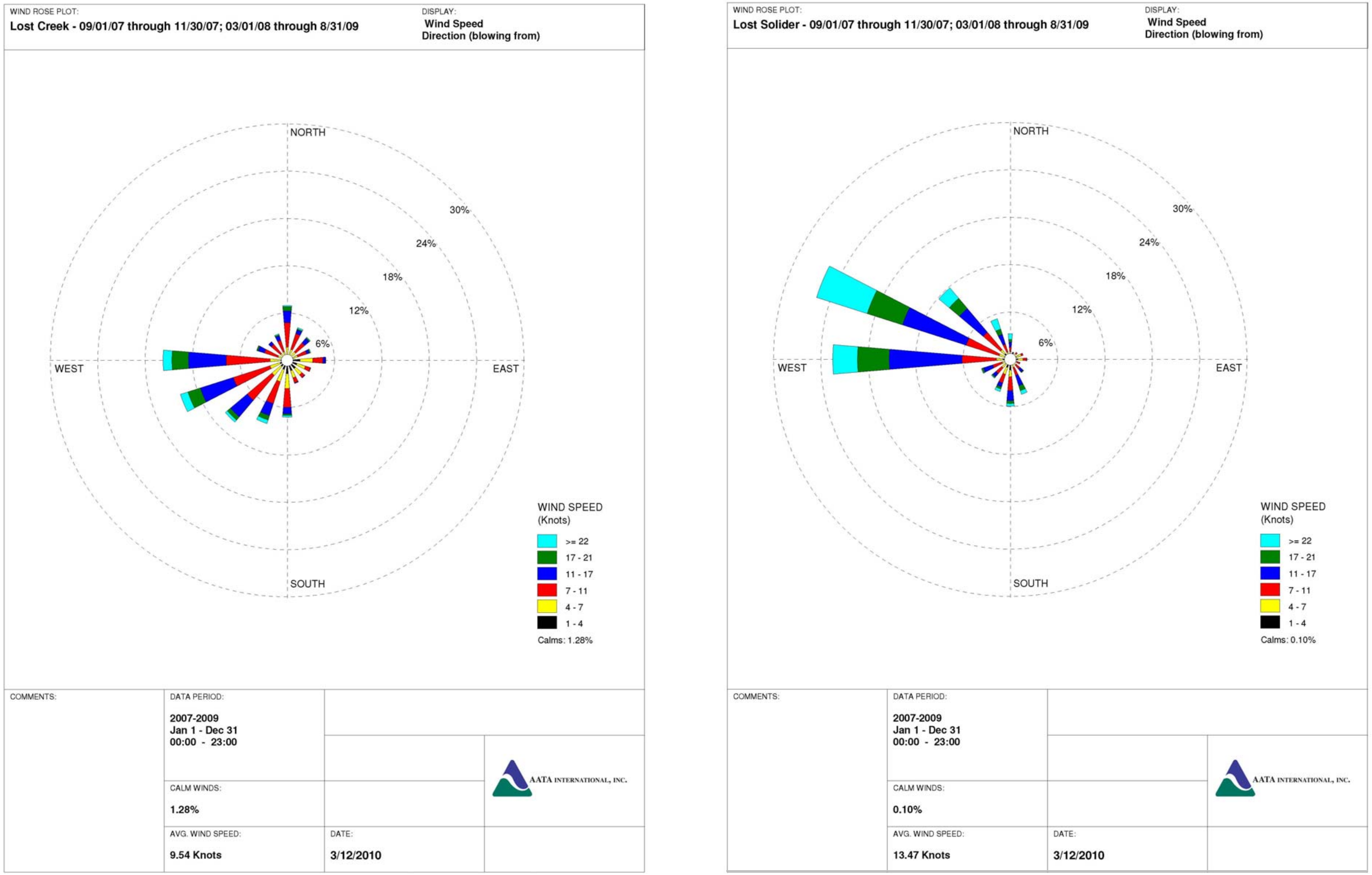
(1) Beginning dates: Q1, 11/10/06; Q2, 2/15/07; Q3 5/10/07; Q4, 8/16/07; Q5 11/28/07.
Sampling concluded 3/14/08.

(2) No 5th quarter data collected at this sites.

(3) Sensor missing; a new undamaged sensor installed for the next quarter.

(4) No data available for first quarter due to later sample installation.

Figure 2.5-3b Wind Speed and Direction at the LS and LC Meteorological Stations



WIND ROSE PLOT:
Lost Creek - 09/01/07 through 11/30/07; 03/01/08 through 8/31/09

DISPLAY:
Wind Speed
Direction (blowing from)

COMMENTS:

DATA PERIOD:
2007-2009
Jan 1 - Dec 31
00:00 - 23:00

CALM WINDS:
1.28%

AVG. WIND SPEED:
9.54 Knots

DATE:
3/12/2010

WIND ROSE PLOT:
Lost Solider - 09/01/07 through 11/30/07; 03/01/08 through 8/31/09

DISPLAY:
Wind Speed
Direction (blowing from)

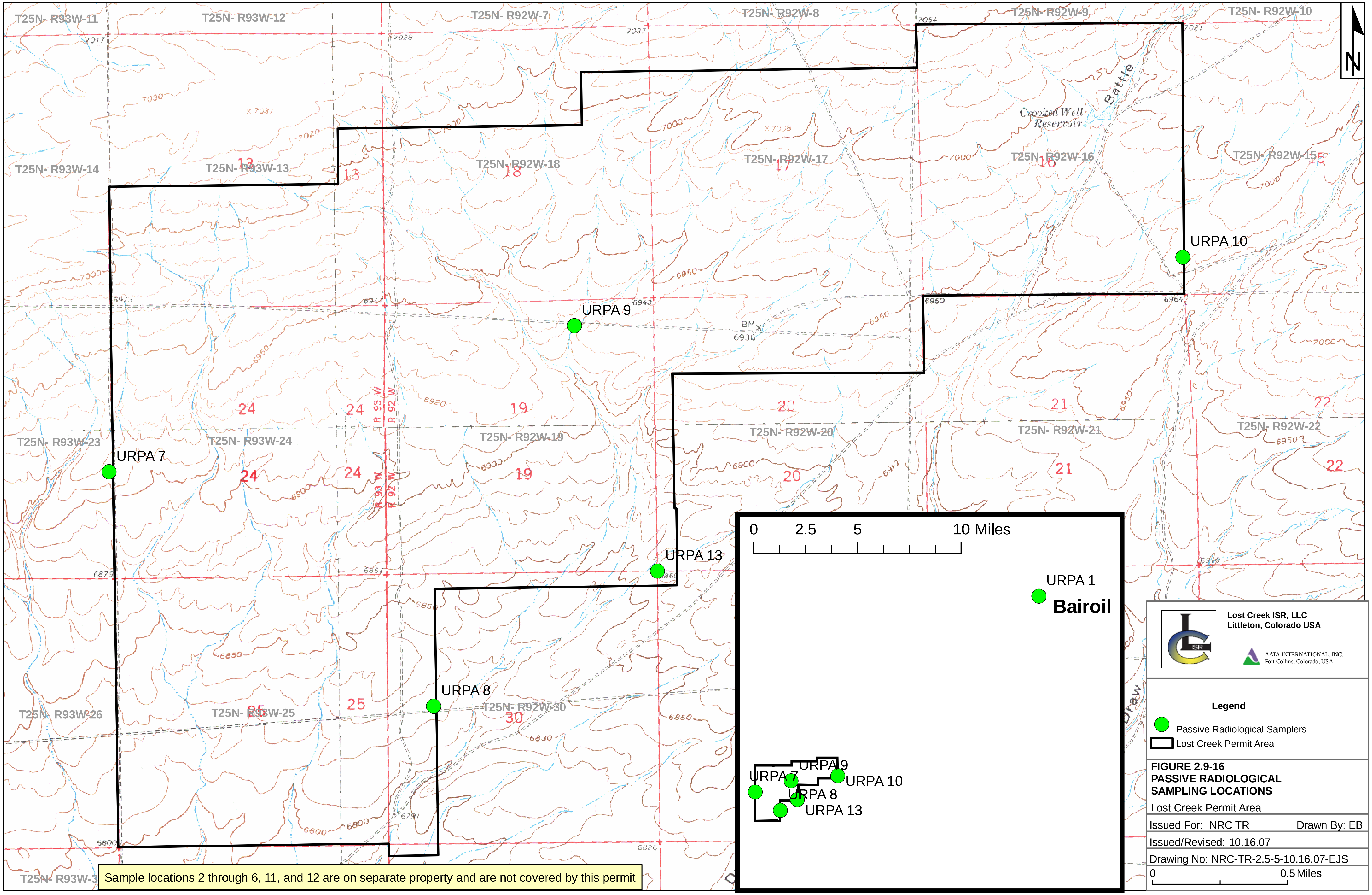
COMMENTS:

DATA PERIOD:
2007-2009
Jan 1 - Dec 31
00:00 - 23:00

CALM WINDS:
0.10%

AVG. WIND SPEED:
13.47 Knots

DATE:
3/12/2010



Sample locations 2 through 6, 11, and 12 are on separate property and are not covered by this permit

Lost Creek ISR, LLC
Littleton, Colorado USA

AATA INTERNATIONAL, INC.
Fort Collins, Colorado, USA

Legend

● Passive Radiological Samplers

▭ Lost Creek Permit Area

FIGURE 2.9-16
PASSIVE RADIOLOGICAL
SAMPLING LOCATIONS

Lost Creek Permit Area

Issued For: NRC TR Drawn By: EB

Issued/Revised: 10.16.07

Drawing No: NRC-TR-2.5-5-10.16.07-EJS

Appendix 11

Kennecott Uranium Company - Sweetwater Uranium Facility

UPWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	STATION AIR 2 - A pCi/L	STATION AIR 2 -B pCi/L	AIR 3A pCi/L
1981	1-Jan-81	01-Feb-81	PRM	0.66	-	0.12
	1-Feb-81	01-Mar-81	PRM	0.60	-	0.19
	1-Mar-81	01-Apr-81	PRM	0.52	-	0.24
	1-Apr-81	01-May-81	PRM	0.41	-	0.27
	1-May-81	01-Jun-81	PRM	0.22	-	0.28
	1-Jun-81	01-Jul-81	PRM	0.21	-	0.48
	1-Jul-81	01-Aug-81	PRM	1.00	-	0.54
	1-Aug-81	01-Sep-81	PRM	2.10	-	0.20
	1-Sep-81	01-Oct-81	PRM	0.73	-	0.90
	1-Oct-81	01-Nov-81	PRM	4.02	-	0.59
	1-Nov-81	01-Dec-81	PRM	1.07	-	1.65
	1-Dec-81	01-Jan-82	PRM	2.10	-	0.22
1982	1-Jan-82	01-Feb-82	PRM	0.04	-	1.09
	1-Feb-82	01-Mar-82	PRM	1.01	-	0.42
	1-Mar-82	01-Apr-82	PRM	1.68	-	1.07
	1-Apr-82	01-May-82	PRM	6.86	-	0.41
	1-May-82	01-Jun-82	PRM	0.91	-	0.45
	1-Jun-82	01-Jul-82	PRM	1.96	-	0.29
	1-Jul-82	01-Aug-82	PRM	1.96	-	0.29
	1-Aug-82	01-Sep-82	PRM	0.45	-	0.24
	1-Sep-82	01-Oct-82	PRM	0.85	-	0.37
	1-Oct-82	01-Nov-82	PRM	2.25	-	1.24
	1-Nov-82	01-Dec-82	PRM	5.23	-	1.04
	1-Dec-82	01-Jan-83	PRM	1.39	-	0.89
1983	1-Jan-83	01-Feb-83	PRM	1.85	-	0.20
	1-Feb-83	01-Mar-83	PRM	1.03	-	0.31
	1-Mar-83	01-Apr-83	PRM	0.44	-	1.21
	1-Apr-83	01-May-83	PRM	1.22	-	0.52
	1-May-83	01-Jun-83	PRM	0.56	-	2.95
	1-Jun-83	01-Jul-83	PRM	2.38	-	1.57
	1-Jul-83	01-Aug-83	PRM	-	-	1.72
	1-Aug-83	01-Sep-83	PRM	-	-	0.52
	1-Sep-83	01-Oct-83	PRM	-	-	2.04
	1-Oct-83	01-Nov-83	PRM	-	-	2.04
	1-Nov-83	01-Dec-83	PRM	-	-	0.20
	1-Dec-83	01-Jan-84	PRM	-	-	0.04
1984	1-Jan-84	01-Feb-84	PRM	-	-	1.32
	1-Feb-84	01-Mar-84	PRM	-	-	1.79
	1-Mar-84	01-Apr-84	PRM	-	-	1.18
	1-Apr-84	01-May-84	PRM	-	-	1.21
	1-May-84	01-Jun-84	PRM	-	-	1.10
	1-Jun-84	01-Jul-84	PRM	-	-	2.15
	1-Jul-84	01-Aug-84	PRM	-	-	-
	1-Aug-84	01-Sep-84	PRM	-	-	-
	1-Sep-84	01-Oct-84	PRM	-	-	-
	1-Oct-84	01-Nov-84	PRM	-	-	-
	1-Nov-84	01-Dec-84	PRM	-	-	-
	1-Dec-84	01-Jan-85	PRM	-	-	-

UPWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	STATION AIR 2 - A pCi/L	STATION AIR 2 -B pCi/L	AIR 3A pCi/L
1985	1-Jan-85	01-Feb-85	PRM	-	-	-
	1-Feb-85	01-Mar-85	PRM	-	-	-
	1-Mar-85	01-Apr-85	PRM	-	-	-
	1-Apr-85	01-May-85	PRM	-	-	-
	1-May-85	01-Jun-85	PRM	-	-	-
	1-Jun-85	01-Jul-85	PRM	-	-	-
	1-Jul-85	01-Aug-85	PRM	-	-	-
	1-Aug-85	01-Sep-85	PRM	-	-	-
	1-Sep-85	01-Oct-85	PRM	-	-	-
	1-Oct-85	01-Nov-85	PRM	-	-	-
	1-Nov-85	01-Dec-85	PRM	-	-	-
	1-Dec-85	01-Jan-86	PRM	-	-	-
1986	1-Jan-86	01-Feb-86	PRM	-	-	-
	1-Feb-86	01-Mar-86	PRM	-	-	-
	1-Mar-86	01-Apr-86	PRM	-	-	-
	1-Apr-86	01-May-86	PRM	-	-	-
	1-May-86	01-Jun-86	PRM	-	-	-
	1-Jun-86	01-Jul-86	PRM	-	-	-
	1-Jul-86	01-Aug-86	PRM	-	-	-
	1-Aug-86	01-Sep-86	PRM	-	-	-
	1-Sep-86	01-Oct-86	PRM	-	-	-
	1-Oct-86	01-Nov-86	PRM	-	-	-
	1-Nov-86	01-Dec-86	PRM	-	-	-
	1-Dec-86	01-Jan-87	PRM	-	-	-
1987	1-Jan-87	01-Feb-87	PRM	-	-	-
	1-Feb-87	01-Mar-87	PRM	-	-	-
	1-Mar-87	01-Apr-87	PRM	-	-	-
	1-Apr-87	01-May-87	PRM	-	-	-
	1-May-87	01-Jun-87	PRM	-	-	-
	1-Jun-87	01-Jul-87	PRM	-	-	-
	1-Jul-87	01-Aug-87	PRM	-	-	-
	1-Aug-87	01-Sep-87	PRM	-	-	-
	1-Sep-87	01-Oct-87	PRM	-	-	-
	1-Oct-87	01-Nov-87	PRM	-	-	-
	1-Nov-87	01-Dec-87	PRM	-	-	-
	1-Dec-87	01-Jan-88	PRM	-	-	-
1988	1-Jan-88	01-Feb-88	PRM	-	-	-
	1-Feb-88	01-Mar-88	PRM	-	-	-
	1-Mar-88	01-Apr-88	PRM	-	-	-
	1-Apr-88	01-May-88	PRM	-	-	-
	1-May-88	01-Jun-88	PRM	-	-	-
	1-Jun-88	01-Jul-88	PRM	-	-	-
	1-Jul-88	01-Aug-88	PRM	-	-	-
	1-Aug-88	01-Sep-88	PRM	-	-	-
	1-Sep-88	01-Oct-88	PRM	-	-	-
	1-Oct-88	01-Nov-88	PRM	-	-	-
	1-Nov-88	01-Dec-88	PRM	-	-	-
	1-Dec-88	01-Jan-89	PRM	-	-	-
1989	1-Jan-89	01-Feb-89	PRM	-	-	-
	1-Feb-89	01-Mar-89	PRM	-	-	-

UPWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	STATION AIR 2 - A pCi/L	STATION AIR 2 -B pCi/L	AIR 3A pCi/L
	1-Mar-89	01-Apr-89	PRM	-	-	-
	1-Apr-89	01-May-89	PRM	-	-	-
	1-May-89	01-Jun-89	PRM	-	-	-
	1-Jun-89	01-Jul-89	PRM	-	-	-
	1-Jul-89	01-Aug-89	PRM	-	-	-
	1-Aug-89	01-Sep-89	PRM	-	-	-
	1-Sep-89	01-Oct-89	PRM	-	-	-
	1-Oct-89	01-Nov-89	PRM	-	-	-
	1-Nov-89	01-Dec-89	PRM	-	-	-
	1-Dec-89	01-Jan-90	PRM	-	-	-
1990	1-Jan-90	01-Feb-90	PRM	-	-	-
	1-Feb-90	01-Mar-90	PRM	-	-	-
	1-Mar-90	01-Apr-90	PRM	-	-	-
	1-Apr-90	01-May-90	PRM	-	-	-
	1-May-90	01-Jun-90	PRM	-	-	-
	1-Jun-90	01-Jul-90	PRM	-	-	-
	1-Jul-90	01-Aug-90	PRM	-	-	-
	1-Aug-90	01-Sep-90	PRM	-	-	-
	1-Sep-90	01-Oct-90	PRM	-	-	-
	1-Oct-90	01-Nov-90	PRM	-	-	-
	1-Nov-90	01-Dec-90	PRM	-	-	-
	1-Dec-90	01-Jan-91	PRM	-	-	-
1991	1-Jan-91	01-Feb-91	PRM	2.00	-	-
	1-Feb-91	01-Mar-91	PRM	2.00	-	-
	1-Mar-91	01-Apr-91	PRM	2.00	-	-
	1-Apr-91	01-May-91	TRACKETCH	(3)	-	-
	1-May-91	01-Jun-91	TRACKETCH	(3)	-	-
	1-Jun-91	01-Jul-91	TRACKETCH	(3)	-	-
	1-Jul-91	01-Aug-91	TRACKETCH	4.20	-	-
	1-Aug-91	01-Sep-91	TRACKETCH	4.20	-	-
	1-Sep-91	01-Oct-91	TRACKETCH	4.20	-	-
	1-Oct-91	01-Nov-91	TRACKETCH	2.80	-	-
	1-Nov-91	01-Dec-91	TRACKETCH	2.80	-	-
	1-Dec-91	03-Jan-92	TRACKETCH	2.80	-	-
1992	10-Jan-92	07-Feb-92	TRACKETCH	3.90	-	-
	7-Feb-92	03-Mar-92	TRACKETCH	3.20	-	-
	3-Mar-92	02-Apr-92	TRACKETCH	5.93	-	-
	2-Apr-92	11-May-92	TRACKETCH	3.07	-	-
	11-May-92	01-Jun-92	TRACKETCH	3.07	-	-
	1-Jun-92	01-Jul-92	TRACKETCH	3.07	-	-
	1-Jul-92	01-Aug-92	TRACKETCH	3.80	-	-
	1-Aug-92	01-Sep-92	TRACKETCH	3.80	-	-
	1-Sep-92	06-Oct-92	TRACKETCH	3.80	-	-
	6-Oct-92	01-Nov-92	TRACKETCH	3.00	-	-
	1-Nov-92	01-Dec-92	TRACKETCH	3.00	-	-
	1-Dec-92	04-Jan-93	TRACKETCH	3.00	-	-
1993	4-Jan-93	01-Feb-93	TRACKETCH	3.20	-	-
	1-Feb-93	01-Mar-93	TRACKETCH	3.20	-	-
	1-Mar-93	01-Apr-93	TRACKETCH	3.20	-	-
	1-Apr-93	01-May-93	TRACKETCH	2.50	-	-

UPWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	STATION AIR 2 - A pCi/L	STATION AIR 2 -B pCi/L	AIR 3A pCi/L
	1-May-93	01-Jun-93	TRACKETCH	2.50	-	-
	1-Jun-93	30-Jun-93	TRACKETCH	2.50	-	-
	30-Jun-93	01-Aug-93	TRACKETCH	4.80	-	-
	1-Aug-93	18-Aug-93	TRACKETCH	4.80	-	-
	18-Aug-93	01-Oct-93	TRACKETCH	4.80	-	-
	1-Oct-93	04-Nov-93	TRACKETCH	4.80	-	-
	4-Nov-93	30-Nov-93	TRACKETCH	4.80	-	-
	30-Nov-93	03-Jan-94	TRACKETCH	4.80	-	-
1994	3-Jan-94	31-Jan-94	TRACKETCH	5.30	-	-
	31-Jan-94	21-Feb-94	TRACKETCH	5.30	-	-
	21-Feb-94	31-Mar-94	TRACKETCH	5.30	-	-
	31-Mar-94	27-Apr-94	TRACKETCH	3.10	-	-
	27-Apr-94	31-May-94	TRACKETCH	3.10	-	-
	31-May-94	01-Jul-94	TRACKETCH	3.10	-	-
	1-Jul-94	03-Aug-94	TRACKETCH	3.70	-	-
	3-Aug-94	07-Sep-94	TRACKETCH	3.70	-	-
	7-Sep-94	03-Oct-94	TRACKETCH	3.70	-	-
	3-Oct-94	02-Nov-94	TRACKETCH	3.00	-	-
	2-Nov-94	01-Dec-94	TRACKETCH	3.00	-	-
	1-Dec-94	03-Jan-95	TRACKETCH	3.00	-	-
1995	3-Jan-95	01-Feb-95	TRACKETCH	3.10	-	-
	1-Feb-95	02-Mar-95	TRACKETCH	3.10	-	-
	2-Mar-95	31-Mar-95	TRACKETCH	3.10	-	-
	31-Mar-95	30-Apr-95	TRACKETCH	2.40	-	-
	30-Apr-95	31-May-95	TRACKETCH	2.40	-	-
	31-May-95	30-Jun-95	TRACKETCH	2.40	-	-
	30-Jun-95	31-Jul-95	TRACKETCH	4.50	-	-
	31-Jul-95	31-Aug-95	TRACKETCH	4.50	-	-
	31-Aug-95	30-Sep-95	TRACKETCH	4.50	-	-
	30-Sep-95	31-Oct-95	TRACKETCH	4.80	-	-
	31-Oct-95	30-Nov-95	TRACKETCH	4.80	-	-
	30-Nov-95	03-Jan-96	TRACKETCH	4.80	-	-
1996	3-Jan-96	01-Feb-96	TRACKETCH	2.20	-	-
	1-Feb-96	01-Mar-96	TRACKETCH	2.20	-	-
	1-Mar-96	01-Apr-96	TRACKETCH	2.20	-	-
	1-Apr-96	01-May-96	TRACKETCH	2.90	-	-
	1-May-96	01-Jun-96	TRACKETCH	2.90	-	-
	1-Jun-96	01-Jul-96	TRACKETCH	2.90	-	-
	1-Jul-96	01-Aug-96	TRACKETCH	4.10	-	-
	1-Aug-96	01-Sep-96	TRACKETCH	4.10	-	-
	1-Sep-96	30-Sep-96	TRACKETCH	4.10	-	-
	30-Sep-96	01-Nov-96	TRACKETCH	2.90	-	-
	1-Nov-96	01-Dec-96	TRACKETCH	2.90	-	-
	1-Dec-96	03-Jan-97	TRACKETCH	2.90	-	-
1997	3-Jan-97	01-Feb-97	TRACKETCH	1.70	-	-
	1-Feb-97	01-Mar-97	TRACKETCH	1.70	-	-
	1-Mar-97	01-Apr-97	TRACKETCH	1.70	-	-
	1-Apr-97	01-May-97	TRACKETCH	3.40	-	-
	1-May-97	01-Jun-97	TRACKETCH	3.40	-	-
	1-Jun-97	30-Jun-97	TRACKETCH	3.40	-	-

UPWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	STATION AIR 2 - A pCi/L	STATION AIR 2 -B pCi/L	AIR 3A pCi/L
	30-Jun-97	01-Aug-97	TRACKETCH	2.70	-	-
	1-Aug-97	01-Sep-97	TRACKETCH	2.70	-	-
	1-Sep-97	01-Oct-97	TRACKETCH	2.70	-	-
	1-Oct-97	01-Nov-97	TRACKETCH	3.90	-	-
	1-Nov-97	01-Dec-97	TRACKETCH	3.90	-	-
	1-Dec-97	03-Jan-98	TRACKETCH	3.90	-	-
1998	3-Jan-98	01-Feb-98	TRACKETCH	2.40	-	-
	1-Feb-98	01-Mar-98	TRACKETCH	2.40	-	-
	1-Mar-98	01-Apr-98	TRACKETCH	2.40	-	-
	1-Apr-98	01-May-98	TRACKETCH	2.20	-	-
	1-May-98	01-Jun-98	TRACKETCH	2.20	-	-
	1-Jun-98	01-Jul-98	TRACKETCH	2.20	-	-
	1-Jul-98	01-Aug-98	TRACKETCH	3.00	-	-
	1-Aug-98	01-Sep-98	TRACKETCH	3.00	-	-
	1-Sep-98	30-Sep-98	TRACKETCH	3.00	-	-
	30-Sep-98	01-Nov-98	TRACKETCH	2.80	-	-
	1-Nov-98	01-Dec-98	TRACKETCH	2.80	-	-
	1-Dec-98	04-Jan-99	TRACKETCH	2.80	-	-
1999	4-Jan-99	01-Feb-99	TRACKETCH	2.60	-	-
	1-Feb-99	01-Mar-99	TRACKETCH	2.60	-	-
	1-Mar-99	11-Apr-99	TRACKETCH	2.60	-	-
	11-Apr-99	01-May-99	TRACKETCH	2.70	-	-
	1-May-99	01-Jun-99	TRACKETCH	2.70	-	-
	1-Jun-99	04-Jul-99	TRACKETCH	2.70	-	-
	4-Jul-99	01-Aug-99	TRACKETCH	3.90	-	-
	1-Aug-99	01-Sep-99	TRACKETCH	3.90	-	-
	1-Sep-99	03-Oct-99	TRACKETCH	3.90	-	-
	3-Oct-99	01-Nov-99	TRACKETCH	6.40	-	-
	1-Nov-99	01-Dec-99	TRACKETCH	6.40	-	-
	1-Dec-99	02-Jan-00	TRACKETCH	6.40	-	-
2000	2-Jan-00	01-Feb-00	TRACKETCH	1.80	-	-
	1-Feb-00	01-Mar-00	TRACKETCH	1.80	-	-
	1-Mar-00	04-Apr-00	TRACKETCH	1.80	-	-
	4-Apr-00	01-May-00	TRACKETCH	3.50	-	-
	1-May-00	01-Jun-00	TRACKETCH	3.50	-	-
	1-Jun-00	05-Jul-00	TRACKETCH	3.50	-	-
	5-Jul-00	01-Aug-00	TRACKETCH	5.70	-	-
	1-Aug-00	01-Sep-00	TRACKETCH	5.70	-	-
	1-Sep-00	02-Oct-00	TRACKETCH	5.70	-	-
	2-Oct-00	01-Nov-00	TRACKETCH	78.8	-	-
	1-Nov-00	01-Dec-00	TRACKETCH	78.8	-	-
	1-Dec-00	01-Jan-01	TRACKETCH	78.8	-	-
2001	2-Jan-01	01-Feb-01	TRACKETCH	6.20	-	-
	1-Feb-01	01-Mar-01	TRACKETCH	6.20	-	-
	1-Mar-01	01-Apr-01	TRACKETCH	6.20	-	-
	1-Apr-01	01-May-01	TRACKETCH	2.50	-	-
	1-May-01	01-Jun-01	TRACKETCH	2.50	-	-
	1-Jun-01	01-Jul-01	TRACKETCH	2.50	-	-
	1-Jul-01	01-Aug-01	TRACKETCH	3.10	-	-
	1-Aug-01	01-Sep-01	TRACKETCH	3.10	-	-

UPWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	STATION AIR 2 - A pCi/L	STATION AIR 2 -B pCi/L	AIR 3A pCi/L
	1-Sep-01	01-Oct-01	TRACKETCH	3.10	-	-
	1-Oct-01	01-Nov-01	TRACKETCH	4.10	-	-
	1-Nov-01	01-Dec-01	TRACKETCH	4.10	-	-
	1-Dec-01	02-Jan-02	TRACKETCH	4.10	-	-
2002	2-Jan-02	01-Feb-02	TRACKETCH	2.70	-	-
	1-Feb-02	01-Mar-02	TRACKETCH	2.70	-	-
	1-Mar-02	31-Mar-02	TRACKETCH	2.70	-	-
	31-Mar-02	01-May-02	TRACKETCH	2.30	-	-
	1-May-02	01-Jun-02	TRACKETCH	2.30	-	-
	1-Jun-02	01-Jul-02	TRACKETCH	2.30	-	-
	1-Jul-02	01-Aug-02	TRACKETCH	3.30	-	-
	1-Aug-02	01-Sep-02	TRACKETCH	3.30	-	-
	1-Sep-02	01-Oct-02	TRACKETCH	3.30	-	-
	1-Oct-02	01-Nov-02	TRACKETCH	4.20	-	-
	1-Nov-02	01-Dec-02	TRACKETCH	4.20	-	-
	1-Dec-02	02-Jan-03	TRACKETCH	4.20	-	-
2003	2-Jan-03	02-Feb-03	TRACKETCH	2.60	-	-
	1-Feb-03	01-Mar-03	TRACKETCH	2.60	-	-
	1-Mar-03	31-Mar-03	TRACKETCH	2.60	-	-
	31-Mar-03	01-May-03	TRACKETCH	3.90	-	-
	1-May-03	01-Jun-03	TRACKETCH	3.90	-	-
	1-Jun-03	30-Jun-03	TRACKETCH	3.90	-	-
	30-Jun-03	01-Aug-03	TRACKETCH	NO DATA	-	-
	1-Aug-03	01-Sep-03	TRACKETCH	NO DATA	-	-
	1-Sep-03	01-Oct-03	TRACKETCH	NO DATA	-	-
	1-Oct-03	01-Nov-03	TRACKETCH	3.50	-	-
	1-Nov-03	01-Dec-03	TRACKETCH	3.50	-	-
	1-Dec-03	01-Jan-04	TRACKETCH	3.50	-	-
2004	1-Jan-04	01-Feb-04	TRACKETCH	2.70	-	-
	1-Feb-04	01-Mar-04	TRACKETCH	2.70	-	-
	1-Mar-04	01-Apr-04	TRACKETCH	2.70	-	-
	1-Apr-04	01-May-04	TRACKETCH	2.40	-	-
	1-May-04	01-Jun-04	TRACKETCH	2.40	-	-
	1-Jun-04	30-Jun-04	TRACKETCH	2.40	-	-
	30-Jun-04	01-Aug-04	TRACKETCH	3.60	-	-
	1-Aug-04	01-Sep-04	TRACKETCH	3.60	-	-
	1-Sep-04	03-Oct-04	TRACKETCH	3.60	-	-
	3-Oct-04	01-Nov-04	TRACKETCH	3.90	-	-
	1-Nov-04	01-Dec-04	TRACKETCH	3.90	-	-
	1-Dec-04	01-Jan-05	TRACKETCH	3.90	-	-
2005	1-Jan-05	01-Feb-05	TRACKETCH	2.30	-	-
	1-Feb-05	01-Mar-05	TRACKETCH	2.30	-	-
	1-Mar-05	04-Apr-05	TRACKETCH	2.30	-	-
	4-Apr-05	01-May-05	TRACKETCH	2.60	-	-
	1-May-05	01-Jun-05	TRACKETCH	2.60	-	-
	1-Jun-05	03-Jul-05	TRACKETCH	2.60	-	-
	3-Jul-05	01-Aug-05	TRACKETCH	4.30	-	-
	1-Aug-05	01-Sep-05	TRACKETCH	4.30	-	-
	1-Sep-05	01-Oct-05	TRACKETCH	4.30	-	-
	1-Oct-05	01-Nov-05	TRACKETCH	3.90	-	-

UPWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	STATION AIR 2 - A pCi/L	STATION AIR 2 -B pCi/L	AIR 3A pCi/L
	1-Nov-05	01-Dec-05	TRACKETCH	3.90	-	-
	1-Dec-05	01-Jan-06	TRACKETCH	3.90	-	-
2006	1-Jan-06	01-Feb-06	TRACKETCH	2.60	-	-
	1-Feb-06	01-Mar-06	TRACKETCH	2.60	-	-
	1-Mar-06	03-Apr-06	TRACKETCH	2.60	-	-
	3-Apr-06	03-May-06	TRACKETCH	4.60	-	-
	3-May-06	03-Jun-06	TRACKETCH	4.60	-	-
	3-Jun-06	05-Jul-06	TRACKETCH	4.60	-	-
	5-Jul-06	05-Aug-06	TRACKETCH	3.60	-	-
	5-Aug-06	05-Sep-06	TRACKETCH	3.60	-	-
	5-Sep-06	02-Oct-06	TRACKETCH	3.60	-	-
	2-Oct-06	02-Nov-06	TRACKETCH	3.50	-	-
	2-Nov-06	02-Dec-06	TRACKETCH	3.50	-	-
	2-Dec-06	02-Jan-07	TRACKETCH	3.50	-	-
2007	2-Jan-07	01-Feb-07	TRACKETCH	16.9	-	-
	1-Feb-07	01-Mar-07	TRACKETCH	16.9	-	-
	1-Mar-07	02-Apr-07	TRACKETCH	16.9	-	-
	2-Apr-07	01-May-07	TRACKETCH	NO DATA	-	-
	1-May-07	01-Jun-07	TRACKETCH	NO DATA	-	-
	1-Jun-07	03-Jul-07	TRACKETCH	NO DATA	-	-
	3-Jul-07	01-Aug-07	TRACKETCH	3.90	-	-
	1-Aug-07	01-Sep-07	TRACKETCH	3.90	-	-
	1-Sep-07	03-Oct-07	TRACKETCH	3.90	-	-
	3-Oct-07	01-Nov-07	TRACKETCH	3.40	-	-
	1-Nov-07	01-Dec-07	TRACKETCH	3.40	-	-
	1-Dec-07	02-Jan-08	TRACKETCH	3.40	-	-
2008	2-Jan-08	01-Feb-08	TRACKETCH	3.40	-	-
	1-Feb-08	01-Mar-08	TRACKETCH	3.40	-	-
	1-Mar-08	01-Apr-08	TRACKETCH	3.40	-	-
	1-Apr-08	01-May-08	TRACKETCH	2.20	-	-
	1-May-08	01-Jun-08	TRACKETCH	2.20	-	-
	1-Jun-08	02-Jul-08	TRACKETCH	2.20	-	-
	2-Jul-08	01-Aug-08	TRACKETCH	5.10	-	-
	1-Aug-08	01-Sep-08	TRACKETCH	5.10	-	-
	6-Aug-08	1-Sep-08	TRACKETCH	NO DATA	2.00	-
	1-Sep-08	01-Oct-08	TRACKETCH	5.10	2.00	-
	1-Oct-08	01-Nov-08	TRACKETCH	3.20	3.60	-
	1-Nov-08	01-Dec-08	TRACKETCH	3.20	3.60	-
	1-Dec-08	04-Jan-09	TRACKETCH	3.20	3.60	-
2009	4-Jan-09	01-Feb-09	TRACKETCH	2.70	2.90	-
	1-Feb-09	01-Mar-09	TRACKETCH	2.70	2.90	-
	31-Mar-09	1-Apr-09	TRACKETCH	2.70	2.90	-
	1-Apr-09	01-May-09	TRACKETCH	2.50	2.60	-
	1-May-09	29-Jun-09	TRACKETCH	2.50	2.60	-
	29-Jun-09	01-Jul-09	TRACKETCH	2.50	2.60	-
	1-Jul-09	01-Aug-09	TRACKETCH	3.10	3.70	-
	1-Aug-09	01-Sep-09	TRACKETCH	3.10	3.70	-
	1-Sep-09	01-Oct-09	TRACKETCH	3.10	3.70	-
	1-Oct-09	01-Nov-09	TRACKETCH	3.40	4.10	-
	01-Nov-09	01-Dec-09	TRACKETCH	3.40	4.10	-

UPWIND RADON DATA

START DATE	END DATE	DETECTOR TYPE	STATION AIR 2 - A pCi/L	STATION AIR 2 -B pCi/L	AIR 3A pCi/L
01-Dec-09	31-Dec-09	TRACKETCH	3.40	4.10	-
1-Jan-10	1-Feb-10	TRACKETCH	NO DATA	3.30	-
1-Feb-10	1-Mar-10	TRACKETCH	NO DATA	3.30	-
1-Mar-10	1-Apr-10	TRACKETCH	NO DATA	3.30	-
1-Apr-10	1-May-10	TRACKETCH	1.70	1.70	-
1-May-10	1-Jun-10	TRACKETCH	1.70	1.70	-
1-Jun-10	1-Jul-10	TRACKETCH	1.70	1.70	-
1-Jul-10	1-Aug-10	TRACKETCH	2.20	2.80	-
1-Aug-10	1-Sep-10	TRACKETCH	2.20	2.80	-
1-Sep-10	1-Oct-10	TRACKETCH	2.20	2.80	-
1-Oct-10	1-Nov-10	TRACKETCH	1.90	2.40	-
1-Nov-10	1-Dec-10	TRACKETCH	1.90	2.40	-
1-Dec-10	1-Jan-11	TRACKETCH	1.90	2.40	-
1-Jan-11	1-Feb-11	TRACKETCH	0.90	0.90	-
1-Feb-11	1-Mar-11	TRACKETCH	0.90	0.90	-
1-Mar-11	1-Apr-11	TRACKETCH	0.90	0.90	-
1-Apr-11	1-May-11	TRACKETCH	1.70	1.90	-
1-May-11	1-Jun-11	TRACKETCH	1.70	1.90	-
1-Jun-11	1-Jul-11	TRACKETCH	1.70	1.90	-
AVERAGE			**3.29**	**2.68**	**0.85**
MINIMUM			**0.90**	**0.90**	**0.04**
MAXIMUM			**6.40**	**4.10**	**2.95**
STD. DEV.			**1.06**	**0.90**	**0.68**
VARIANCE			**1.12**	**0.81**	**0.47**

	Operating Period Air 2
AVERAGE	1.56
MINIMUM	0.04
MAXIMUM	6.86
STD. DEV.	1.57
VARIANCE	2.45

🟦 April 1, 1991 to July 1, 2011

1-IF MORE THAN ONE READING WAS TAKEN FOR THE PERIOD THEN THE RESULT SHOWN IS AN AVERAGE OF THE READINGS TAKEN

2-IF THREE (3) IDENTICAL READINGS FOR A SINGLE STATION APPEAR IN SUCCESSION AND ARE MARKED BY A SINGLE VERTICAL LINE IN ALL THREE MONTHS OF A GIVEN CALENDER QUARTER THEN THE DETECTOR WAS PLACED FOR THE ENTIRE QUARTER AND THE INDIVIDUAL MONTHLY READINGS ARE THE SINGLE QUARTERLY READING REPEATED FOR EACH MONTH

3-DETECTOR PROBLEM CAUSED ERRONEOUS READING WHICH IS NOT INCLUDED IN RESULTS

Kennecott Uranium Company - Sweetwater Uranium Facility

DOWNWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	AIR 4 pCi/L	AIR 4A pCi/L	AIR 5A pCi/L	AIR 7 (RAWLINS) pCi/l
1981	01-Jan-81	01-Feb-81	PRM	0.39	-	0.26	0.10
	01-Feb-81	01-Mar-81	PRM	0.31	-	0.54	0.07
	01-Mar-81	01-Apr-81	PRM	0.30	-	0.48	0.11
	01-Apr-81	01-May-81	PRM	0.25	-	0.38	0.15
	01-May-81	01-Jun-81	PRM	0.18	-	0.24	0.02
	01-Jun-81	01-Jul-81	PRM	0.41	-	0.42	0.12
	01-Jul-81	01-Aug-81	PRM	0.92	-	0.96	0.08
	01-Aug-81	01-Sep-81	PRM	2.90	-	1.10	0.23
	01-Sep-81	01-Oct-81	PRM	2.30	-	0.76	0.32
	01-Oct-81	01-Nov-81	PRM	1.57	-	3.47	0.08
	01-Nov-81	01-Dec-81	PRM	0.31	-	1.30	0.36
	01-Dec-81	01-Jan-82	PRM	0.70	-	1.00	0.10
1982	01-Jan-82	01-Feb-82	PRM	2.37	-	2.15	0.52
	01-Feb-82	01-Mar-82	PRM	0.32	-	0.06	0.33
	01-Mar-82	01-Apr-82	PRM	1.90	-	0.73	0.13
	01-Apr-82	01-May-82	PRM	1.98	-	1.01	0.03
	01-May-82	01-Jun-82	PRM	0.99	-	0.81	0.42
	01-Jun-82	01-Jul-82	PRM	1.02	-	0.41	0.03
	01-Jul-82	01-Aug-82	PRM	1.02	-	0.41	0.03
	01-Aug-82	01-Sep-82	PRM	0.91	-	0.66	0.59
	01-Sep-82	01-Oct-82	PRM	0.36	-	0.03	0.03
	01-Oct-82	01-Nov-82	PRM	0.16	-	2.21	0.22
	01-Nov-82	01-Dec-82	PRM	0.25	-	0.58	0.18
	01-Dec-82	01-Jan-83	PRM	0.75	-	1.45	0.14
1983	01-Jan-83	01-Feb-83	PRM	0.88	-	0.70	0.05
	01-Feb-83	01-Mar-83	PRM	2.56	-	1.14	0.82
	01-Mar-83	01-Apr-83	PRM	0.40	-	1.09	0.05
	01-Apr-83	01-May-83	PRM	0.66	-	0.41	0.24
	01-May-83	01-Jun-83	PRM	0.70	-	0.47	0.32
	01-Jun-83	01-Jul-83	PRM	0.68	-	0.87	1.43
	01-Jul-83	01-Aug-83	PRM	-	-	0.83	-
	01-Aug-83	01-Sep-83	PRM	-	-	1.17	-
	01-Sep-83	01-Oct-83	PRM	-	-	3.92	-
	01-Oct-83	01-Nov-83	PRM	-	-	3.92	-
	01-Nov-83	01-Dec-83	PRM	-	-	0.62	-
	01-Dec-83	01-Jan-84	PRM	-	-	1.39	-
1984	01-Jan-84	01-Feb-84	PRM	-	-	0.96	-
	01-Feb-84	01-Mar-84	PRM	-	-	1.06	-
	01-Mar-84	01-Apr-84	PRM	-	1.56	-	-
	01-Apr-84	01-May-84	PRM	-	0.03	-	-
	01-May-84	01-Jun-84	PRM	-	1.44	-	-
	01-Jun-84	01-Jul-84	PRM	-	2.81	-	-
	01-Jul-84	01-Aug-84	PRM	-	1.14	-	-
	01-Aug-84	01-Sep-84	PRM	-	1.22	-	-
	01-Sep-84	01-Oct-84	PRM	-	2.76	-	-
	01-Oct-84	01-Nov-84	PRM	-	3.23	-	-
	01-Nov-84	01-Dec-84	PRM	-	1.07	-	-
	01-Dec-84	01-Jan-85	PRM	-	2.11	-	-

DOWNWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	AIR 4 pCi/L	AIR 4A pCi/L	AIR 5A pCi/L	AIR 7 (RAWLINS) pCi/l
1985	01-Jan-85	01-Feb-85	PRM	-	3.10	-	-
	01-Feb-85	01-Mar-85	PRM	-	9.03	-	-
	01-Mar-85	01-Apr-85	PRM	-	2.40	-	-
	01-Apr-85	01-May-85	PRM	-	0.72	-	-
	01-May-85	01-Jun-85	PRM	-	2.32	-	-
	01-Jun-85	01-Jul-85	PRM	-	1.69	-	-
	01-Jul-85	01-Aug-85	PRM	-	1.48	-	-
	01-Aug-85	01-Sep-85	PRM	-	1.79	-	-
	01-Sep-85	01-Oct-85	PRM	-	1.07	-	-
	01-Oct-85	01-Nov-85	PRM	-	4.68	-	-
	01-Nov-85	01-Dec-85	PRM	-	1.04	-	-
	01-Dec-85	01-Jan-86	PRM	-	7.12	-	-
1986	01-Jan-86	01-Feb-86	PRM	-	0.03	-	-
	01-Feb-86	01-Mar-86	PRM	-	2.74	-	-
	01-Mar-86	01-Apr-86	PRM	-	0.48	-	-
	01-Apr-86	01-May-86	PRM	-	1.88	-	-
	01-May-86	01-Jun-86	PRM	-	0.30	-	-
	01-Jun-86	01-Jul-86	PRM	-	2.30	-	-
	01-Jul-86	01-Aug-86	PRM	-	1.76	-	-
	01-Aug-86	01-Sep-86	PRM	-	2.49	-	-
	01-Sep-86	01-Oct-86	PRM	-	0.94	-	-
	01-Oct-86	01-Nov-86	PRM	-	5.50	-	-
	01-Nov-86	01-Dec-86	PRM	-	1.26	-	-
	01-Dec-86	01-Jan-87	PRM	-	3.14	-	-
1987	01-Jan-87	01-Feb-87	PRM	-	1.80	-	-
	01-Feb-87	01-Mar-87	PRM	-	0.03	-	-
	01-Mar-87	01-Apr-87	PRM	-	1.06	-	-
	01-Apr-87	01-May-87	PRM	-	3.98	-	-
	01-May-87	01-Jun-87	PRM	-	1.05	-	-
	01-Jun-87	01-Jul-87	PRM	-	2.60	-	-
	01-Jul-87	01-Aug-87	PRM	-	2.32	-	-
	01-Aug-87	01-Sep-87	PRM	-	0.27	-	-
	01-Sep-87	01-Oct-87	PRM	-	0.03	-	-
	01-Oct-87	01-Nov-87	PRM	-	1.57	-	-
	01-Nov-87	01-Dec-87	PRM	-	3.17	-	-
	01-Dec-87	01-Jan-88	PRM	-	1.37	-	-
1988	01-Jan-88	01-Feb-88	PRM	-	1.02	-	-
	01-Feb-88	01-Mar-88	PRM	-	1.59	-	-
	01-Mar-88	01-Apr-88	PRM	-	1.19	-	-
	01-Apr-88	01-May-88	PRM	-	4.13	-	-
	01-May-88	01-Jun-88	PRM	-	0.64	-	-
	01-Jun-88	01-Jul-88	PRM	-	1.24	-	-
	01-Jul-88	01-Aug-88	PRM	-	0.00	-	-
	01-Aug-88	01-Sep-88	PRM	-	0.00	-	-
	01-Sep-88	01-Oct-88	PRM	-	0.00	-	-
	01-Oct-88	01-Nov-88	PRM	-	0.00	-	-
	01-Nov-88	01-Dec-88	PRM	-	0.00	-	-
	01-Dec-88	01-Jan-89	PRM	-	0.00	-	-
1989	01-Jan-89	01-Feb-89	PRM	-	3.04	-	-
	01-Feb-89	01-Mar-89	PRM	-	3.58	-	-

DOWNWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	AIR 4 pCi/L	AIR 4A pCi/L	AIR 5A pCi/L	AIR 7 (RAWLINS) pCi/l
	01-Mar-89	01-Apr-89	PRM	-	4.00	-	-
	01-Apr-89	01-May-89	PRM	-	2.02	-	-
	01-May-89	01-Jun-89	PRM	-	3.62	-	-
	01-Jun-89	01-Jul-89	PRM	-	2.53	-	-
	01-Jul-89	01-Aug-89	PRM	-	2.69	-	-
	01-Aug-89	01-Sep-89	PRM	-	1.37	-	-
	01-Sep-89	01-Oct-89	PRM	-	5.28	-	-
	01-Oct-89	01-Nov-89	PRM	-	4.22	-	-
	01-Nov-89	01-Dec-89	PRM	-	2.19	-	-
	01-Dec-89	01-Jan-90	PRM	-	6.41	-	-
1990	01-Jan-90	01-Feb-90	PRM	-	1.20	-	-
	01-Feb-90	01-Mar-90	PRM	-	2.88	-	-
	01-Mar-90	01-Apr-90	PRM	-	0.94	-	-
	01-Apr-90	01-May-90	PRM	-	2.75	-	-
	01-May-90	01-Jun-90	PRM	-	2.64	-	-
	01-Jun-90	01-Jul-90	PRM	-	3.35	-	-
	01-Jul-90	01-Aug-90	PRM	-	1.91	-	-
	01-Aug-90	01-Sep-90	PRM	-	2.14	-	-
	01-Sep-90	01-Oct-90	PRM	-	1.60	-	-
	01-Oct-90	01-Nov-90	PRM	-	3.22	-	-
	01-Nov-90	01-Dec-90	PRM	-	0.96	-	-
	01-Dec-90	01-Jan-91	PRM	-	3.99	-	-
1991	01-Jan-91	01-Feb-91	PRM	-	1.19	-	-
	01-Feb-91	01-Mar-91	PRM	-	4.45	-	-
	01-Mar-91	01-Apr-91	PRM	-	1.78	-	-
	01-Apr-91	01-May-91	TRACKETCH	-	1.60	-	-
	01-May-91	01-Jun-91	TRACKETCH	-	1.60	-	-
	01-Jun-91	01-Jul-91	TRACKETCH	-	1.60	-	-
	01-Jul-91	01-Aug-91	TRACKETCH	-	2.60	-	-
	01-Aug-91	01-Sep-91	TRACKETCH	-	2.60	-	-
	01-Sep-91	01-Oct-91	TRACKETCH	-	2.60	-	-
	01-Oct-91	01-Nov-91	TRACKETCH	-	2.20	-	-
	01-Nov-91	01-Dec-91	TRACKETCH	-	2.20	-	-
	01-Dec-91	03-Jan-92	TRACKETCH	-	2.20	-	-
1992	10-Jan-92	07-Feb-92	TRACKETCH	-	4.66	-	-
	07-Feb-92	03-Mar-92	TRACKETCH	-	4.66	-	-
	03-Mar-92	02-Apr-92	TRACKETCH	-	4.66	-	-
	02-Apr-92	11-May-92	TRACKETCH	-	2.63	-	-
	11-May-92	01-Jun-92	TRACKETCH	-	2.63	-	-
	01-Jun-92	01-Jul-92	TRACKETCH	-	2.63	-	-
	01-Jul-92	01-Aug-92	TRACKETCH	-	2.87	-	-
	01-Aug-92	01-Sep-92	TRACKETCH	-	2.87	-	-
	01-Sep-92	06-Oct-92	TRACKETCH	-	2.87	-	-
	06-Oct-92	01-Nov-92	TRACKETCH	-	3.10	-	-
	01-Nov-92	01-Dec-92	TRACKETCH	-	3.10	-	-
	01-Dec-92	04-Jan-93	TRACKETCH	-	3.10	-	-
1993	04-Jan-93	01-Feb-93	TRACKETCH	-	2.90	-	-
	01-Feb-93	01-Mar-93	TRACKETCH	-	2.90	-	-
	01-Mar-93	01-Apr-93	TRACKETCH	-	2.90	-	-
	01-Apr-93	01-May-93	TRACKETCH	-	3.00	-	-

DOWNWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	AIR 4 pCi/L	AIR 4A pCi/L	AIR 5A pCi/L	AIR 7 (RAWLINS) pCi/l
	01-May-93	01-Jun-93	TRACKETCH	-	3.00	-	-
	01-Jun-93	30-Jun-93	TRACKETCH	-	3.00	-	-
	30-Jun-93	01-Aug-93	TRACKETCH	-	4.20	-	-
	01-Aug-93	18-Aug-93	TRACKETCH	-	4.20	-	-
	18-Aug-93	01-Oct-93	TRACKETCH	-	4.20	-	-
	01-Oct-93	04-Nov-93	TRACKETCH	-	4.00	-	-
	04-Nov-93	30-Nov-93	TRACKETCH	-	4.00	-	-
	30-Nov-93	03-Jan-94	TRACKETCH	-	4.00	-	-
1994	03-Jan-94	31-Jan-94	TRACKETCH	-	4.00	-	-
	31-Jan-94	21-Feb-94	TRACKETCH	-	4.00	-	-
	21-Feb-94	31-Mar-94	TRACKETCH	-	4.00	-	-
	31-Mar-94	27-Apr-94	TRACKETCH	-	3.30	-	-
	27-Apr-94	31-May-94	TRACKETCH	-	3.30	-	-
	31-May-94	01-Jul-94	TRACKETCH	-	3.30	-	-
	01-Jul-94	03-Aug-94	TRACKETCH	-	3.30	-	-
	03-Aug-94	07-Sep-94	TRACKETCH	-	3.30	-	-
	07-Sep-94	03-Oct-94	TRACKETCH	-	3.30	-	-
	03-Oct-94	02-Nov-94	TRACKETCH	-	3.50	-	-
	02-Nov-94	01-Dec-94	TRACKETCH	-	3.50	-	-
	01-Dec-94	03-Jan-95	TRACKETCH	-	3.50	-	-
1995	03-Jan-95	01-Feb-95	TRACKETCH	-	1.70	-	-
	01-Feb-95	02-Mar-95	TRACKETCH	-	1.70	-	-
	02-Mar-95	31-Mar-95	TRACKETCH	-	1.70	-	-
	31-Mar-95	30-Apr-95	TRACKETCH	-	2.60	-	-
	30-Apr-95	31-May-95	TRACKETCH	-	2.60	-	-
	31-May-95	30-Jun-95	TRACKETCH	-	2.60	-	-
	30-Jun-95	31-Jul-95	TRACKETCH	-	3.90	-	-
	31-Jul-95	31-Aug-95	TRACKETCH	-	3.90	-	-
	31-Aug-95	30-Sep-95	TRACKETCH	-	3.90	-	-
	30-Sep-95	31-Oct-95	TRACKETCH	-	3.50	-	-
	31-Oct-95	30-Nov-95	TRACKETCH	-	3.50	-	-
	30-Nov-95	03-Jan-96	TRACKETCH	-	3.50	-	-
1996	03-Jan-96	01-Feb-96	TRACKETCH	-	1.90	-	-
	01-Feb-96	01-Mar-96	TRACKETCH	-	1.90	-	-
	01-Mar-96	01-Apr-96	TRACKETCH	-	1.90	-	-
	01-Apr-96	01-May-96	TRACKETCH	-	3.40	-	-
	01-May-96	01-Jun-96	TRACKETCH	-	3.40	-	-
	01-Jun-96	01-Jul-96	TRACKETCH	-	3.40	-	-
	01-Jul-96	01-Aug-96	TRACKETCH	-	3.10	-	-
	01-Aug-96	01-Sep-96	TRACKETCH	-	3.10	-	-
	01-Sep-96	30-Sep-96	TRACKETCH	-	3.10	-	-
	30-Sep-96	01-Nov-96	TRACKETCH	-	3.30	-	-
	01-Nov-96	01-Dec-96	TRACKETCH	-	3.30	-	-
	01-Dec-96	03-Jan-97	TRACKETCH	-	3.30	-	-
1997	03-Jan-97	01-Feb-97	TRACKETCH	-	1.10	-	-
	01-Feb-97	01-Mar-97	TRACKETCH	-	1.10	-	-
	01-Mar-97	01-Apr-97	TRACKETCH	-	1.10	-	-
	01-Apr-97	01-May-97	TRACKETCH	-	3.00	-	-
	01-May-97	01-Jun-97	TRACKETCH	-	3.00	-	-
	01-Jun-97	30-Jun-97	TRACKETCH	-	3.00	-	-

DOWNWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	AIR 4 pCi/L	AIR 4A pCi/L	AIR 5A pCi/L	AIR 7 (RAWLINS) pCi/l
	30-Jun-97	01-Aug-97	TRACKETCH	-	2.40	-	-
	01-Aug-97	01-Sep-97	TRACKETCH	-	2.40	-	-
	01-Sep-97	01-Oct-97	TRACKETCH	-	2.40	-	-
	01-Oct-97	01-Nov-97	TRACKETCH	-	3.80	-	-
	01-Nov-97	01-Dec-97	TRACKETCH	-	3.80	-	-
1998	01-Dec-97	03-Jan-98	TRACKETCH	-	3.80	-	-
	03-Jan-98	01-Feb-98	TRACKETCH	-	2.30	-	-
	01-Feb-98	01-Mar-98	TRACKETCH	-	2.30	-	-
	01-Mar-98	01-Apr-98	TRACKETCH	-	2.30	-	-
	01-Apr-98	01-May-98	TRACKETCH	-	2.00	-	-
	01-May-98	01-Jun-98	TRACKETCH	-	2.00	-	-
	01-Jun-98	01-Jul-98	TRACKETCH	-	2.00	-	-
	01-Jul-98	01-Aug-98	TRACKETCH	-	2.40	-	-
	01-Aug-98	01-Sep-98	TRACKETCH	-	2.40	-	-
	01-Sep-98	30-Sep-98	TRACKETCH	-	2.40	-	-
	30-Sep-98	01-Nov-98	TRACKETCH	-	3.00	-	-
	01-Nov-98	01-Dec-98	TRACKETCH	-	3.00	-	-
	01-Dec-98	04-Jan-99	TRACKETCH	-	3.00	-	-
1999	04-Jan-99	01-Feb-99	TRACKETCH	-	2.40	-	-
	01-Feb-99	01-Mar-99	TRACKETCH	-	2.40	-	-
	01-Mar-99	11-Apr-99	TRACKETCH	-	2.40	-	-
	11-Apr-99	01-May-99	TRACKETCH	-	2.60	-	-
	01-May-99	01-Jun-99	TRACKETCH	-	2.60	-	-
	01-Jun-99	04-Jul-99	TRACKETCH	-	2.60	-	-
	04-Jul-99	01-Aug-99	TRACKETCH	-	3.50	-	-
	01-Aug-99	01-Sep-99	TRACKETCH	-	3.50	-	-
	01-Sep-99	03-Oct-99	TRACKETCH	-	3.50	-	-
	03-Oct-99	01-Nov-99	TRACKETCH	-	4.70	-	-
	01-Nov-99	01-Dec-99	TRACKETCH	-	4.70	-	-
2000	01-Dec-99	02-Jan-00	TRACKETCH	-	4.70	-	-
	02-Jan-00	01-Feb-00	TRACKETCH	-	2.40	-	-
	01-Feb-00	01-Mar-00	TRACKETCH	-	2.40	-	-
	01-Mar-00	04-Apr-00	TRACKETCH	-	2.40	-	-
	04-Apr-00	01-May-00	TRACKETCH	-	3.20	-	-
	01-May-00	01-Jun-00	TRACKETCH	-	3.20	-	-
	01-Jun-00	05-Jul-00	TRACKETCH	-	3.20	-	-
	05-Jul-00	01-Aug-00	TRACKETCH	-	4.20	-	-
	01-Aug-00	01-Sep-00	TRACKETCH	-	4.20	-	-
	01-Sep-00	02-Oct-00	TRACKETCH	-	4.20	-	-
	02-Oct-00	01-Nov-00	TRACKETCH	-	3.70	-	-
	01-Nov-00	01-Dec-00	TRACKETCH	-	3.70	-	-
	01-Dec-00	01-Jan-01	TRACKETCH	-	3.70	-	-
2001	02-Jan-01	01-Feb-01	TRACKETCH	-	3.90	-	-
	01-Feb-01	01-Mar-01	TRACKETCH	-	3.90	-	-
	02-Mar-01	01-Apr-01	TRACKETCH	-	3.90	-	-
	01-Apr-01	01-May-01	TRACKETCH	-	1.50	-	-
	01-May-01	01-Jun-01	TRACKETCH	-	1.50	-	-
	01-Jun-01	01-Jul-01	TRACKETCH	-	1.50	-	-
	01-Jul-01	01-Aug-01	TRACKETCH	-	2.50	-	-
	01-Aug-01	01-Sep-01	TRACKETCH	-	2.50	-	-

DOWNWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	AIR 4 pCi/L	AIR 4A pCi/L	AIR 5A pCi/L	AIR 7 (RAWLINS) pCi/l
	01-Sep-01	01-Oct-01	TRACKETCH	-	2.50	-	-
	01-Oct-01	01-Nov-01	TRACKETCH	-	2.00	-	-
	01-Nov-01	01-Dec-01	TRACKETCH	-	2.00	-	-
	01-Dec-01	02-Jan-02	TRACKETCH	-	2.00	-	-
2002	02-Jan-02	02-Feb-02	TRACKETCH	-	2.70	-	-
	02-Feb-02	01-Mar-02	TRACKETCH	-	2.70	-	-
	01-Mar-02	31-Mar-02	TRACKETCH	-	2.70	-	-
	31-Mar-02	01-May-02	TRACKETCH	-	2.00	-	-
	01-May-02	01-Jun-02	TRACKETCH	-	2.00	-	-
	01-Jun-02	01-Jul-02	TRACKETCH	-	2.00	-	-
	01-Jul-02	01-Aug-02	TRACKETCH	-	2.20	-	-
	01-Aug-02	01-Sep-02	TRACKETCH	-	2.20	-	-
	01-Sep-02	01-Oct-02	TRACKETCH	-	2.20	-	-
	01-Oct-02	01-Nov-02	TRACKETCH	-	2.80	-	-
	01-Nov-02	01-Dec-02	TRACKETCH	-	2.80	-	-
	01-Dec-02	02-Jan-03	TRACKETCH	-	2.80	-	-
2003	02-Jan-03	01-Feb-03	TRACKETCH	-	1.40	-	-
	01-Feb-03	01-Mar-03	TRACKETCH	-	1.40	-	-
	01-Mar-03	31-Mar-03	TRACKETCH	-	1.40	-	-
	31-Mar-03	01-May-03	TRACKETCH	-	3.50	-	-
	01-May-03	01-Jun-03	TRACKETCH	-	3.50	-	-
	01-Jun-03	30-Jun-03	TRACKETCH	-	3.50	-	-
	30-Jun-03	01-Aug-03	TRACKETCH	-	NO DATA	-	-
	01-Aug-03	01-Sep-03	TRACKETCH	-	NO DATA	-	-
	01-Sep-03	01-Oct-03	TRACKETCH	-	NO DATA	-	-
	01-Oct-03	01-Nov-03	TRACKETCH	-	2.10	-	-
	01-Nov-03	01-Dec-03	TRACKETCH	-	2.10	-	-
	01-Dec-03	01-Jan-04	TRACKETCH	-	2.10	-	-
2004	01-Jan-04	01-Feb-04	TRACKETCH	-	2.70	-	-
	01-Feb-04	01-Mar-04	TRACKETCH	-	2.70	-	-
	01-Mar-04	01-Apr-04	TRACKETCH	-	2.70	-	-
	01-Apr-04	01-May-04	TRACKETCH	-	1.70	-	-
	01-May-04	01-Jun-04	TRACKETCH	-	1.70	-	-
	01-Jun-04	30-Jun-04	TRACKETCH	-	1.70	-	-
	30-Jun-04	01-Aug-04	TRACKETCH	-	3.10	-	-
	01-Aug-04	01-Sep-04	TRACKETCH	-	3.10	-	-
	01-Sep-04	03-Oct-04	TRACKETCH	-	3.10	-	-
	03-Oct-04	01-Nov-04	TRACKETCH	-	2.80	-	-
	01-Nov-04	01-Dec-04	TRACKETCH	-	2.80	-	-
	01-Dec-04	01-Jan-05	TRACKETCH	-	2.80	-	-
2005	01-Jan-05	01-Feb-05	TRACKETCH	-	1.80	-	-
	01-Feb-05	01-Mar-05	TRACKETCH	-	1.80	-	-
	01-Mar-05	04-Apr-05	TRACKETCH	-	1.80	-	-
	04-Apr-05	01-May-05	TRACKETCH	-	1.50	-	-
	01-May-05	01-Jun-05	TRACKETCH	-	1.50	-	-
	01-Jun-05	03-Jul-05	TRACKETCH	-	1.50	-	-
	03-Jul-05	01-Aug-05	TRACKETCH	-	3.00	-	-
	01-Aug-05	01-Sep-05	TRACKETCH	-	3.00	-	-
	01-Sep-05	01-Oct-05	TRACKETCH	-	3.00	-	-
	01-Oct-05	01-Nov-05	TRACKETCH	-	3.10	-	-

DOWNWIND RADON DATA

	START DATE	END DATE	DETECTOR TYPE	AIR 4 pCi/L	AIR 4A pCi/L	AIR 5A pCi/L	AIR 7 (RAWLINS) pCi/l
	01-Nov-05	01-Dec-05	TRACKETCH	-	3.10	-	-
	01-Dec-05	01-Jan-06	TRACKETCH	-	3.10	-	-
2006	01-Jan-06	01-Feb-06	TRACKETCH	-	2.40	-	-
	01-Feb-06	01-Mar-06	TRACKETCH	-	2.40	-	-
	01-Mar-06	03-Apr-06	TRACKETCH	-	2.40	-	-
	03-Apr-06	03-May-06	TRACKETCH	-	2.50	-	-
	03-May-06	03-Jun-06	TRACKETCH	-	2.50	-	-
	03-Jun-06	05-Jul-06	TRACKETCH	-	2.50	-	-
	05-Jul-06	05-Aug-06	TRACKETCH	-	3.10	-	-
	05-Aug-06	05-Sep-06	TRACKETCH	-	3.10	-	-
	05-Sep-06	02-Oct-06	TRACKETCH	-	3.10	-	-
	02-Oct-06	02-Nov-06	TRACKETCH	-	2.60	-	-
	02-Nov-06	02-Dec-06	TRACKETCH	-	2.60	-	-
	02-Dec-06	02-Jan-07	TRACKETCH	-	2.60	-	-
2007	02-Jan-07	02-Feb-07	TRACKETCH	-	2.00	-	-
	02-Feb-07	02-Mar-07	TRACKETCH	-	2.00	-	-
	02-Mar-07	02-Apr-07	TRACKETCH	-	2.00	-	-
	02-Apr-07	02-May-07	TRACKETCH	-	2.90	-	-
	02-May-07	02-Jun-07	TRACKETCH	-	2.90	-	-
	02-Jun-07	03-Jul-07	TRACKETCH	-	2.90	-	-
	03-Jul-07	01-Aug-07	TRACKETCH	-	3.70	-	-
	01-Aug-07	01-Sep-07	TRACKETCH	-	3.70	-	-
	01-Sep-07	03-Oct-07	TRACKETCH	-	3.70	-	-
	03-Oct-07	01-Nov-07	TRACKETCH	-	3.20	-	-
	01-Nov-07	01-Dec-07	TRACKETCH	-	3.20	-	-
	01-Dec-07	02-Jan-08	TRACKETCH	-	3.20	-	-
2008	02-Jan-08	01-Feb-08	TRACKETCH	-	2.10	-	-
	01-Feb-08	01-Mar-08	TRACKETCH	-	2.10	-	-
	01-Mar-08	01-Apr-08	TRACKETCH	-	2.10	-	-
	01-Apr-08	01-May-08	TRACKETCH	-	1.60	-	-
	01-May-08	01-Jun-08	TRACKETCH	-	1.60	-	-
	01-Jun-08	02-Jul-08	TRACKETCH	-	1.60	-	-
	02-Jul-08	01-Aug-08	TRACKETCH	-	2.90	-	-
	01-Aug-08	01-Sep-08	TRACKETCH	-	2.90	-	-
	01-Sep-08	01-Oct-08	TRACKETCH	-	2.90	-	-
	01-Oct-08	01-Nov-08	TRACKETCH	-	2.90	-	-
	01-Nov-08	01-Dec-08	TRACKETCH	-	2.90	-	-
	01-Dec-08	04-Jan-09	TRACKETCH	-	2.90	-	-
2009	04-Jan-09	01-Feb-09	TRACKETCH	-	2.70	-	-
	01-Feb-09	1-Mar-09	TRACKETCH	-	2.70	-	-
	1-Mar-09	31-Mar-09	TRACKETCH	-	2.70	-	-
	31-Mar-09	01-May-09	TRACKETCH	-	2.30	-	-
	01-May-09	01-Jun-09	TRACKETCH	-	2.30	-	-
	01-Jun-09	29-Jun-09	TRACKETCH	-	2.30	-	-
	29-Jun-09	01-Aug-09	TRACKETCH	-	2.90	-	-
	01-Aug-09	01-Sep-09	TRACKETCH	-	2.90	-	-
	01-Sep-09	01-Oct-09	TRACKETCH	-	2.90	-	-
	1-Oct-09	01-Nov-09	TRACKETCH	-	2.80	-	-
	01-Nov-09	01-Dec-09	TRACKETCH	-	2.80	-	-
	01-Dec-09	31-Dec-09	TRACKETCH	-	2.80	-	-

DOWNWIND RADON DATA

START DATE	END DATE	DETECTOR TYPE	AIR 4 pCi/L	AIR 4A pCi/L	AIR 5A pCi/L	AIR 7 (RAWLINS) pCi/l
1-Jan-10	1-Feb-10	TRACKETCH	-	2.70	-	-
1-Feb-10	1-Mar-10	TRACKETCH	-	2.70	-	-
1-Mar-10	1-Apr-10	TRACKETCH	-	2.70	-	-
1-Apr-10	1-May-10	TRACKETCH	-	1.70	-	-
1-May-10	1-Jun-10	TRACKETCH	-	1.70	-	-
1-Jun-10	1-Jul-10	TRACKETCH	-	1.70	-	-
1-Jul-10	1-Aug-10	TRACKETCH	-	2.20	-	-
1-Aug-10	1-Sep-10	TRACKETCH	-	2.20	-	-
1-Sep-10	1-Oct-10	TRACKETCH	-	2.20	-	-
1-Oct-10	1-Nov-10	TRACKETCH	-	1.60	-	-
1-Nov-10	1-Dec-10	TRACKETCH	-	1.60	-	-
1-Dec-10	1-Jan-11	TRACKETCH	-	1.60	-	-
1-Jan-11	1-Feb-11	TRACKETCH	-	1.00	-	-
1-Feb-11	1-Mar-11	TRACKETCH	-	1.00	-	-
1-Mar-11	1-Apr-11	TRACKETCH	-	1.00	-	-
1-Apr-11	1-May-11	TRACKETCH	-	1.60	-	-
1-May-11	1-Jun-11	TRACKETCH	-	1.60	-	-
1-Jun-11	1-Jul-11	TRACKETCH	-	1.60	-	-
	AVERAGE		**0.95**	**2.72**	**1.05**	**0.24**
	MINIMUM		**0.16**	**1.00**	**1.05**	**0.24**
	MAXIMUM		**2.90**	**4.70**	**1.05**	**0.24**
	STD. DEV.		**0.77**	**0.80**	**1.05**	**0.29**
	VARIANCE		**0.60**	**0.64**	**1.05**	**0.08**

	Operating Period - Air 4
AVERAGE	0.99
MINIMUM	0.16
MAXIMUM	2.90
STD. DEV.	0.82
VARIANCE	0.67

April 1, 1991 to July 1, 2011

1-IF MORE THAN ONE READING WAS TAKEN FOR THE PERIOD THEN THE RESULT SHOWN IS AN AVERAGE OF THE READINGS TAKEN

2-IF THREE (3) IDENTICAL READINGS FOR A SINGLE STATION APPEAR IN SUCCESSION AND ARE MARKED BY A SINGLE VERTICAL LINE IN ALL THREE MONTHS OF A GIVEN CALENDER QUARTER THEN THE DETECTOR WAS PLACED FOR THE ENTIRE QUARTER AND THE INDIVIDUAL MONTHLY READINGS ARE THE SINGLE QUARTERLY READING REPEATED FOR EACH MONTH

Filename: E:\100123\DWGS\OPER8183.dwg
Date: 05/22/1998

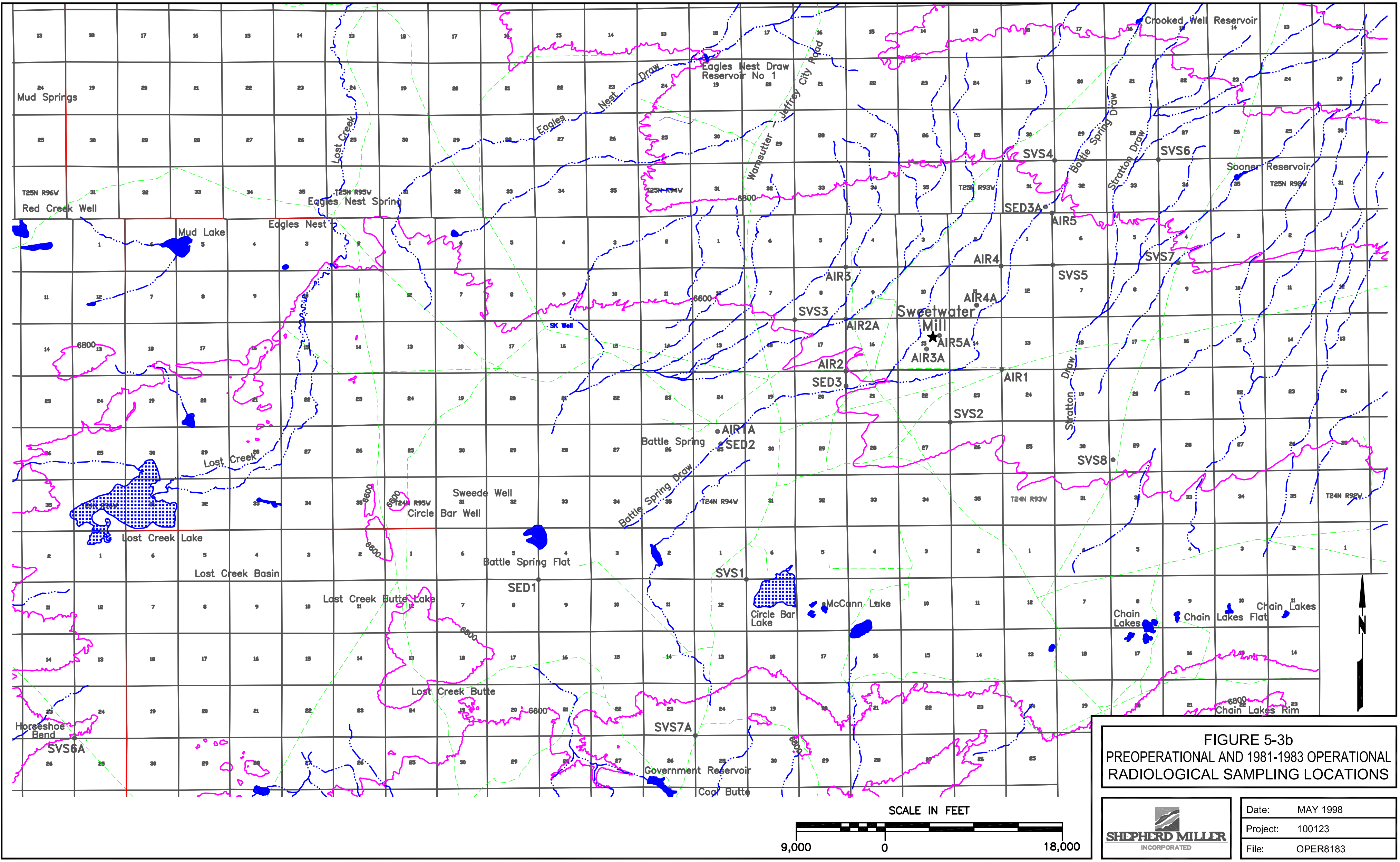
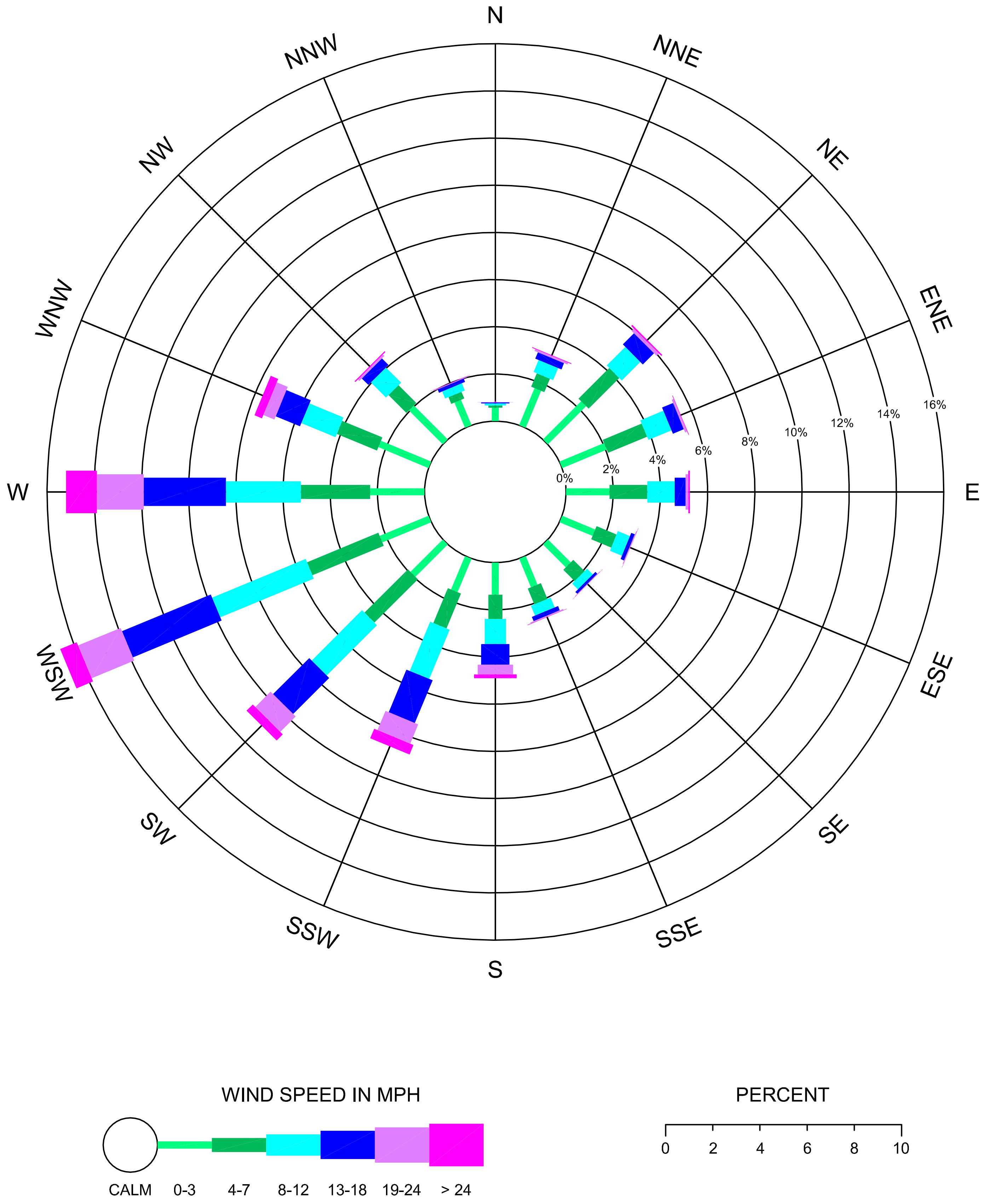


FIGURE 5-3b
PREOPERATIONAL AND 1981-1983 OPERATIONAL
RADIOLOGICAL SAMPLING LOCATIONS

SHEPHERD MILLER
INCORPORATED

Date:	MAY 1998
Project:	100123
File:	OPER8183



SHEPHERD MILLER
INCORPORATED

FIGURE 5-2
SWEETWATER URANIUM PROJECT
ANNUAL WIND ROSE, 1994 THROUGH 1997

Date:	APRIL 1998
Project:	100123
File:	WINDROSE.DWG

Appendix 12

Application of United States Environmental Protection Agency 40 CFR Part 61, Subpart W Regulations to Uranium Recovery Facilities

I. INTRODUCTION

The United States Environmental Protection Agency (EPA) appears to be taking the position that the ***work practice standard***s in its 40 CFR Part 61, Subpart W *National Emissions Standards for Radon Emissions from Operating Mill Tailings* apply to evaporation ponds at conventional and in situ uranium recovery (ISR) sites licensed by the Nuclear Regulatory Commission (NRC) or its Agreement States. This memorandum evaluates the legal and regulatory bases for any potential applicability of the EPA's 40 CFR Part 61, Subpart W regulations to evaporation ponds at currently operating and future operating uranium recovery facilities, including specifically ISR facilities.

A. Atomic Energy Act of 1954 and the Uranium Mill Tailings Radiation Control Act of 1978

1. Statutory and Regulatory Program

Currently, uranium recovery facilities and the 11e.(2) byproduct material (mill process tailings and other related wastes)[1] that they produce are actively regulated by NRC under the Atomic Energy Act of 1954, as amended by the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA). As a general proposition, the AEA was intended to promote the expeditious and efficient recovery of source material for the purposes of national defense and, later, a domestic nuclear power industry. To oversee its implementation, the AEA granted broad regulatory authority to the Atomic Energy Commission (AEC) (now NRC) to regulate source material (uranium) recovery processes after the removal of the source material from its place in nature by surface or underground uranium *mining*.

As concerns about the potential hazards from uranium recovery wastes developed, the AEC/NRC determined that it had no authority to regulate the wastes generated by uranium recovery (i.e., uranium milling) upon the cessation of active recovery operations as such wastes no longer qualified as *licensable* source material under the AEA (i.e., they contained less than 0.05%, by weight, uranium and/or thorium). As a result of this and the potential radiological and *non*-radiological hazards associated with such wastes, in 1978, Congress enacted UMTRCA with two specific intentions: (1) to facilitate the remediation of abandoned "inactive" mill tailings sites that were no longer operated under an active AEA license (Title I) and (2) to provide AEA statutory authority to regulate the management and disposal of wastes from the uranium recovery processing at active (licensed) uranium recovery facilities (Title II).

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[1] *See also* 42 U.S.C. § 7911 (UMTRCA definition of "residual radioactive material").

In order to address the management and control of wastes located at such facilities, UMTRCA created a new category of AEA material known as 11e.(2) byproduct material, which it defined as, "the tailings or wastes produced by the extraction or concentration of uranium or thorium from any *ore* processed *primarily* for its source material content." 42 U.S.C. § 2014(e)(2) (2007).

UMTRCA outlined a comprehensive, multi-agency regulatory oversight process by which appropriate regulations governing the safe management and containment of 11e.(2) byproduct material were to be promulgated and implemented. UMTRCA assigned EPA the authority to promulgate standards of general applicability (for both Title I and Title II programs) addressing both the radiological and *non*-radiological hazards of uranium mill tailings and related wastes. For the *non*-radiological hazards, these generally applicable standards were to provide protection equivalent to that provided by Subtitle C of the Solid Waste Disposal Act (SWDA), which is better known as the Resource Conservation and Recovery Act (RCRA). EPA purposely was not given any enforcement or implementation authority over 11e.(2) byproduct material under RCRA or UMTRCA.

In 1983, pursuant to Congress' mandate in UMTRCA, EPA promulgated its final regulations for active uranium mill tailings facilities at 40 CFR Part 192. UMTRCA directed the Commission (NRC) to implement and enforce the generally applicable standards developed by EPA through its regulations and licenses.[2] Although required to conform its general regulatory requirements to EPA's 40 CFR Part 192 regulations, UMTRCA also granted NRC expanded authority to develop its own requirements for the management of 11e.(2) byproduct material to protect public health, safety, and the environment. Specifically, Section 84(a) of the AEA (Section 205 of UMTRCA) directs NRC to ensure that any 11e.(2) *byproduct material* is managed in a manner:

> that the Commission deems appropriate to protect health, safety, and the environment from the potential *radiological* and *non-radiological* hazards associated with such materials….

42 U.S.C. § (2007).

Thus, UMTRCA amended the AEA to provide EPA/NRC with express authority to regulate both the radiological and the *non*-radiological hazards associated with 11e.(2) byproduct material, whether in the soil, in the air or in the groundwater. The primary concern, however, was the uncontrolled tailings solids (i.e., sands and slimes).[3]

It should also be noted that uranium mills are subject to additional EPA AEA regulation for radiation dosage to members of the public and the general environment, *excluding radon*, as a result of *operations*. Pursuant to its

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[2] 42 U.S.C. § 2022(d).

[3] Tailings solids (sands) had been used in construction activities which generated radiation exposure concerns.

Reorganization Plan No. 3 of 1970 authority, EPA developed a dose limit applicable to *all* AEA fuel cycle facilities, including uranium mills, of 25 mrem/year to the nearest receptor from all potential pathways, excluding the dose from radon. The annual dose to the entire body of a human being must not exceed 25 millirems, 75 millirems to the thyroid, and 25 millirems to any other organ of a member of the public. These standards apply to doses associated with the milling of uranium *ore* as of December 1, 1980. Since 40 CFR Part 190 excludes radon, as a practical matter, its provisions primarily address radioactive particulate emissions from mill facilities, including (1) yellowcake dust and (2) windblown tailings. Thus, there are both EPA and NRC regulations that address the radiological and *non*-radiological effluents from active uranium mills and an EPA fuel cycle standard that addresses what effectively is airborne radiological particulate contamination from such mills.[4]

These requirements have been in place since the early 1980s and have evolved over time to create a robust regulatory program for the safe and effective management of uranium mill tailings facilities. As a necessary part of this regulatory evolution, NRC and its licensees sought to further define the extent of NRC's authority to regulate 11e.(2) byproduct material, particularly with respect to the extent of EPA and State authority over *non*-radiological aspects of 11e.(2) byproduct material. Given that 11e.(2) byproduct material contains both radiological and *non*-radiological constituents and that there were potentially significant conflicts between NRC and EPA/States relating to regulatory authority over the latter, it was inevitable that jurisdictional authority over 11e.(2) byproduct material needed to be defined more precisely.

As a general proposition, NRC has preemptive regulatory authority to address the potential *radiological* hazards associated with AEA licensed facilities, including uranium recovery facilities, their tailings impoundments, evaporation ponds, and other site facilities. In 1980, NRC's Office of Executive Legal Director "(OELD)" issued an advisory legal opinion concluding that the AEA, as amended by UMTRCA, did not preempt the exercise of *non*-Agreement State authority over the *non-radiological* components of 11e.(2) *byproduct material*. In reaching this conclusion, OELD conceded that:

> the question is *so close* that the Commission *could reasonably choose either interpretation*, but that *the better legal view* is that non-Agreement States and the NRC have concurrent jurisdiction to regulate the *non-radiological* hazards of mill tailings, both before and after the November 8, 1981 date upon which the Mill Tailings Act becomes fully effective.[5]

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[4] It is important to note that, prior to the enactment of UMTRCA, *non*-radiological (hazardous) contaminants at AEA-licensed facilities typically were regulated by the States.

[5] Memorandum from Howard K. Shapar, Executive Legal Director, NRC, to Chairman Ahearne, NRC re: OELD Legal Opinion on Two Questions Relating to the Operation of the Uranium Mill Tailings Radiation Control Act of 1978, Attachment B, 2-3 (April 28, 1980) (emphasis added).

After careful consideration of the uranium recovery industry's analysis of this "concurrent jurisdiction" issue in NMA's White Paper entitled *Recommendations for a Coordinated Approach to Regulating the Uranium Recovery Industry* disputing the OELD opinion and the position of NRC Staff in SECY-99-277[6] supporting the OELD opinion, in 2000, the Commission determined that the OELD opinion should be overturned and that the Commission, indeed, exercises exclusive jurisdiction over both the radiological *and non*-radiological aspects of 11e.(2) byproduct material.[7] As a result, implementation and enforcement of relevant AEA regulatory programs for licensed uranium recovery operations is under the exclusive authority of NRC and its Agreement States, including mill facility construction and operations, tailings impoundment construction, operations, and final closure, and associated uranium recovery facilities such as evaporation ponds.

B. Clean Air Act of 1977 and Implementing Regulations (40 CFR Part 61)

In addition to the authority vested in EPA under UMTRCA, Congress granted EPA additional authority to regulate certain aspects of uranium recovery facilities. In 1977, Congress enacted the Clean Air Act (CAA) under which EPA was directed to address potentially hazardous *radiological* air emissions at a variety of facilities, including uranium mills. In response to this statutory mandate and pursuant to Section 112 of the CAA, EPA promulgated 40 CFR Part 61 to address radiological air emissions from such facilities.

40 CFR Part 61, Subpart T *National Emission Standards for Radon Emissions from the Disposal of* ***Uranium Mill Tailings*** were promulgated by EPA to address potential hazardous air pollutants (e.g., radon as particulate emissions were addressed effectively under the above-noted 40 CFR Part 190 fuel cycle regulations) at mill tailings facilities regulated under Title II of UMTRCA, which were *no longer operational*. Subpart T stated, in pertinent part:

> Radon-222 emissions to the ambient air from uranium mill tailings pile that are no longer operational shall not exceed 20 pCi/(m^2 -sec) (1.9 pCi/(ft^2 -sec)) of radon-222.

Subsequently, after challenges to Subpart T were filed in the United States Court of Appeals for the District of Columbia Circuit (D.C. Circuit), Subpart T was the subject of settlement discussions between the American Mining Congress (now NMA), EPA, NRC, and environmental groups, with NRC and Agreement States monitoring as interested, but not formally litigating, parties. These negotiations ultimately led to NRC revising its mill tailings regulations to require licensees to achieve enforceable "milestones" leading to accelerated placement of radon barriers at *non-operational*

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[6] United States Nuclear Regulatory Commission, *Concurrent Jurisdiction of Non-Radiological of Uranium Mill Tailings*, SECY-99-277 (December 2, 1999).

[7] United States Nuclear Regulatory Commission, Staff Requirements Memorandum, *Concurrent Jurisdiction of Non-Radiological of Uranium Mill Tailings,* SECY-99-277 (August 11, 2000).

(i.e., no longer actively milling or on standby) Title II mill tailings disposal sites[8] to satisfy EPA's and the environmental groups' concerns that the potential threat from radon emissions be addressed by the prompt placement of radon barriers over disposal areas.[9] After NRC finalized its revisions to 10 CFR Part 40, Appendix A in accordance with this settlement, EPA rescinded Subpart T of its 40 CFR Part 61 regulations and, as such, its requirements no longer apply to operating uranium mills.[10]

40 CFR Part 61, Subpart W entitled *National Emission Standards for Radon Emissions from* ***Operating Mill Tailings*** was promulgated to address radon emissions at *active* (including standby) uranium mill tailings facilities. Thus, Subpart W applies to operators of uranium mill tailings facilities while they are processing uranium/thorium ores and creating 11e.(2) byproduct material:

> The provisions of this subpart apply to owners or operators of facilities licensed to manage uranium byproduct materials during and following the processing of uranium ores, commonly referred to as uranium mills and their *associated tailings*. This subpart does not apply to the disposal of *tailings*.

New tailings impoundments constructed after December 15, 1989 must comply with one of two *work practice* standards:[11] (1) *phased disposal* in lined impoundments of forty (40) acres and meet the requirements of 40 CFR § 192.32(a) with no more than two impoundments in operation at one time; or (2) *continuous disposal* of tailings that are dewatered and immediately disposed of with no more than ten acres uncovered at one time. EPA's radon measurement Method 115 requires measurement of the different "regions" of tailings disposal facilities except those covered by water.[12]

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[8] 59 Fed. Reg. 28,220 (1994).

[9] EPA was clearly concerned with prompt placement of radon barriers over tailings piles and EPA, thus, indicated that the primary purpose of the settlement was:

> "to ensure that owners of uranium mill tailings disposal sites ... bring those piles into compliance with the 20 pCi/m^2s flux standard as expeditiously as practicable considering technological feasibility . . . with the goal that all current disposal sites be closed and in compliance with the radon emission standard by the end of 1997, or within seven years of the date on which existing operations and standby sites enter disposal status.

59 Fed. Reg. 36,280, 36,282 (1994).

[10] *See* 61 Fed. Reg. 68972 (December 30, 1996) (emphasis added).

[11] 40 CFR § 61.252(a) (2007).

[12] The Response to Comments to EPA's Final Rule on radon-222 emissions from licensed mill tailings demonstrates that EPA considered an emission standard and determined that "boundaries could be changed to comply with an emission standard which is not an acceptable practice under the Clean Air Act. Also, methods to determine emissions from tailings piles also have not been sufficiently developed to provide accurate and consistent measurements of radon emissions." United States Environmental Protection Agency, Office of Radiation Programs, *Final Rule for Radon-222 Emissions from Licensed Uranium Mill Tailings*, Response to Comments (August, 1986).

C. Application of Subpart W Work Practice Standards to Conventional and ISR Facilities

Whether Subpart W's work practice standards apply to other than *active* mill tailings impoundments at uranium recovery facilities is informed by review and analysis of the regulatory records associated with both Subparts T and W, since both were promulgated at the same time and, as these Subparts' titles suggest, were intended to address only uranium mill tailings disposal facilities.

1. Promulgation of Subpart T Regulations and Subpart W Work Practice Standards (Proposed Rule): March 7, 1989

On March 7, 1989, EPA issued a Proposed Rule for the regulation of hazardous air pollutants at uranium milling facilities, both active and inactive. First, 40 CFR Part 61, Subpart T entitled *National Emission Standards for Radon Emissions From the Disposal of* ***Uranium Mill Tailings*** were promulgated by EPA to address potential hazardous air pollutants (e.g., radon) at mill tailings facilities regulated under Title II of UMTRCA, which were no longer operational. Subpart T stated, in pertinent part:

> Radon-222 emissions to the ambient air from uranium mill tailings pile *that are no longer operational* shall not exceed 20 pCi/(m^2 -sec) (1.9 pCi/(ft^2 -sec)) of radon-222.

Second, 40 CFR Part 61, Subpart W entitled *National Emission Standards for Radon Emissions from* ***Operating Mill Tailings*** addresses radon emissions at *active* (including standby) uranium mill tailings facilities. Subpart W covers the owners and operators of uranium mill tailings facilities while they are processing uranium/thorium ores and creating 11e.(2) byproduct material:

> The provisions of this subpart apply to owners or operators of facilities licensed to manage uranium byproduct materials during and following the processing of uranium ores, commonly referred to as uranium mills and their associated tailings. This subpart does not apply to the disposal of tailings.

Neither the titles of these two Subparts nor the language of the Proposed Rules provide any indication that they were intended to apply to anything other than uranium mill tailings impoundments, as opposed to impoundments used solely as evaporation ponds.

2. Promulgation of Subpart T Regulations and Subpart W Work Practice Standards (Final Rule, Response to Comments, and Analysis): December 15, 1989

As noted above, on March 7, 1989, EPA proposed a new set of CAA regulations to reduce potential radon-222 emissions from inoperative uranium mill tailings impoundments and new work practice standards for active tailings impoundments constructed after the Rule's effective date.

On December 15, 1989, EPA published a Federal Register notice promulgating its final Section 112 NESHAP standards governing radon emission standards for *non*-operational and operational uranium mill tailings impoundments, as well as future impoundments, analyzing the risks associated with radon emissions from such impoundments, and discussing the potential effects of the newly proposed 20 pCi/m2-s standard on such impoundments. The final rule makes no reference whatsoever to evaporation ponds at uranium mill sites, but did explicitly reference the types of radon source terms to which Subparts T and W were intended to apply. For example, when describing the process of uranium milling, EPA states:

> The process of separating uranium from its ore creates waste material called uranium mill tailings….These tailings are collected in impoundments that vary in size from 20 to 400 acres….For the current radionuclides NESHAP rulemaking, EPA is promulgating rules for three different subcategories that deal with mill tailings: operating mill tailings—existing *piles*, operating mill tailings—new technology, and disposal of uranium mill tailings (as a separate source category….Existing mill tailings *piles are large piles of wastes that emit radon*.

As discussed below, the use of the term mill tailings *piles* in this notice is consistent with the language used by Congress when defining "tailings" in UMTRCA:

> the remaining portion of a metal-bearing ore after some or all of such metal, such as uranium, has been extracted."[13]

This notice also reinforced a commonly accepted premise that would suggest that an evaporation pond would not be a significant radon source term because, as EPA states, "[r]adon emissions from these piles are retarded by the presence of water. However, if operations cease, and the pit is allowed to dry out, emissions can increase significantly."[14] Thus, EPA expressly recognized that the presence of water *in tailings* will significantly retard radon emission from given source terms. Accordingly, evaporation ponds which are constructed and used to contain significant amounts of process or waste water presumably would not represent a significant potential source of radon emissions.

3. Rescission of 40 CFR Part 61, Subpart T (Proposed Rule): December 31, 1991

On December 31, 1991, EPA proposed to rescind 40 CFR Part 61, Subpart T "as

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[13] It is also common sense that a uranium mill tailings *pile* would not be an evaporation pond, because water generally does not collect and remain in a *pile*.

[14] 54 Fed. Reg. 51654 (December 15, 1989).

it applies to owners and operators of uranium mill tailings disposal sites that are licensed by the Nuclear Regulatory Commission (NRC) or an affected NRC Agreement State…."[15] EPA's proposed rescission notice included a section specifically devoted to the question of "whether the requirement extends to the evaporation pond thereby jeopardizing the other remedial aspects of the UMTRCA program."[16] This discussion recognized that evaporation ponds play an important role in the UMTRCA remedial action programs at uranium mill tailings sites:

> The regulations contemplated by this notice seek to control the emission of radon-222 by requiring the installation of an earthen cover over the disposal piles as expeditiously as practicable considering technological feasibility. However, there are other aspects to the UMTRCA regulatory scheme, including the long-term maintenance of the piles (once controlled) against erosion, and the reclamation and maintenance of groundwater….*These actions entail the use of evaporation ponds that in some instances….have been placed directly upon the disposal site*.[17]

After discussing whether evaporation ponds were to be subject to its 40 CFR Part 61, Subpart T standard, EPA concluded:

> EPA does not intend that the expeditious radon cover requirement extend to the areas where evaporation ponds are located, even if on the pile itself, to the extent that such evaporation pond is deemed by the implementing agency (NRC or an affected Agreement State) to be an appropriate aspect to the overall remedial program for the particular site involved.[18]

Indeed, EPA's Proposed Rule prescribed an approach to evaporation pond remediation as follows: "the evaporation pond area may be covered to control radon *after it is no longer in use and ready for covering*."[19] EPA supported this conclusion by reasoning that:

> the ponds themselves serve as an effective radon barrier, thus this decision is bolstered by the absence of any evidence that there is a significant public health risk presented by the radon emissions from

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[15] 56 Fed. Reg. 67561. This language demonstrates that EPA acknowledges that evaporation ponds are not to be considered as part of the class of facilities known as "uranium mill tailings piles."

[16] *Id.*

[17] *Id.* (emphasis added). The fact that evaporation ponds could be (and had been) located on top of an inoperative tailings piles to de-water piles and assist in groundwater corrective action was made known to EPA by American Mining Congress (AMC) negotiators during the settlement negotiations that ultimately led to the rescission of Subpart T.

[18] *Id.*

[19] 56 Fed. Reg. 67561 (emphasis added).

> these evaporation ponds during the period they are employed as part of the overall remediation of the site.[20]

Based on this determination, EPA concluded:

> EPA believes the overall public health interest in comprehensively resolving the problems associated with each site is best served by requiring that the radon cover be expeditiously installed in a manner that does not require interruption of this other aspect of remediation....Rather, EPA believes that provided all other parts of the pile are covered with the earthen cover, compliance with the 20 pCi/m2 standard will result....[21]

EPA's conclusions about the potential radon source term from evaporation ponds being actively used in uranium mill tailings site reclamation efforts are no less valid for such ponds being actively used during uranium recovery operations at an operational facility subject to Subpart W work practice standards.

4. Rescission of Subpart T (Final Rule): December 30, 1996

Five years after the issuance of its Proposed Rule for the rescission of Subpart T, EPA released its Final Rule declaring that Subpart T was indeed rescinded and noted that Subpart W work practice standards continued to apply to uranium mill tailings facilities constructed after December 15, 1989.[22] EPA's Final Rule contained no statements indicating any change in its interpretation of the scope of these standards, as offered in the Proposed Rule.

5. Amendments to EPA Mill Tailings Regulations (Final Rule): November 15, 1993

On November 15, 1993, EPA promulgated a Final Rule containing amendments to its regulations applicable to operational NRC/Agreement State licensed uranium mill tailings facilities. In this Federal Register notice/Final Rule, EPA responded to a number of public comments, including comments related to the application of Subpart W requirements to evaporation ponds. As stated by EPA:

> *EPA reiterates that the Agency does not intend the expeditious radon cover requirement to extend to areas where evaporation ponds are located*, even if on the pile itself, to the extent that such evaporation pond is deemed by the implementing agency...to be an appropriate aspect of the overall remedial program for the particular site.[23]

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[20] *Id.*
[21] *Id.*
[22] *Id.*
[23] 56 Fed. Reg. 67561 (emphasis added).

Essentially, in this Final Rule, EPA restated its conclusion in the Subpart T rescission regulatory record that active evaporation ponds do not represent a significant potential radon source term.[24]

6. Current Statutory and Regulatory Language

On the face of it, while fluids can be 11e.(2) byproduct material if they are no longer to be used in process operations, such fluids deposited in evaporation ponds do not qualify as "tailings" as the term is generally understood under any relevant regulatory definitions. As demonstrated by a variety of statutory and regulatory materials, despite the fact that evaporation pond fluids contain some fines from mill processing that are either suspended in the fluids or that have settled on the liner of the pond as such fluids have evaporated (which can be considered "tailings-like" 11e.(2) byproduct material), neither the fluids with entrained solid fines nor the fines themselves typically would be considered "tailings" in a pond used solely for evaporation purposes during *active* or closure operations. An *active* tailings pile/impoundment is one into which tailings (a mixture of sands, slimes, and fluids) are placed during uranium recovery. The sands and slimes constitute the bulk of the material (typically 70% plus).

First, UMTRCA's definition of "tailings," as incorporated by EPA in 40 CFR Part 61 from UMTRCA, indicates: "[t]he term 'tailings' means *the remaining portion of a metal-bearing ore after some or all of such metal, such as uranium, has been extracted*."[25] Water stored in an evaporation pond from either active recovery operations or groundwater corrective action is not consistent with the UMTRCA definition of "tailings" as the water is added to the processing circuit for the ore (or removed from the groundwater), and is not part of "the remaining portion of the metal-bearing ore from which uranium was extracted." Given that EPA's regulations in 40 CFR Part 61, Subpart T incorporate the UMTRCA definition of "tailings,"[26] EPA arguably has accepted the distinction between tailings in a tailings pile or impoundment and water related to uranium milling in an evaporation pond that may have resulted either from processing or from a groundwater corrective action program.

Second, as discussed above, EPA's 40 CFR Part 61, Subpart W regulations consistently utilize the terms "tailings pile" and "tailings impoundment" when discussing the site facilities that are covered by Subpart W work practice standards, which, on its face, does not apply to a liquid storage facility. For example, 40 CFR § 61.221 states in pertinent part:

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[24] *Id.*

[25] 42 U.S.C. § 7911(8)

[26] It should be noted that Subpart W's definition of "uranium byproduct material or tailings" adopts essentially the same definition of "11e.(2) byproduct material in Section 11(e) of the AEA, as amended by UMTRCA.

> As used in this subpart, all terms not defined here have the meanings given them in the Clean Air Act or subpart A of part 61. The following terms shall have the following specific meanings:
>
> (a) *Long term stabilization* means the addition of material on a uranium mill *tailings pile* for the purpose of ensuring compliance with the requirements of 40 CFR 192.02(a). These actions shall be considered complete when the Nuclear Regulatory Commission determines that the requirements of 40 CFR 192.02(a) have been met.[27]

In addition, when prescribing the 20 pCi/m2-s standard in Subpart T, EPA states:

> (a) Radon-222 emissions to the ambient air from uranium mill *tailings pile* that are no longer operational shall not exceed 20 pCi/(m^2 -sec) (1.9 pCi/(ft^2 -sec)) of radon-222.
>
> (b) Once a uranium mill *tailings pile or impoundment* ceases to be operational it must be disposed of and brought into compliance with this standard within two years of the effective date of the standard. If it is not physically possible for an owner or operator to complete disposal within that time, EPA shall, after consultation with the owner or operator, establish a compliance agreement which will assure that disposal will be completed as quickly as possible.[28]

EPA's Subpart W regulations use both the term "tailings impoundment" and "tailings pile" when discussing the facilities to which Subpart W's 20 pCi/m2-s radon emission standard applies and the work practice standards for operational and potential future tailings facilities.[29] The use of the term "pile" is consistent with prior practices at uranium mill tailings sites where mill tailings were routinely placed in a "pile" rather than the current practice of placing mill tailings in an "impoundment." However, the random use of the terms "pile" and "impoundment" suggests that as technology was transforming, the terms were being interchangeably applied to mill "tailings" disposal facilities. As a result, Subpart W appears to apply to "tailings" as described in EPA's rulemaking materials, whether the term "piles" or "impoundments" is used.

Additional evidence for the positions espoused above can be found in EPA's background and guidance documents on NESHAPs, its Final Rule on Subpart W work practice standards, and their application to uranium mill tailings piles/impoundments and the appendix setting out Method 115 entitled *Monitoring*

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[27] 40 CFR § 61.221(a-b).

[28] 40 CFR § 61.222(a-b).

[29] *Compare* 40 CFR § 61.252(a); 40 CFR § 61.252(b-c). This is entirely consistent with the history of the development of uranium mill tailings disposal facilities in that the older uranium mills constructed "piles" for disposal of tailings; but by the time that EPA's CAA regulations were being developed and promulgated, the technology had advanced to use "impoundments" which were, and are, more stable and controllable in both the short and long-term context than the old "piles."

for Radon Emissions. Initially, EPA's NESHAP documents expressly recognize that the scope of the Subpart W work practice standards was intended to reach *tailings* stored in on-site tailings piles/impoundments *and not* to other site facilities such as evaporation ponds:

> As with any ore-processing operation, uranium milling produces large quantities of waste rock. Uranium mill wastes, *or tailings*, are usually stored in an impoundment located on the mill site.[30]

Further, EPA's guidance on work practices includes a discussion of potential work practice procedures for controlling radon emissions from milling operations that result in tailings. These practices include the use of "earthen covers" to be applied to tailings to reduce potential fugitive emissions such as radon:

> Earth covers which consist of layered soil approximately 3 meters deep are frequently used on waste piles, reclaimed lands, or inactive surface mining areas to reduce both particulate and radon emissions.[31]

However, the use of an earthen cover to retard radon emissions from an evaporation ponds rather than a mill tailings pile/impoundment is unnecessary because the water in the pond retards such emissions, and EPA's recognition that, when the pond is no longer actively used, it will be dried and covered.

EPA's background document for its Subpart W work practice standards contains additional evidence to support the conclusion that such standards do not apply to evaporation ponds. When describing what is encompassed by the term "tailings," EPA states:

> Tailings include the barren crushed ore material plus process solutions. These tailings consist of mixtures of sands and slimes (coarse and fine tailings). *Evaporation ponds used to contain excess liquid from tailings impoundments also contain suspended...tailings....*[32]

This statement appears to support the fact that the term "tailings" is intended to apply to the materials in a site's active mill tailings impoundments and not to fluids in impoundments used solely as evaporation ponds, as evaporation ponds are considered a separate point of analysis from mill tailings impoundments. EPA's

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[30] United States Environmental Protection Agency, *Radionuclides: Background Information Document for Final Rules*, Volume I at 4-29 (October, 1984).

[31] United States Environmental Protection Agency, *Final Rule for Radon-222 Emissions from Licensed Uranium Mill Tailings: Background Information Document* at 7-2 to 7-3 (August, 1986).

[32] *Id.* at 3-19. In addition, the statement following this quote further demonstrates that EPA considered fluids in evaporation ponds to not be a radon source term: "*If exposed*, these solids are assumed to emit radon-222 at the same specific flux as tailings impoundments." The low nature of tailings covered by water is also noted by EPA in Volume I of its Background Information Document on *Radionuclides*: "When tailings impoundment areas are almost completely covered by water, radionuclide emissions will be low."

Response to Comments also includes evidence that the work practice standards were not intended to apply to evaporation ponds due to their minimal radon emissions:

> Recent technical assessments of radon emission rates from tailings indicate that radon emissions from tailings covered with less than one meter of water, or merely saturated with water, are about 2% of emissions from dry tailings. *Tailings covered with more than one meter of water are estimated to have a zero emissions rate. The Agency believes this calculated difference between 0% and 2% is negligible*. *The Agency used an emission rate of zero for all tailings covered with water or saturated with water in estimating radon emissions.*[33]

Additionally, as Method 115, paragraph 2.1.3 states, "radon flux measurements shall be made within each region on the pile, *except for those areas covered with water*." Paragraph 2.1.3(a) also states, "*Water covered area*--no measurements required as radon flux assumed to be *zero*."[34]

Finally, significantly, EPA also discusses the relatively small amount of radon potentially emitted from on-site impoundments at *in situ* uranium recovery (ISR) sites: "A small amount of radon is released from the waste impoundments use to store contaminated liquids from the operation." Further, EPA's Background Information Document on *Radionuclides* states regarding ISR projects: "The radioactive emissions from this source are small compared to the other sources."[35] These statements are bolstered by EPA's response to comments on its final NESHAP for underground uranium mines rule:

> The Agency has not ignored the risks from surface and in situ uranium mining...Standards were not proposed for either of these technologies as the maximum ground level air concentrations of radon emitted from these activities are significantly lower than those which result from underground mining.[36]

Thus, the records in the Subpart T, Subpart W, and Subpart B proceedings and EPA's Method 115 rationale and proceedings suggest strongly that evaporation

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[33] United States Environmental Protection Agency, *Final Rule for Radon-222 Emissions from Licensed Uranium Mill Tailings: Response to Comments* at 11 (October, 1984).

[34] Emphasis added. *See also* Method 115, Paragraph 2.1.6 *Radon Flux Measurement*…The radon collector is placed *on the surface* of the pile area to be measured and allowed to collect radon for a time period of 24 hours. The detailed measurement procedure provided in Appendix A of EPA 520/5-85-0029(1) shall be used to measure the radon flux on the uranium mill tailings except the *surface of tailings* shall not be penetrated by the lip of the radon detector as directed in the procedure, rather the collector shall be carefully positioned *on a flat surface* with soil or tailings used to seal the edge.

[35] *See* United States Environmental Protection Agency, *Radionuclides, Background Information Document for Final Rules*, Volume II, p. 5-2 (October, 1984).

[36] United States Environmental Protection Agency, *Radionuclides: Response to Comments for Final Rules*, Volume I at 87 (October, 1984).

ponds at conventional uranium milling facilities, much less those at ISR facilities do not warrant the application of work practice standards to control radon emissions.

D. Conclusions

Therefore, based on the foregoing discussion, it appears that EPA’s 40 CFR Part 61, Subpart W work practice standards do not apply to evaporation ponds at uranium recovery facilities.

Appendix 13

NRC FORM 374

U.S. NUCLEAR REGULATORY COMMISSION

MATERIALS LICENSE

Pursuant to the Atomic Energy Act of 1954, as amended, the Energy Reorganization Act of 1974 (Public Law 93-438), and the applicable parts of Title 10, Code of Federal Regulations, Chapter I, Parts 19, 20, 30, 31, 32, 33, 34, 35, 36, 39, 40, 51, 70, and 71, and in reliance on statements and representations heretofore made by the licensee, a license is hereby issued authorizing the licensee to receive, acquire, possess, and transfer byproduct, source, and special nuclear material designated below; to use such material for the purpose(s) and at the place(s) designated below; to deliver or transfer such material to persons authorized to receive it in accordance with the regulations of the applicable Part(s). This license shall be deemed to contain the conditions specified in Section 183 of the Atomic Energy Act of 1954, as amended, and is subject to all applicable rules, regulations, and orders of the Nuclear Regulatory Commission now or hereafter in effect and to any conditions specified below.

Licensee	
1. Kennecott Uranium Company Sweetwater Project	3. License Number SUA-1350, Amendment 28
2. P.O. Box 1500 Rawlins, Wyoming 82301-1500	4. Expiration Date November 10, 2014 5. Docket No. 40-8584 Reference No.

6. Byproduct Source, and/or Special Nuclear Material	7. Chemical and/or Physical Form	8. Maximum amount that Licensee May Possess at Any One Time Under This License
Natural Uranium and/or Natural Uranium Byproducts	Any	Unlimited

Section 9: Administrative Conditions

9.1 The authorized place of use shall be the licensee's Sweetwater uranium milling facility, located in Township 24 North, Range 93W, Sweetwater County, Wyoming.

9.2 All written notices and reports to the Nuclear Regulatory Commission (NRC) required under this license, with the exception of incident and event notifications, shall be sent to the following address: ATTN: Document Control Desk, c/o Deputy Director, Decommissioning and Uranium Recovery Licensing Directorate, Division of Waste Management and Environmental Protection, Office of Federal and State Materials and Environmental Management Programs, Washington, DC 20555, Mail Stop T-8 F5, or by express delivery to 11545 Rockville Pike, Rockville, Maryland 20852-2738.

Incident and event notifications, which require telephone notification under 10 CFR 20.2202 and 10 CFR 40.60, shall be made to the NRC Operations Center at (301) 816-5100.

[Applicable Amendments: 16, 18, 25, 26]

9.3 Changes, Tests and Experiments

(a) The licensee may, without obtaining a license amendment pursuant to §40.44, and subject to conditions specified in (b) of this condition:

i. make changes in the facility as described in the license application (as updated),

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ii make changes in the procedures as described in the license application (as updated), and

iii conduct test or experiments not described in the license application (as updated).

(b) The licensee shall obtain a license amendment pursuant to §40.44 prior to implementing a proposed change, test or experiment if the change, test, or experiment would:

i Result in any appreciable increase in the frequency of occurrence of an accident previously evaluated in the license application (as updated);

ii Result in any appreciable increase in the likelihood of occurrence of a malfunction of a structure, system, or component (SSC) important to safety previously evaluated in the license application (as updated);

iii Result in any appreciable increase in the consequences of an accident previously evaluated in the license application (as updated);

iv Result in any appreciable increase in the consequences of a malfunction of an SSC previously evaluated in the license application (as updated);

v Create a possibility for an accident of a different type than any previously evaluated in the license application (as updated);

vi Create a possibility for a malfunction of an SSC with a different result than previously evaluated in the license application (as updated);

vii Result in a departure from the method of evaluation described in the license application (as updated) used in establishing the Final Safety Evaluation Report (FSER) or the Environmental Assessment (EA) or Technical Evaluation Reports (TERs) or other analysis and evaluations for license amendments;

viii For purposes of this paragraph as applied to this license, SSC means any SSC which has been referenced in a staff SER, TER, EA, or Environmental Impact Statement (EIS) and supplements and amendments thereof.

(c) Additionally, the licensee must obtain a license amendment unless the change, test, or experiment is consistent with the NRC conclusions, or the basis of, or analysis leading to, the conclusions of actions, designs, or design configurations analyzed and selected in the site or facility SER, TER, and EIS or EA. This would include all supplements and amendments, and TERs, EAs, EISs issued with amendments to this license.

d) The licensee's determinations concerning (b) and (c) of this condition shall be made by a Safety and Environmental Review Panel (SERP). The SERP shall consist of a minimum of three individuals. One member of the SERP shall have expertise in management (e.g., Plant Manager) and shall be responsible for financial approval for changes; one member shall have expertise in operations and/or construction and shall have responsibility for implementing any operational changes; and, one member shall be the radiation safety officer (RSO) or equivalent, with the responsibility of assuring changes conform to radiation safety and environmental requirements. Additional members may be included in the SERP as appropriate, to address technical aspects such as groundwater, hydrology, surface-water hydrology, specific earth sciences, and other technical disciplines. Temporary members or permanent members, other than the three above-specified individuals, may be consultants.

e) The licensee shall maintain records of any changes made pursuant to this condition until license termination. These records shall include written safety and environmental evaluations made by the SERP that provide the basis for determining changes are in compliance with (b) of this condition. The licensee shall furnish, in an annual report to the NRC, a description of such changes, test, or experiments, including a summary of the safety and environmental evaluation of each. In addition, the licensee shall annually submit to the NRC changed pages, which shall include both a change indicator for the area changed, e.g., a bold line vertically drawn in the margin adjacent to the portion actually changed, and a page change identification (date of change or change number or both), to the operations plan and reclamation plan of the approved license application (as updated) to reflect changes made under this condition.

[Applicable Amendment: 18]

9.4 The licensee is hereby authorized to possess byproduct material in the form of uranium waste tailings and other uranium byproduct waste generated by the licensee's milling operations authorized by this license.

The licensee is authorized to operate an ion exchange (IX) uranium recovery facility in accordance with submittals dated September 27, 1989, and October 18, 1991. Contaminated liquid and solid wastes from the IX plant shall be placed in the tailings impoundment.

The licensee is not authorized to produce any other uranium concentrates until a pre-operational inspection has been completed and any safety issues resolved. The inspection should confirm, in part, that operating procedures and approved radiation safety and environmental monitoring programs are in place, and that pre-operational testing is complete.

For monitoring purposes, the standby mode of operation is applicable for any continuous 90-day or longer period when no yellowcake is produced by the mill. The NRC shall be notified at least ninety (90) days prior to any planned resumption of uranium milling operations.

9.5 The licensee shall conduct operations in accordance with statements, representations, and conditions contained in Sections 5.2, 5.3, 5.4, and 6.0 of the original license application as revised, dated August, 1978; in Sections 2.0, 3.0, and 4.0 of the renewal application dated March 1984, as supplemented by submittals dated April 3, 1983, and January 17, 1985; and the Final Design Volume VII of the license renewal application submitted September 18, 1997, with page changes submitted April 13, June 10, July 1, and July 20,1998, and March 25, 1999; and the renewal application dated May 25, 2004, except where superseded by license conditions below.

Whenever the word "will" is used in the above referenced submittals, it shall denote a requirement.

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9.6 Standard operating procedures (SOPs) shall be established and followed for all operational process activities involving radioactive materials that are handled, processed, or stored. These SOPs for operational activities shall enumerate pertinent radiation safety practices to be followed and will be available for the pre-operational inspection.

Additionally, written procedures shall be established for non-operational activities to include in-plant and environmental monitoring, bioassay analyses, and instrument calibrations. An up-to-date copy of each written procedure shall be kept in the mill area to which it applies.

All SOPs (for both operational and non-operational activities) shall be reviewed and approved in writing by the RSO before implementation and whenever a change in procedure is proposed to ensure that proper radiation protection principles are being applied. In addition, the RSO shall perform a documented review of all existing operating procedures at least annually.

9.7 The licensee shall maintain an NRC-approved financial surety arrangement, consistent with 10 CFR 40, Appendix A, Criteria 9 and 10, adequate to cover the estimated costs, if accomplished by a third party, for decommissioning and decontamination of the mill and mill site, reclamation of any existing or approved tailings or waste disposal areas, reclamation of approved evaporation ponds, groundwater restoration, and the long-term surveillance fee. With submittal of a revised reclamation/decommissioning plan, the licensee shall submit, for NRC review and approval, a proposed revision to the financial surety arrangement, if estimated costs in the proposed plan exceed the amount covered in the existing financial surety. The NRC-approved revision to the cost estimate shall be incorporated into the next annual surety amount.

For the approved reclamation plan referenced in License Condition 10.5, the licensee shall provide the NRC-approved surety amount (adjusted for inflation) for reclamation of the proposed structures associated with resumption of mill operation (e.g., tailings impoundment, evaporation ponds, and diversion channels) before commencement of construction of any of these structures.

Annual updates to the surety amount required by 10 CFR 40, Appendix A, Criteria 9 and 10, shall be submitted to the NRC at least three (3) months prior to the anniversary date (October 30) of the approved surety arrangement. If the NRC has not approved a proposed revision to the surety coverage thirty (30) days prior to the expiration date of the existing surety arrangement, the licensee shall extend the existing surety arrangement. The revised surety amount will be in effect within three (3) months of written NRC approval.

The licensee's currently NRC-approved surety (performance bond) shall be continuously maintained in an amount no less than $10,113,000 for the purpose of complying with 10 CFR 40, Appendix A, Criteria 9 and 10, for decommissioning costs related to the existing facility, until a replacement amount is authorized by the NRC.

[Applicable Amendments: 16, 17, 18, 19, 20, 23, 24, 26, 27, 28]

9.8 The licensee shall have an archeological survey performed prior to disturbing any previously unsurveyed areas. Such surveys shall be submitted to the NRC and the State Historic Preservation Office (SHPO) for review and approval. No such disturbance shall occur until authorization to proceed has been granted by the NRC and SHPO. In addition, all work in the immediate vicinity of any buried cultural deposits unearthed during the disturbance of land shall cease until approval to proceed has been granted by the NRC and SHPO.

9.9 The licensee is hereby exempted from the requirements of Section 20.1902(e) of 10 CFR Part 20 for areas within the mill buildings, provided that all entrances to the mill buildings are conspicuously posted in accordance with Section 20.1902(e) and with the words, "Any Area Within this Mill May Contain Radioactive Material."

9.10 Decommissioning of the facility shall be performed as presented in the Final Design, Volume VI, Part 2 - “Mill Decommissioning Addendum to the Existing Impoundment Reclamation Plan,” submitted May 28, 1998, as supplemented by the response to comments submitted February 3, 1999, and the catchment basin remediation plan dated May 12, 2004, as revised July 22, 2004, December 15, 2004, January 18, 2005, and October 3, 2006. The verification results of this remediation are to be submitted to NRC for approval, as soon as reasonably possible. The catchment basin verification report and NRC’s approval letter shall be referenced in the Final Status Survey Report. Residual contamination remaining under structural foundations after the catchment basin remediation shall be removed at the time the structures are decommissioned. The NRC shall be notified and detailed SOPs for decommissioning (land and buildings) shall be available for review at least three (3) months before decommissioning begins.

[Applicable Amendments: 21, 25]

Section 10: Operational Controls, Limits, and Restrictions

10.1 The mill production per calendar year shall not exceed 4,100,000 pounds of yellowcake, as referenced in the Revised Environmental Report, dated August 1994.

10.2 All liquid effluents from mill process buildings, with the exception of sanitary wastes, shall be returned to the mill circuit or discharged to the tailings impoundment.

10.3 The licensee shall construct and operate the proposed tailings impoundment, liner system, evaporation ponds, and tailings disposal system in compliance with Volumes III, IV, and VII of the Final Design application submitted by cover dated June 11, July 23, and September 18, 1997, including page changes submitted April 13, June 10, July 1, and July 20, 1998, and March 25, and June 21,1999.

The licensee is currently authorized to construct up to eight evaporation ponds and one new impoundment. An additional two evaporation ponds and an additional five impoundments, as described in the above documents, may be constructed after: 1) notification of NRC; 2) submittal of data confirming the proposed design; and 3) an increase in the surety amount, based on the NRC-approved cost estimate for reclaiming the additional structures.

[Applicable Amendment: 17]

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	Docket or Reference Number 40-8584
	Amendment No. 28

10.4 A detailed embankment monitoring program shall be submitted for NRC approval at least three (3) months prior to placing tailings effluent.

10.5 The existing tailings impoundment, the proposed tailings impoundments, and the proposed evaporation ponds shall be reclaimed in accordance with the Final Design Volumes V, VI, and VI Part 2 of the license renewal application submitted August 1, 1997, August 20, 1997, and May 28, 1998, with page changes submitted June 10, 1998, and supplements submitted February 3, February 25, and June 21, 1999.

10.6 During any period of mill standby, the licensee shall not add tailings or other solid wastes to the tailings impoundment, except byproduct material in the form of debris generated by routine site maintenance. The licensee may add a maximum of 2,800 cubic yards of 11e.(2) byproduct material generated by Crow Butte Resources, Inc. in the course of operating its Crow Butte In Situ Leach (ISL) facility that is licensed by SUA-1534 and solid and liquid wastes from the site's IX plant. Disposal of the Crow Butte ISL materials shall be in accordance with the licensee's submittal of July 9, 1996.

During any period of mill standby at least a weekly inspection of the tailings area shall be performed and documented.

[Applicable Amendment: 22]

Section 11: Monitoring and Recordkeeping Requirements

11.1 The results of sampling, analyses, surveys and monitoring, and of calibration of equipment, as well as reports on audits and inspections, and any subsequent reviews, investigations, and corrective actions, shall be documented. Unless otherwise specified in NRC regulations or this license, all such documentation shall be maintained for a period of at least five (5) years.

11.2 The licensee shall conduct an annual survey of land use (private residence, grazing areas, private and public potable water and agricultural wells, and nonresidential structures and uses) in the area within five (5) miles of any portion of the restricted area boundary.

11.3 The licensee shall conduct a corrective action program (CAP) with the objective of returning the ground-water concentrations of chromium, natural uranium, and combined radium-226/228 to the levels referenced in “Addendum to the Revised Environmental Report, Background Ground Water Quality and Detection Standards,“ January 1996, as revised by page changes January 8, 1998 (approved by the NRC letter of May 28, 1998), and the catchment basin ground-water corrective action plan dated May 12, 2004, as revised July 22, 2004, December 15, 2004, and January 18, 2005.

The ground-water protection standards at point of compliance (POC) wells TMW-15, 16, 17, and 18, with background being defined in the above Addendum are: arsenic = 0.05 mg/L, beryllium = 0.01 mg/L, cadmium = 0.01 mg/L, chromium = 0.05 mg/L, lead-210 = 8.9 pCi/L, nickel = 0.01 mg/L, combined radium-226/228 = 5.8 pCi/L, selenium = 0.01 mg/L, thorium-230 = 7.0 pCi/L, natural uranium = 36.0 pCi/L, and gross alpha = 15.0 pCi/L, manganese = 0.2 mg/L, and iron = 0.6 mg/L.

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Pump-back wells may be added or removed from service with the goal of improving the performance of the CAP. POC, monitoring, and pump-back wells shall be sampled at the locations, at the frequency, and for the parameters provided in Table 5-1 (for existing impoundment) of the Final Design Volume VII, submitted (page change) June 21, 1999. Reporting limits for sampled constituents shall be as provided in Table 5-11 of the Final Design Volume VII, submitted April 13, 1998.

The catchment basin pump-back wells and monitoring wells TMW-92, 93, 94, 95, 97, 98, 99, 100, 101, 104, 111, 112, 113, and 115 will be sampled quarterly for diesel range and gasoline range organics and volatile organic compounds, in addition to the above constituents. The ground-water protection standards to be used to assess data from these wells are as follows: 1,1-dichloroethane = 3.0 mg/L, 1,1-dichloroethene = 0.007 mg/L, DRO = 10 mg/L, GRO = 10 mg/L, naphthalene = 1.5 mg/L, toluene = 1 mg/L, 1,1,1-trichloroethane = 0.20 mg/L, 1,2,4-trimethylbenzene = 0.012 mg/L, 1,3,5-trimethylbenzene = 0.012 mg/L, m+p xylenes = 10 mg/L, manganese = 0.2 mg/L, aluminum =1.8 mg/L, and iron = 0.6 mg/L.

[Applicable Amendments: 17, 21, 22]

11.4 Upon resumption of milling operations, the licensee shall implement a ground-water detection monitoring program for the tailings impoundment and evaporation ponds to ensure compliance with 10 CFR 40, Appendix A, in accordance with the “Addendum to the Revised Environmental Report, Background Ground Water Quality and Detection Standards,” January 1996, as revised by the submittals of January 8, 1998, and March 25, 1999; and conduct an environmental monitoring program in accordance with on-file SOPs for environmental monitoring, and in accordance with Table 5-2 of the Final Design Volume VII, submitted (page change) June 21, 1999.

[Applicable Amendment: 17]

11.5 During any period of mill standby, the licensee shall conduct an environmental monitoring program in accordance with on-file SOPs for environmental monitoring, and in accordance with Table 5-1 of the Final Design Volume VII, submitted (page change) June 21, 1999, as revised January 18, 2005.

[Applicable Amendments: 17, 21]

Section 12: Reporting Requirements

12.1 An annual report of the review of all existing operating procedures, required to be performed by the RSO, shall be prepared and retained on site.

12.2 Spills, Pond Leaks, Excursions, and Incident/Event Reporting

Until license termination, the licensee shall maintain documentation on unplanned release of source or 11e.(2) byproduct materials and process chemicals. Documented information shall include, but not be limited to: date, volume, total activity of each radionuclide released, radiological survey results, soil sample results (if taken), corrective actions, results of post remediation surveys (if taken), and a map showing the spill location and the impacted area.

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The licensee shall have procedures which will evaluate the consequences of the spill or incident/event against 10 CFR 20, Subpart "M," and 10 CFR 40.60 reporting criteria. If the criteria are met, then report to the NRC Operations Center as required.

If the licensee is required to report any spills, pond leaks, excursions of source, 11e.(2) byproduct material, and process chemicals that may have an impact on the environment, or any other incidents/events to State or Federal Agencies, a notification shall be made to the NRC Headquarters Project Manager (PM) by telephone or electronic mail (e-mail) within 48 hours of the event. This notification shall be followed, within thirty (30) days of the notification, by submittal of a written report to NRC Headquarters PM as per License Condition 9.2, detailing the conditions leading to the spill, pond leak, excursion, or incident/event, corrective actions taken, and results achieved.

[Applicable Amendment: 18]

12.3 An annual report will be submitted to the NRC that includes: (1) description of changes, tests, or experiments approved by the SERP; (2) page changes to the approved license application made by the SERP; (3) a report of the annual land use survey indicating any differences in land use from that described in the previous report; (4) a ground-water CAP review, describing the progress toward attaining the ground-water protection standards including the areal extent and concentration of hazardous constituents and estimates of the time needed to obtain compliance; (5) the ground-water monitoring report for the year; and (6) the ALARA audit report.

12.4 A completion report(s), including as-built drawings, verifying that reclamation and decommissioning of the site has been performed according to the NRC-approved plans shall be provided within six (6) months of completion of the work. The report(s) shall also include summaries of results of the quality assurance and control testing to demonstrate that the approved specifications were met.

FOR THE NUCLEAR REGULATORY COMMISSION

Date: 12/23/2009

/RA/
Keith I. McConnell, Deputy Director
Decommissioning and Uranium Recovery
Licensing Directorate
Division of Waste Management
and Environmental Protection
Office of Federal and State Materials
and Environmental Management Programs

Appendix 14

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

August 6, 1999

MEMORANDUM TO: David L. Meyer, Chief
Rules and Directives Branch
Division of Administrative Services
Office of Administration

FROM: John J. Surmeier, Chief /RA/
Uranium Recovery and
Low-Level Waste Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

SUBJECT: PUBLISHING FONSI IN THE FEDERAL REGISTER CONCERNING APPROVAL OF THE RENEWAL AND AMENDMENT OF SOURCE MATERIAL LICENSE SUA-1350

Attached please find one signed original, five copies, and an electronic version on a floppy diskette of the Federal Register Notice identified below for your transmittal to the Office of the Federal Register for publication.

☒ Notice of Finding of No Significant Impact for the proposed renewal of Source Material License No. SUA-1350 for operation and amendment for the Reclamation Plan for Kennecott Uranium Company's Sweetwater Uranium Mill Site

☐ Notice of Availability of Environmental Report

☒ Notice of Opportunity for Hearing on the proposed license amendment of Source Material License No. SUA-1350

☐ Notice of Availability of License Amendment Application for:

☐ Notice of Availability of Draft EIS for:

CONTACT: Elaine Brummett, NMSS/DWM
(301) 415-6606

☐ Notice of Availability of Final EIS for:____________________

☐ Notice of Issuance of Facility Operating License or Amendment____________________

☐ Notice of Preparation of Environmental Assessment____________________

☐ Environmental Assessment____________________

☐ Other____________________

Docket No. 40-8584
License No. SUA-1350

Attachments: As stated (7)

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[7590-01-P]

NUCLEAR REGULATORY COMMISSION

DOCKET NO. 40-8584

KENNECOTT URANIUM COMPANY

AGENCY: Nuclear Regulatory Commission

ACTION: Final Finding of No Significant Impact
Notice of Opportunity for Hearing

SUMMARY: The U.S. Nuclear Regulatory Commission (NRC) proposes to renew NRC Source Material License SUA-1350 to authorize the licensee, Kennecott Uranium Company (KUC), to resume commercial milling operations at the Sweetwater facility, and to approve the plan for future reclamation of the mill facility, existing and proposed new tailings impoundment, and the proposed evaporation ponds, according to the 1997 Reclamation Plan, as amended. The Sweetwater uranium mill site is located in Sweetwater County, approximately 40 miles (64 kilometers) northwest of the town of Rawlins, Wyoming. An Environmental Assessment (EA) was performed by the NRC staff in support of its review of KUC's license renewal for operation and the amendment request, in accordance with the requirements of 10 CFR Part 51. The conclusion of the EA is a Finding of No Significant Impact (FONSI) for the proposed licensing action.

FOR FURTHER INFORMATION CONTACT: Ms. Elaine Brummett, Uranium Recovery and Low-Level Waste Branch, Division of Waste Management, Office of Nuclear Material Safety and Safeguards, U.S. Nuclear Regulatory Commission, Mail Stop T7-J9, Washington, D.C. 20555. Telephone 301/415-6606.

SUPPLEMENTARY INFORMATION:

Background

The Sweetwater uranium mill site presently is licensed by the NRC under Materials License SUA-1350 to possess byproduct material in the form of uranium waste tailings, as well as other radioactive wastes generated by past milling operations. The mill operated from 1981 to 1983, but is currently in standby status. KUC has requested renewal of the license to allow operation of the mill (includes construction of one new impoundment and up to eight evaporation ponds), and the evaluation of that request has been completed. KUC also has requested approval of the reclamation plan to stabilize the existing tailings impoundment. In addition, the plan provides for the future stabilization of proposed new tailings impoundments, reclamation of land, and decommissioning of the mill facility.

Construction of an additional five new impoundments and two evaporation ponds may be requested if the mill operates for 20 years, and the impact of this was considered in the EA. The additional impoundments would be reclaimed according to the NRC-approved plan and any change in design would require review and approval by the NRC staff.

KUC submitted the operations plan, reclamation plan, and associated information by letters dated June 11, July 3, July 23, August 1, August 20, September 18, and October 7, 1997. The mill and land decommissioning plan portion of the reclamation plan was submitted May 28, 1998. Page changes to various submitted documents and responses to NRC staff comments were provided June 10, July 1, and July 20, 1998, as well as February 3, February 25, March 25, April 21, and June 21, 1999.

Summary of the Environmental Assessment

The NRC staff performed an assessment of the environmental impacts associated with the operations plan and reclamation plan, in accordance with 10 CFR Part 51, Licensing and Regulatory Policy Procedures for Environmental Protection. The license renewal would authorize KUC to resume operation of the mill at a maximum production rate of 4,100,000 pounds (1,859,748 kg) of yellowcake per year, and to possess byproduct material in the form of uranium waste tailings and other uranium byproduct wastes generated by the authorized milling operations. The actual resumption of operations will be conditional on: 1) the NRC review of standard operating procedures for mill operation; 2) a 90-day pre-startup notification to NRC; and 3) the completion of a pre-startup NRC inspection and resolution of any safety issues identified by the inspection. The renewed license also would approve KUC's proposed plan to stabilize and cover the tailings impoundments, and decommission the mill facility (including land and evaporation ponds). All conditions in the renewed license and commitments presented in the licensee's renewal documents are subject to NRC inspection.

In conducting its appraisal, the NRC staff considered the following: (1) information contained in KUC's 1997 license renewal and amendment requests, as revised; (2) previous environmental and safety evaluations of the facility; (3) data contained in land use and environmental monitoring reports; (4) existing license conditions; (5) results of NRC staff site visits and inspections of the Sweetwater facility; and (6) consultations with the U.S. Fish and Wildlife Service, the U.S. Bureau of Land Management, the Wyoming State Historic Preservation Officer, and the Wyoming Department of Environmental Quality. The staff evaluation of the Sweetwater operation plan and associated documents is being evaluated in a

Safety Evaluation Report, and the technical aspects of the reclamation plan are discussed separately in a Technical Evaluation Report that will accompany the final agency licensing action.

The results of the staff environmental review are documented in an EA placed in the docket file. Based on its review, the NRC staff has concluded that there are no significant environmental impacts associated with the proposed action.

Conclusions

The NRC staff has examined actual and potential impacts associated with the operation of the mill, site decommissioning, and reclamation of the tailings impoundments, and has determined that the requested renewal of Source Material License SUA-1350 will: (1) be consistent with requirements of 10 CFR Part 40, Appendix A; (2) not be inimical to public health and safety; and (3) not have long-term detrimental impacts on the environment. The following statements summarize the conclusions resulting from the staff's environmental assessment, and support the FONSI:

1. An acceptable environmental and effluent monitoring program is in place to monitor effluent releases and to detect if applicable regulatory limits are exceeded. Radiological effluents from facility operations have been and are expected to remain below the regulatory limits;
2. Mill tailings and process liquid effluents from the mill circuit will be discharged to a multi-lined impoundment with a leak detection system;
3. The licensee will conduct site decommissioning and reclamation activities in accordance with NRC-approved plans; and

4. Present and potential health risks to the public and risks of environmental damage from the proposed mill operation, decommissioning, and reclamation were assessed. Given the remote location, requirements in place, licensee's inspection and radiation safety programs, area of impact, and past activities on the site, the staff determined that the risk factors for health and environmental hazards are insignificant.

Because the staff has determined that there will be no significant impacts associated with approval of the license renewal (and associated amendments), there can be no disproportionally high and adverse effects or impacts on minority and low-income populations. Consequently, further evaluation of Environmental Justice concerns, as outlined in Executive Order 12898 and NRC's Office of Nuclear Material Safety and Safeguards Policy and Procedures Letter 1-50, Revision 1, is not warranted.

Alternatives to the Proposed Action

The proposed action is to renew NRC Source Material License SUA-1350, for operation of the mill, subsequent decommissioning of the facility, and reclamation of the tailings impoundments, as requested by KUC. Therefore, the principal alternatives available to NRC are to:

1. Approve the license renewal request as submitted; or
2. Renew the license with such additional conditions as are considered necessary or appropriate to protect public health and safety and the environment; or
3. Deny the renewal request.

Based on its review, the NRC staff has concluded that the environmental impacts associated with the proposed action do not warrant either the limiting of KUC's future operations or the denial of the license amendment. Additionally, in the TER prepared for this action, the staff has reviewed the licensee's proposed action with respect to the criteria for reclamation, specified in 10 CFR Part 40, Appendix A, and has no basis for denial of the proposed action. Therefore, the staff considers that Alternative 1 is the appropriate alternative for selection.

FINDING OF NO SIGNIFICANT IMPACT

The NRC staff has prepared an EA for the proposed renewal of NRC Source Material License SUA-1350. On the basis of this assessment, the NRC staff has concluded that the environmental impacts that may result from the proposed action would not be significant, and therefore, preparation of an Environmental Impact Statement is not warranted.

The EA and other documents related to this proposed action are available for public inspection and copying at the NRC Public Document Room, in the Gelman Building, 2120 L Street N.W., Washington, DC 20555.

Notice of Opportunity for Hearing

The Commission hereby provides notice that this is a proceeding on an application for a licensing action falling within the scope of Subpart L, "Informal Hearing Procedures for Adjudications in Materials and Operators Licensing Proceedings," of the Commission's Rules of Practice for Domestic Licensing Proceedings and Issuance of Orders in 10 CFR Part 2 (54 FR 8269). Pursuant to § 2.1205(a), any person whose interest may be affected by this proceeding may file a request for a hearing. In accordance with § 2.1205(c), a request for a hearing must be filed within thirty (30) days from the date of publication of this FEDERAL REGISTER notice. The request for a hearing must be filed with the Office of the Secretary either:

(1) By delivery to the Rulemakings and Adjudications Staff of the Office of the Secretary at One White Flint North, 11555 Rockville Pike, Rockville, MD 20852; or

(2) By mail or telegram addressed to the Secretary, U.S. Nuclear Regulatory Commission, Washington, DC 20555, Attention: Rulemakings and Adjudications Staff.

Each request for a hearing must also be served, by delivering it personally or by mail to:

(1) The applicant, Kennecott Uranium Company, P.O. Box 1500, Rawlins, WY 82301;

(2) The NRC staff, by delivery to the Executive Director of Operations, One White Flint North, 11555 Rockville Pike, Rockville, MD 20852; or

(3) By mail addressed to the Executive Director for Operations, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

In addition to meeting other applicable requirements of 10 CFR Part 2 of the Commission's regulations, a request for a hearing filed by a person other than an applicant must describe in detail:

(1) The interest of the requestor in the proceeding;

(2) How that interest may be affected by the results of the proceeding, including the reasons why the requestor should be permitted a hearing, with particular reference to the factors set out in § 2.1205(g);

(3) The requestor's areas of concern about the licensing activity that is the subject matter of the proceeding; and

(4) The circumstances establishing that the request for a hearing is timely in accordance with § 2.1205(c).

Any hearing that is requested and granted will be held in accordance with the Commission's "Informal Hearing Procedures for Adjudications in Materials and Operator Licensing Proceedings" in 10 CFR Part 2, Subpart L.

Dated at Rockville, Maryland, this 6 day of August 1999

FOR THE NUCLEAR REGULATORY COMMISSION

John Surmeier

John J. Surmeier, Chief
Uranium Recovery and
Low-Level Waste Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

Appendix 15

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION VIII
999 18th STREET - SUITE 500
DENVER, COLORADO 80202-2466

RECEIVED
MAR 26 1996
O. PAULSON

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Ref: 8P2-TX

Oscar A. Paulson, P.G., Supervisor
Sweetwater Uranium Facility
Kennecott Uranium Company
P.O. Box 1500
Rawlins, WY 82301

Dear Mr. Paulson:

This follows our conversation of March 12, 1996, and responds to your correspondence of September 13, 1995, as addressed to Bryon Bunger of EPA's Office of Radiation and Indoor Air.

Your September 15, 1995, correspondence proposes to level tailings within the existing impoundment, instal a new liner system with leak detection capability, and then place the impoundment back into use upon the commencement of milling operations. Your interpretation of 40 CFR Part 61 Subpart W would retain this unit under the definition of "Existing impoundment" as referenced by 61.250(d). This interpretation would allow for the construction and use of one additional impoundment per 61.252(b)(1).

This office concurs with your interpretation of the referenced regulations. Please be reminded that the modified existing impoundment as well as any other subsequent impoundments constructed under 61.252(b)(1) will need with the Radon-222 Emission Standard per 61.252(a).

This office is also in receipt of your February 13, 1996, 40 CFR Part 61 Supart I submittal. Relating to a broad reorganization of the Region VIII EPA offices, please direct all appropriate submittals (Subpart I,W, et.) to myself.

Should you have any questions or comments concerning this letter, please direct them to Mr. Lon Q. Hesla at (303) 312-6036 of my immediate staff or also feel free to contact me directly.

Sincerely,

Milton W. Lammering, Director
Toxics Program

cc: Bryon Bunger - ORIA/HQ
Charlotte Abrams NRC c/o
Uranium Recovery Branch
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Appendix 16

Kennecott Uranium Company
Sweetwater Uranium Project
Tailings Impoundment Radon Release Calculations

Using the average flux for the exposed tailings and the average exposed tailings area (1990 to 2011)

Average Flux (tailings): 8.69 picoCuries per meter2-sec

Average Total Area: 161,809.89 Square meters
Average Ponded Area: 74,103.72 Square meters
Average Exposed Tailings Area: 87,704.82 Square meters

Mill	**Total Area Square meters**	**Ponded Square meters**	**Wet Square meters**	**Dry Square meters**	**Years 15 Curies**	**Years 5 Curies**	**Years 50 Curies**	**Total Years 70 Curies**
Sweetwater	161,809.89	74,103.72	0	87,704.82	361	120	1202	1682

Using the average flux for the entire impoundment and the average impoundment area (1990 to 2011)

Average Flux (impoundment): 4.65 picoCuries per meter2-sec

Total Area: 161,809.89 Square meters
Ponded Area: 74,103.72 Square meters
Average Exposed Tailings Area: 87,704.82 Square meters

Mill	**Total Area Square meters**	**Ponded Square meters**	**Wet Square meters**	**Dry Square meters**	**Years 15 Curies**	**Years 5 Curies**	**Years 50 Curies**	**Total Years 70 Curies**
Sweetwater	161,809.89	74,103.72	0	87,704.82	356	119	1186	1661

OAP:4/4/12
radon_releases.xls

Appendix 17

UNITED STATES
NUCLEAR REGULATORY COMMISSION
Office of Public Affairs
Washington, D.C. 20555

No. S-28-94
Tel. 301-415-8200

Remarks by Dr. E. Gail de Planque
Commissioner, U.S. Nuclear Regulatory Commission
before the
NRC Workshop on Site Characterization for Decommissioning
Rockville, Maryland
November 29, 1994

In Search of . . . Background

It is a pleasure to be here this morning at the NRC Workshop on Site Characterization for Decommissioning. I'm so pleased to see so many in attendance because I think that the issue of decommissioning is one of the most significant issues on the Commission's plate, one that will have long lasting and far reaching impacts.

Introduction

As you know, the NRC is undergoing a lengthy process aimed at formulating radiological criteria for the decommissioning of NRC-licensed facilities. During that process, extensive discussions have focused on four possible approaches to this task: (1) establishing an annual risk or dose limit for an individual; (2) establishing an annual risk or dose goal; (3) requiring use of the best available technology; or (4) requiring return of the site to background radioactivity. While many commenters preferred a risk-based or dose-based standard, many others favored the "return-to-background" approach.

The proposed rule attempts to accommodate both groups by establishing a dose limit for release of the site of 15 millirem per year Total Effective Dose Equivalent (TEDE) for residual radioactivity distinguishable from background with further reductions As Low As Reasonably Achievable, or ALARA.

First, an aside. To make life easier, I will usually use the quantity total effective dose equivalent expressed in units of mrem. But for brevity's sake, I will use the term "dose" when speaking of total effective dose equivalent.

The objective expressed in the proposed rule is to cleanup up to dose levels that are indistinguishable from background. Return to background!

Sounds good, doesn't it? On the surface, this seems like a relatively easy, common-sense approach: for example, survey a nearby spot unaffected by a nuclear facility, use that radiation level as a baseline, clean up the contaminated site to that level, and . . . voila! The site is decommissioned, the method indisputable, the job completed.

But, as we all know, the devil is in the details. And in this case, the devil could produce a series of torments for those involved in returning a site to background.

I'd like to discuss some of the details with you this morning, particularly the details that are relevant to determining what background is and how it is measured. But I'd also like to place this discussion of the details within the broader context of a regulatory decision-making process.

Risk-Based Decision-Making

The decision-making process I'm referring to is "risk-based" decision-making, a process gaining popularity both in the Clinton Administration and in Congress, and widely advocated by the most recent Supreme Court member, Justice Stephen Breyer. Let me say at the outset that as far as I know this particular mode of making decisions was not followed in any rigorous way in formulating the proposed rule. Nevertheless, for reasons which I hope will be clear later in this talk, it may offer a useful framework for working out the details of a decommissioning program.

Risk-based decision-making allows for the assumption that the resources available for limiting risks are not inexhaustible and seeks to ensure that the resources which are available to society as a whole will be put to the best overall use considering risk, cost and benefit. It can be divided into three basic components as illustrated by the following Sydney Harris cartoons: (1) risk assessment, (2) selection of an acceptable level of risk, and (3) risk management. In the context of decommissioning, risk assessment is an evaluation of the hazard associated with residual radioactivity remaining at a site released for unrestricted or restricted use. Selection of an acceptable risk level involves weighing the benefits of lowering risk to a certain level against the costs and may involve comparing the risk at issue with other similar risks confronting society. Risk management consists of a regulatory process designed to keep the risk below the level found to be acceptable.

Risk Assessment

As the NRC begins to formulate a regulatory program to manage the risk associated with sites cleaned up to levels of radiation contamination that are indistinguishable from background, it might be useful to revisit Step 1 of the risk-based decision-making process: risk assessment. Perhaps this can most easily be done by reviewing the levels of radiation to which humans are typically exposed and the health consequences of those levels.

Broadly speaking, the average American's annual radiation dose is attributable to two sources: naturally occurring radiation which, in the U.S., produces about 82% of the dose, and anthropogenic radiation which produces the remaining 18%. Humans are bathed in a sea of naturally-occurring radiation which has been present since the formation of the earth. About 56% of the average annual dose is from radon and its decay products. Another 11% is from other internal sources, mainly from inhalation and ingestion of food and water which contain naturally occurring radioactive elements. The remainder is from external sources, about 7.5% from cosmic rays and about 7.5% from terrestrial gamma ray sources such as uranium, potassium, and thorium, that are present naturally in soil and rocks.

Just to complete the picture, let's look at the anthropogenic sources. About 11% of the average annual dose comes from medical x-rays, about 4% from nuclear medicine, and about 3% from consumer products such as smoke detectors. The small remainder is from fallout from weapons testing, and occupational exposures at various nuclear facilities.

The proposed rule defines "background radiation" as:

> radiation from cosmic sources; naturally occurring radioactive material, including radon (except as a decay product of source or special nuclear material); and global fallout as it exists in the environment from the testing of nuclear explosive devices or from past nuclear accidents like Chernobyl which contribute to background radiation and are not under the control of the licensee.

Although naturally-occurring radiation and fallout from atmospheric weapons testing and the Chernobyl accident are present everywhere, each of these components of what I'll refer to as background, and the corresponding dose delivered, is by no means constant. Background levels fluctuate significantly due to various physical phenomena that differ from place to place and change with time at any given place. For example, over the long-term, cosmic radiation varies by about 10% over the 11 year solar cycle. Seasonal cycles produce changes in soil moisture, rainfall, snow cover, and evapotranspiration that cause variations in the dose from terrestrial gamma radiation, fallout and radon. Many sporadic geophysical phenomena, volcanic eruptions or earthquakes for example, can also introduce radioactivity into the environment.

Temporal variations can also occur over the short term. Rain, for example, will wash out radon and other radionuclides from the air causing an immediate rapid increase in dose that typically decreases exponentially after the rain stops. Doses from radon typically exhibit a diurnal cycle due to local climate conditions.

Radiation varies spatially. The dose from cosmic radiation is a function of both latitude and altitude. The population of the city of Denver, at an altitude of a mile receives an annual cosmic ray dose that is a factor of 2 higher than the U.S. average. Terrestrial gamma radiation, including fallout, varies from place to place because of differing amounts of uranium, potassium and thorium in the earth's surface material and can easily differ by a factor of 10 across the country. Granite, for example, contains higher than average uranium concentrations and monazite sands can have particularly high concentrations of thorium. Furthermore, humans sometimes alter soil content with fertilizer which contains varying amounts of potassium-40. Spatial variations occur locally as well; the well-known Reading Prong in New Jersey provides an interesting regional example. The average annual dose from gamma radiation is approximately 50 mrem but if one resides closer to the rock formations along the prong, the annual dose can be much greater. About sixty miles away at the New Jersey shore, the gamma radiation dose levels fall to less than 10% of the average measured over the Prong.

Even in the immediate environment of a typical facility site (this happens to be Shoreham, Long Island), significant fluctuations occur (Figure 1). For this site with an annual average terrestrial gamma dose of about 35 mrem, when measured simultaneously, levels varied by more than 50% over a distance of only a mile within the site boundary, and the areas within a 4- or 5-mile radius of the site exhibited variations with even greater extremes.

This site in rural New Jersey, used as a background monitoring station, is only 50' by 200' (Figure 2). And even within such a small area, simultaneously measured terrestrial gamma radiation dose levels, which average about 125 mrem per year, differ by as much as 30% from spot to spot. That translates into differences of close to 40 mrem per year.

Other local variations occur due to the types of houses and buildings in which people live and work. Persons living in a wood frame house usually receive lower doses than persons living in an all brick house because, even though brick is a better shield of outdoor radiation, it has higher concentrations of naturally occurring radioactivity than wood. Persons working in granite and marble buildings may receive higher doses due to the radioactivity in the stone. Even moving from a rural to an urban setting may increase an individual's annual dose, due to the level of radioactivity present in concrete. The dose from cosmic rays can be measurably higher on the top floor of a high rise than on the ground floor. Measurements in a 12 story building in Manhattan indicated a cosmic ray dose on the ground floor one third that on the 12th floor, due principally to the shielding effect provided by many stories of concrete from the building in question as well as adjacent structures. In addition, a person's annual dose from radon can vary dramatically, by a factor of 10 or more, depending upon where they are and the adequacy of ventilation.

To further complicate matters, these temporal and spatial variations can be interdependent. For example, determining the average annual dose received from terrestrial gamma radiation cannot be done simply by measuring differences in soil concentration, since it is also affected by weather conditions. Moreover, usage must be considered and can result in what is often referred to as technologically enhanced natural background radiation. Finally, the actual dose to particular humans is heavily dependent upon the specific external and internal pathways of exposure.

Obviously then, there is no single number that represents the annual dose to U.S. citizens from background. But for perspective, it is useful to know that the average annual background dose for the U.S. population is about 300 mrem with about 200 mrem from radon, about 40 mrem from other internal sources, about 25 mrem from cosmic rays and about 25 mrem from terrestrial gamma rays. The average annual dose from fallout is less than 1 mrem.

However, because of the many factors that cause both spatial and temporal variations, the annual U.S. dose from background can easily range from 100 mrem for people who live in well-ventilated wooden houses on sandy soil at sea level to about 1000 mrem for people living in the Denver area, a factor of 10 (Figure 3). At the Shoreham site, annual doses from terrestrial gamma radiation differed with location alone by as much as 25 mrem per year. At the small New Jersey site, the equivalent spot to spot difference was as high as 40 mrem per year. It is in the context of these variations that the selection of 15 mrem over background as the acceptable annual dose for residual radiation from a decommissioned site must be viewed. For additional perspective, consider that we rarely choose our residences or domestic habits based on exposure to background radiation, yet the choice to live in a brick rather than a wood-frame house can increase one's annual dose by 45 or 50 mrem. A gas stove can deliver about 15 mrem per year to the lungs due to naturally occurring radioactive elements in the gas and a single flight across the U.S. yields about 4 mrem. A Denver resident can receive double the cosmic ray dose, triple the terrestrial dose, quadruple the radon dose, and a higher intake of radionuclides in drinking water compared to persons living in a coastal region--and if the house is not well ventilated the total dose could be still higher!

Selection of an Acceptable Level of Risk

To place the risk from exposure to background radiation in context, let's look at some general risks to the population. About 33% of the general population in the United States die of heart disease and about 23% die of cancer. Non-cancerous lung disease (7.7%), strokes (6.7%) and accidents (4.3%) also figure strongly as major causes of death (Figure 4). Comparing these causes of death, all of which carry a risk of greater than 1%, with the elective or accidental risks faced by selected groups or by the general population illustrates the complexity of adding societal choice to risk-based decision-making in terms of selection of an acceptable level of risk (Figure 5). Smoking one pack of cigarettes daily will result in death from a related cause for about 28% of smokers and a motorcyclist has about an 11% lifetime chance of dying in a motorcycle accident. By comparison, the average American's risk of dying in an air accident is several orders of magnitude lower, about 0.02%.

As I said earlier, the annual dose from natural background in the U.S. ranges from 100 to 1,000 mrem with an average of about 300 mrem. When relating these annual doses to risk, the risk assessment models developed by the International Commission of Radiological Protection (or ICRP) are usually applied. The ICRP performs risk assessments for both deterministic and stochastic effects of exposure to radiation based on research reports of radiation effects on tissues and animals, as well as on human epidemiology studies and modeling. For the purposes of radiation protection, the ICRP *assumes* a linear non-threshold dose-effect model and basically extrapolates to estimate the probability of harm resulting from low doses and dose rates where there is little, if any, human health effects data.

Using ICRP's method of risk assessment, the average annual 300 mrem dose from background produces a lifetime risk of fatal cancer of slightly less than 1 in 100, or approximately 0.82%. The corresponding lifetime fatal cancer risk for 100 and 1000 mrem are approximately 0.27% and 2.7%, respectively (Figure 6).

So how would an additional increment of 15 mrem change the public's risk from natural background? Looked at in isolation, 15 mrem per year over a 70-year lifetime would result in a risk of about 0.04% yet another decade lower on this log scale. When added to the risks associated with low, average, and high annual doses from background it is barely distinguishable (Figure 7). Indeed 15 mrem represents 5% of the average annual dose and is lost within the range of background which spans a factor of 10.

It is perhaps useful to note that for members of the public, the NCRP recommends an annual limit of 100 mrem for continuous exposure and an annual limit of 500 mrem for infrequent exposures due to all anthropogenic sources and recommends that ALARA be practiced below that. They further recommend that where there are multiple sources, no single source or set of sources under one control should result in an individual being exposed to more than 25 mrem annually.

What does one conclude from all of this? The limit of 15 mrem, including 4 mrem from drinking water which in itself is material for a lengthy lecture which I won't attempt to address here, carries a risk that is a small increment over the risk from background itself. Given that the risk is small and masked by the variation in the risk over the range of background doses, one must ask what all this should imply for the third or final component of risk-based decision-making, risk management.

Risk Management

The major questions for risk management are: (1) What is it that will be measured or used to represent "background" at a particular decommissioning site? (2) What will be measured to determine compliance with the 15 mrem limit? and (3) What margins of error or what uncertainties will be considered acceptable in determining compliance?

The difficulties involved in answering these questions become apparent when a site's decommissioning efforts are broken down into a series of steps and the complications that can exist with each step are examined. The overall process consists of, first, an analysis of the activities that have been performed at the site to be decommissioned; second, an assessment or survey to establish what represents background and a survey of the site to determine the degree of cleanup required; third, cleanup; fourth, a resurvey of the site; and, finally, release of the decontaminated site.

Each of these activities can be further broken down into sub-steps. For example, the person performing an analysis of the activity at the site must ask a series of questions: (1) Did the licensed activities involve single or multiple radionuclides? (2) With respect to each radionuclide, does it also exist in background or is it only produced as a result of licensed activities at the site? (3) For each radionuclide, are there single or multiple pathways that may result in exposure to humans?

Surveying also has multiple sub-steps. Survey methods and the required number of surveys of each type must be determined to establish the background level or levels. The corresponding number of site surveys that will be necessary to establish the level of residual radioactivity on site with reasonable confidence must be determined and the background surveys and initial site surveys must then be performed.

The site is now ready for cleanup. Based on the analysis and survey results, the appropriate methods must be chosen and cleanup performed with periodic re-surveying to determine the level of progress until the release criteria are met and the site is ready for release.

Let's consider a few examples of how this process actually works. First, consider a simple example in which the residual radioactivity involves a single, non-naturally occurring nuclide. For simplicity's sake, postulate that the radionuclide has only one pathway of exposure. This will result in a single set of surveys, presumably a single method of decontamination, and a straightforward path toward releasing the site.

For a second example, let's consider a slightly more complicated scenario, involving multiple naturally occurring nuclides, at least one of which is known to result in human exposure via several pathways. This analysis is still relatively simple, but the surveys will be somewhat more complex. In this situation background will have to be established in a manner that accounts for variability, and that will differentiate quantitatively between background radiation and that produced by site activities. The clean-up may also be somewhat more complex due to the multiple nuclides and pathways of exposure.

The third scenario, unfortunately, may be the most realistic picture for most licensees, including reactor facilities. In this case, the analysis may involve a whole spectrum of radionuclides, some, but not all, of which occur in background. It may also involve a variety of interrelated pathways of human exposure. As a result, establishing background becomes much more complicated, even for a site with a detailed pre-operational survey. Multiple elements of spatial and temporal variation will complicate this scenario further, requiring a higher number of surveys and sometimes multiple methods to achieve the necessary degree of confidence. The decontamination of such a site, of course, will be correspondingly more difficult, involving multiple clean-up methods and, quite possibly, repeated attempts, with re-surveys performed as necessary until the criterion of 15 mrem above background has been met and the site is ready for unrestricted release.

How does this affect cost, certainly an element in risk-based decision-making? Survey costs alone, not even considering cleanup costs, will vary based on the complexity of the situation considering the number of surveys taken and the quality of those surveys in terms of the degree of confidence required, or level of uncertainty considered acceptable.

Consider the cost per sample of various radiation measurements likely to be used in any major decommissioning effort (Figure 8).[1] Assessing the potential radiation dose to humans for a multi-nuclide site could require a complete pathway analysis, including measurements of external gamma dose; air, soil and vegetation samples; and samples of surface water, drinking water, and precipitation. Obviously, to attempt to sample and measure every cubic meter of the relevant environment would be both impractical and prohibitively expensive. Instead, a sampling strategy must be developed combining radiation survey readings over large areas with selective sampling and analysis at representative locations, using the results of past measurement programs as appropriate.

Even with an efficient sampling strategy, however, the cost of performing surveys just to establish background can escalate sharply depending on the degree of uncertainty that is acceptable, which will directly influence both the survey methods employed and the number of surveys taken. In general, measuring smaller doses means increasing costs as more sophisticated techniques are employed.

Similarly the costs of site surveys and decontamination increase based on the background criteria employed and the level of sensitivity and confidence desired. For some radionuclides, the detection limits of standard laboratory instruments can be reached, causing the survey costs to rise dramatically as sophisticated research techniques become necessary. For naturally occurring radionuclides or those present in residual levels from weapons fallout, it may be virtually impossible to distinguish the contribution of site activities given the spatial and temporal variations in background discussed earlier.

Just as an example, consider the cost of measuring cesium-137 in soil (Figure 9).[2] At dose increments of about 30 mrem per year or higher, the cost is about $50 per sample. The cost roughly quadruples when trying to measure at levels of 10 mrem per year or less--based on the need for more sensitive laboratory methods--and increases dramatically again, to about $500 per sample, when measuring at a level of 0.3 mrem per year, which requires sophisticated research techniques. Because cesium-137 is present in residual radioactivity from weapons fallout, the typical levels and degree of variability make the cost of measuring this radionuclide at dose increments of 0.1 mrem per year more or less indeterminate.

What all this reveals is that every assessment of dose due to either natural or anthropogenic radiation will entail some degree of uncertainty. Whether that uncertainty stems from spatial or temporal variations, the limitations of the measurement technique, or the ability of the analyst to interpret data, it is still uncertainty, and it can never be entirely eliminated. Now let's review how the compliance process might work. First, background (χ_a) must be

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[1] NUREG-1496, Vol 2, "Generic Environmental Impact Statement in Support of Rulemaking on radiological Arteria for Decommissioning of NRC-Licensed Nuclear Facilities," Appendices, p. A-44, August, 1994.

[2] NUREG-1496, Vol 2, "Generic Environmental Impact Statement in Support of Rulemaking on radiological Arteria for Decommissioning of NRC-Licensed Nuclear Facilities," Appendices, p. A-53, August, 1994.

determined. But, unless it is zero, this is clearly not well-defined and carries an uncertainty (σ_o). To determine if cleanup is sufficient, the site must be surveyed to determine what remains (χ_1) which may or may not include natural background as discussed earlier. This, too, of course, carries an uncertainty (σ_1). Compliance requires that what remains after cleanup not contribute more than 15 mrem above background.

In addition, the proposed rule requires that further reductions be made As Low As Reasonably Achievable. Defining ALARA, in this framework, might be much more problematic than when working with higher, more readily measurable doses. Can ALARA be assigned a cost-per-dose-increment value, as is done for occupational exposures? Is it simply a matter of vague principle? And how will it take into consideration other risks, such as those associated with the decommissioning activities themselves? These are the questions of the risk management phase of risk-based decision-making.

Now let us return to the framework of risk-based decision-making which is premised on balancing risk, cost, and benefit. To implement the 15 mrem criterion, as well as ALARA, in this context, one needs to ask at least two fundamental questions:

1) How should both background and residual radioactivity be defined or measured in practical terms, and what degree of uncertainty will be considered acceptable? Recall from the examples of our earlier discussion that if one takes into account spatial or temporal variations of background, not to mention measurement uncertainties, the sigma may easily be of the same order as, or even multiples of, the 15 mrem criterion.

2) The second question follows naturally from the first: given that the risk associated with a 15 mrem residual dose adds very little to the risk of exposure to background and indeed is buried in the noise of the natural variations of that background, then how much money and effort should be spent not only to clean up to this level, but to assure compliance?

Conclusion

These are among the questions that we, as regulators, licensees, and members of the public must consider as we proceed toward final decommissioning rulemaking. And remember, I've only touched the surface. For example, we haven't even discussed the proposed 4 mrem criterion for the water pathway and the associated risk management scheme necessary to assure compliance. These are challenges of risk-based decision-making as we all go in search of background.

In this endeavor, I would urge that we be ever mindful of our goal as captured in the NRC's mission, that is, "to help assure that the use of nuclear materials is carried out in such a way that public health and safety, the common defense and security and environment are protected," and that we be mindful of the principles of good regulation, namely, independence, openness, efficiency, clarity, and reliability. This is our challenge as we strive to protect the citizens of our nation and fulfill our responsibilities as stewards of our planet. I, for one, welcome the challenge, daunting as it may seem, and I look forward to the contributions and participation of all parties as we proceed toward what I hope will be rational and responsible final rulemaking.

#

RELATIVE TERRESTRIAL GAMMA RADIATION LEVELS (MAY 1974)

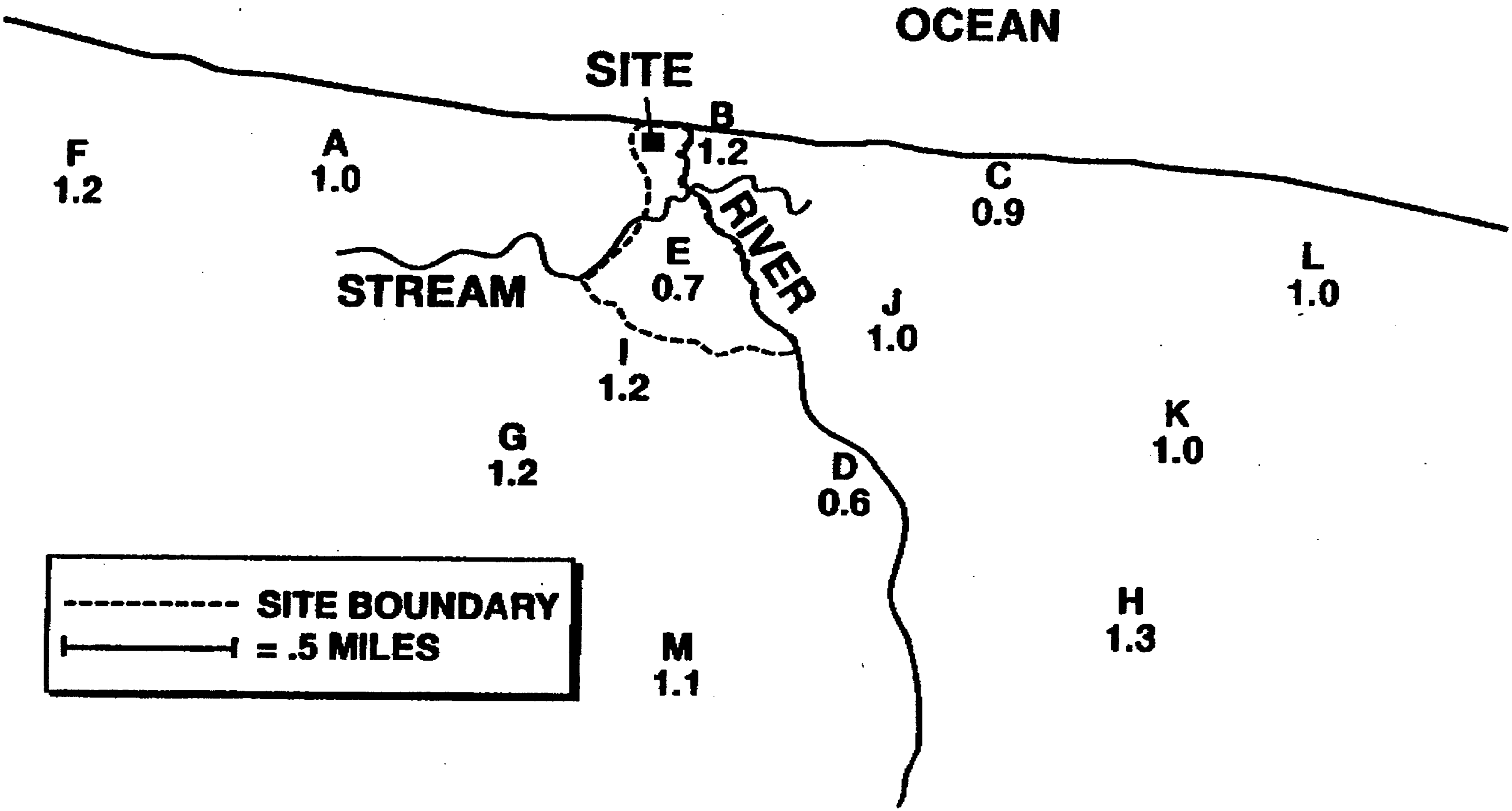


FIGURE 1

RELATIVE TERRESTRIAL GAMMA RADIATION LEVELS (SEPTEMBER 1974)

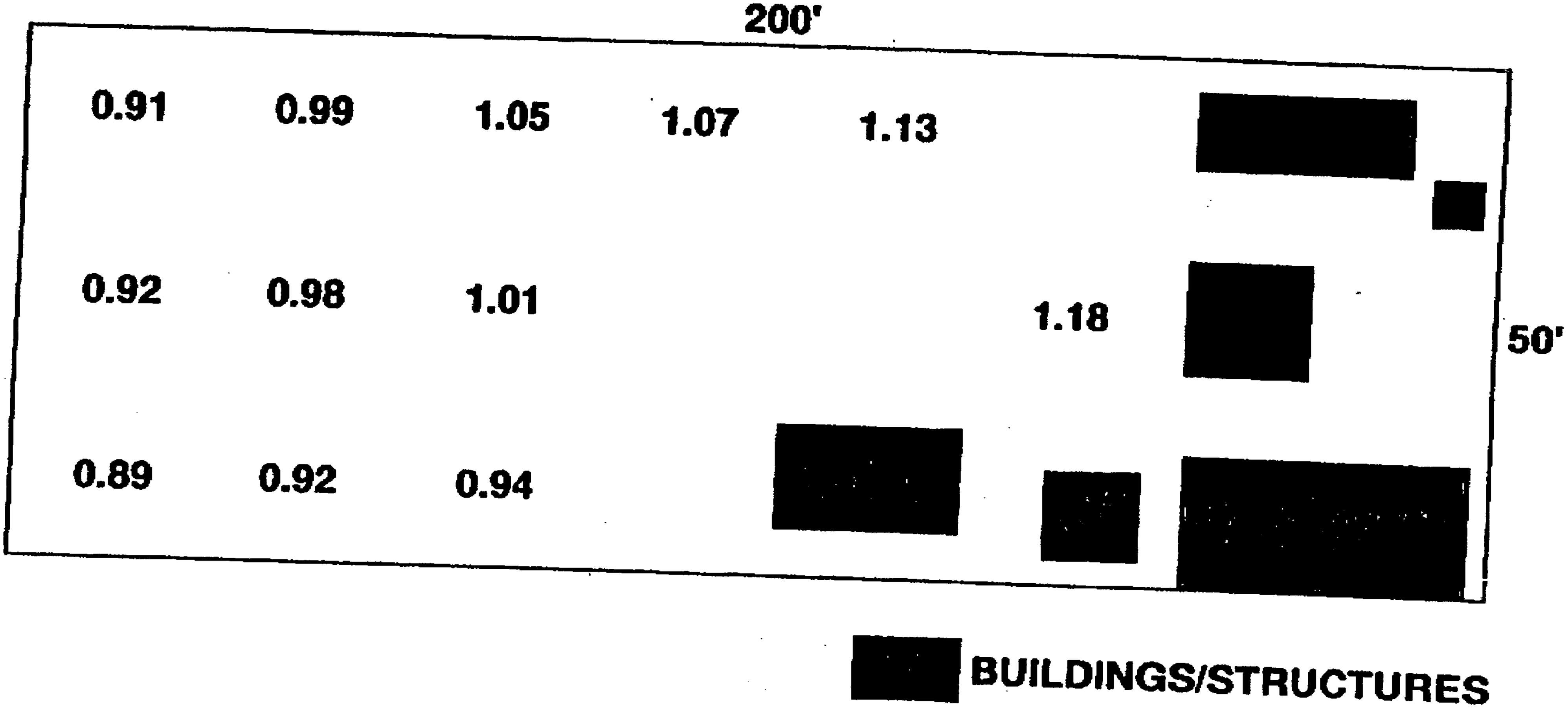


FIGURE 2

RANGE OF ANNUAL RADIATION DOSE: NATURAL SOURCES (MREM)

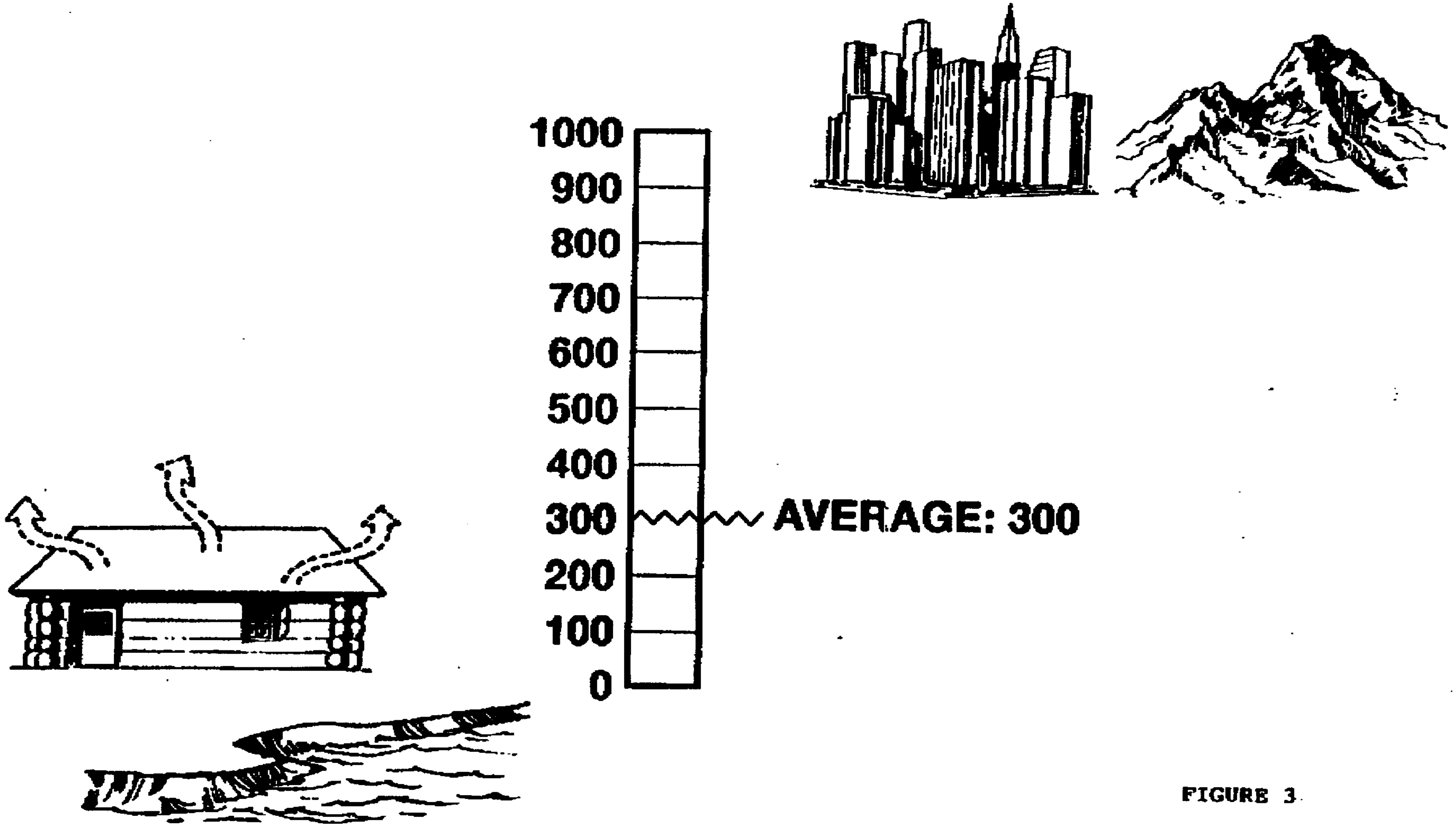


FIGURE 3

LIFETIME MORTALITY RISKS
(PERCENT OF GENERAL POPULATION)

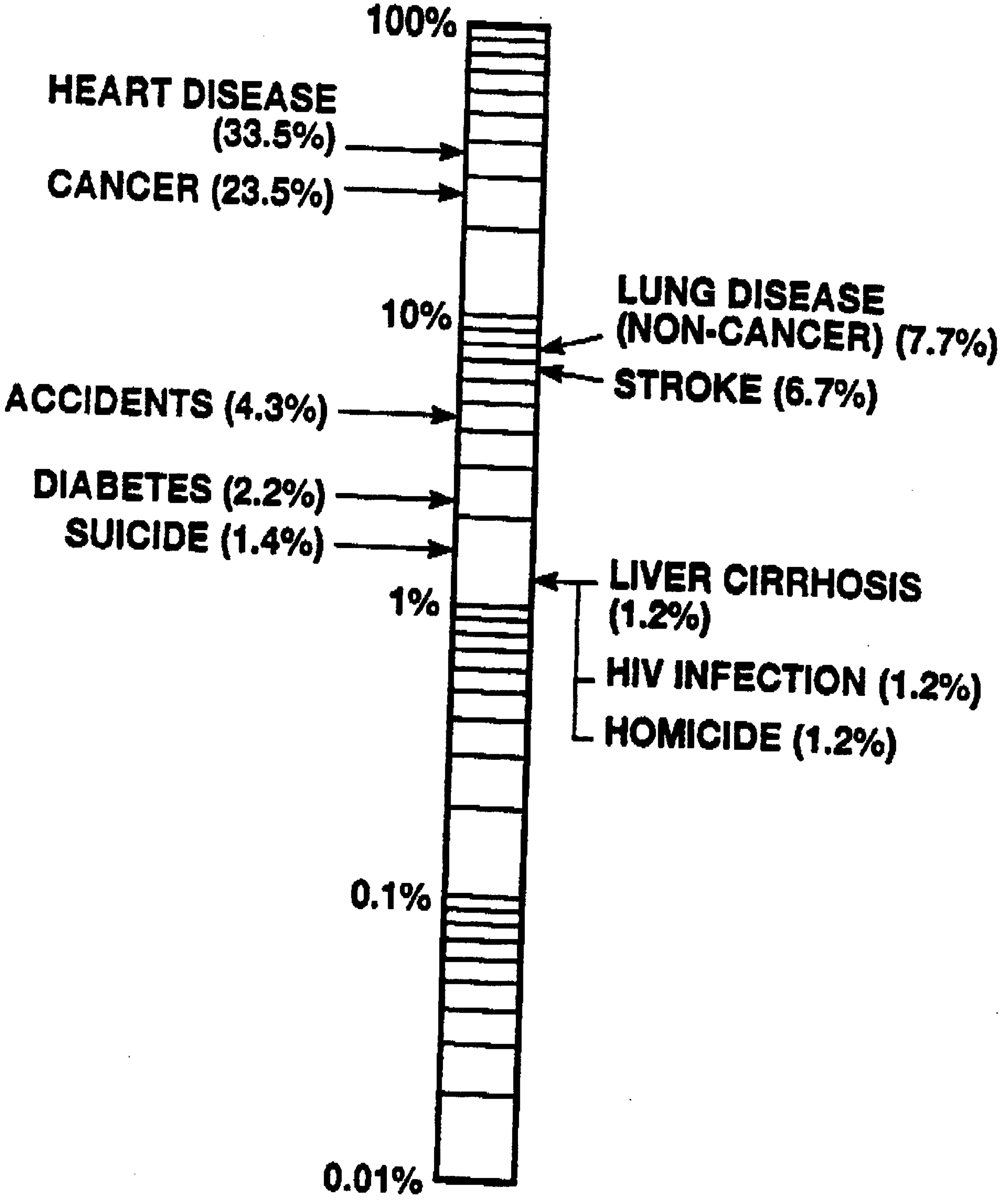


FIGURE 4

LIFETIME MORTALITY RISKS
(PERCENT)

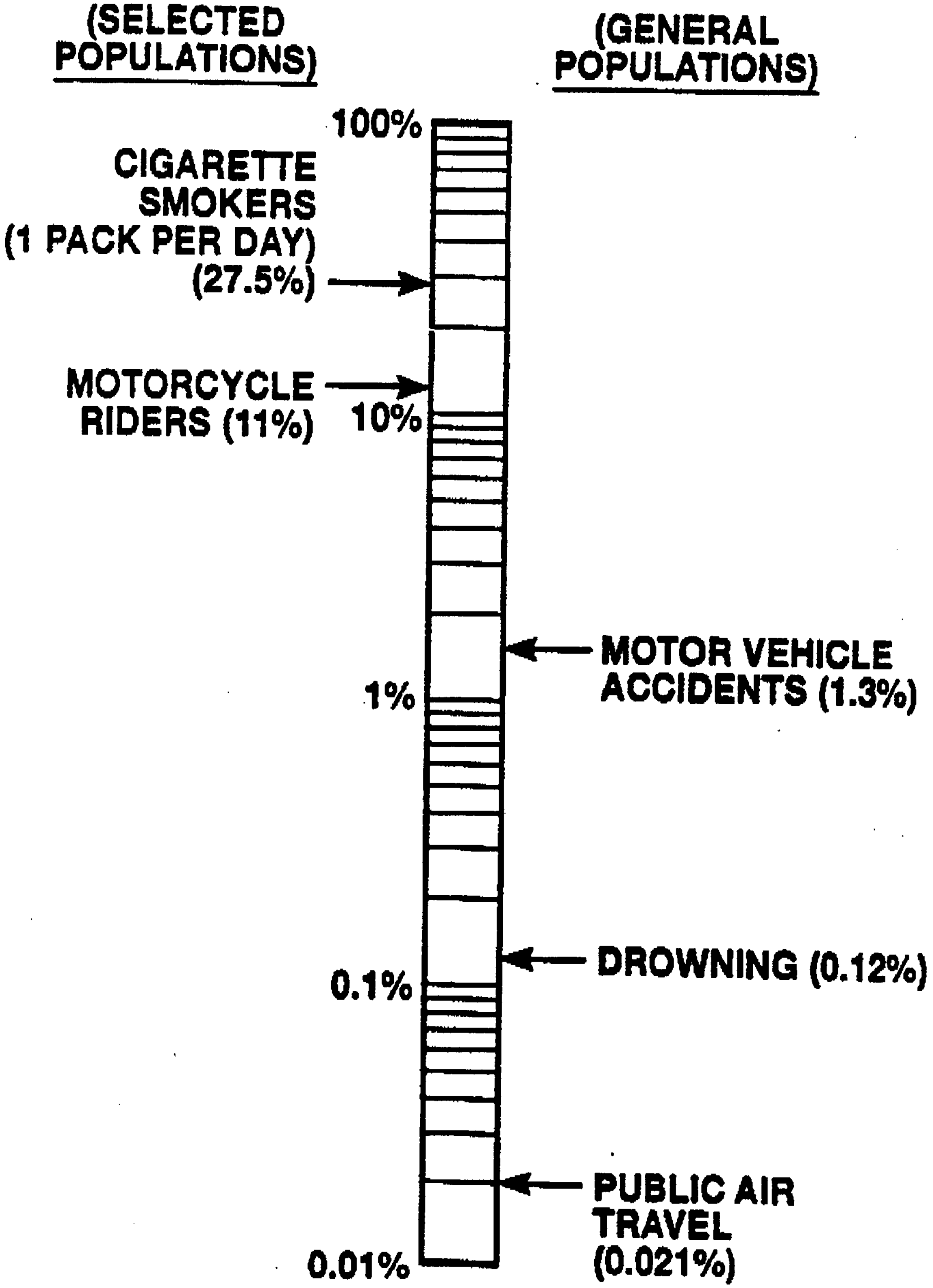
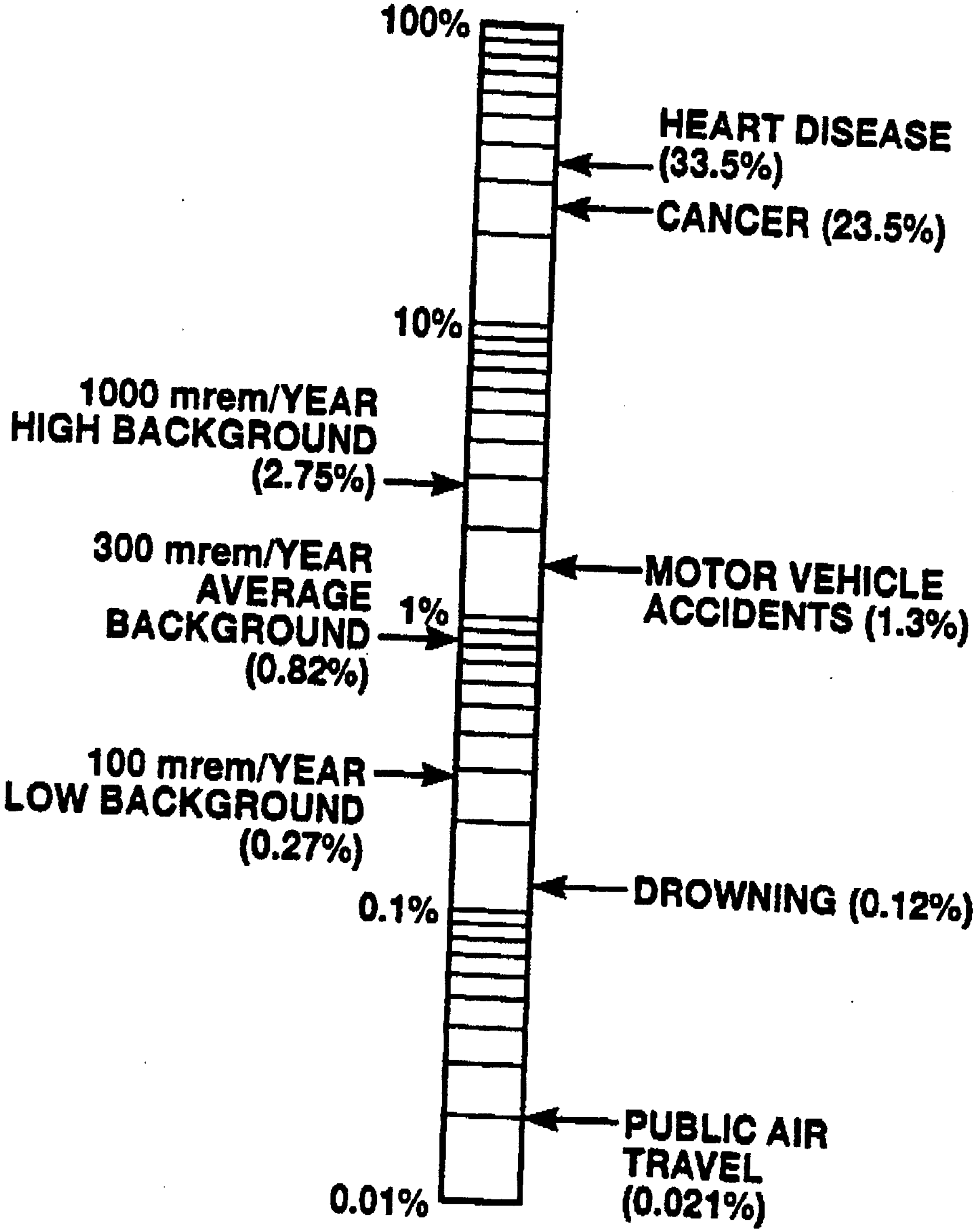


FIGURE 5

LIFETIME MORTALITY RISKS
(PERCENT)



LIFETIME MORTALITY RISKS
(PERCENT)

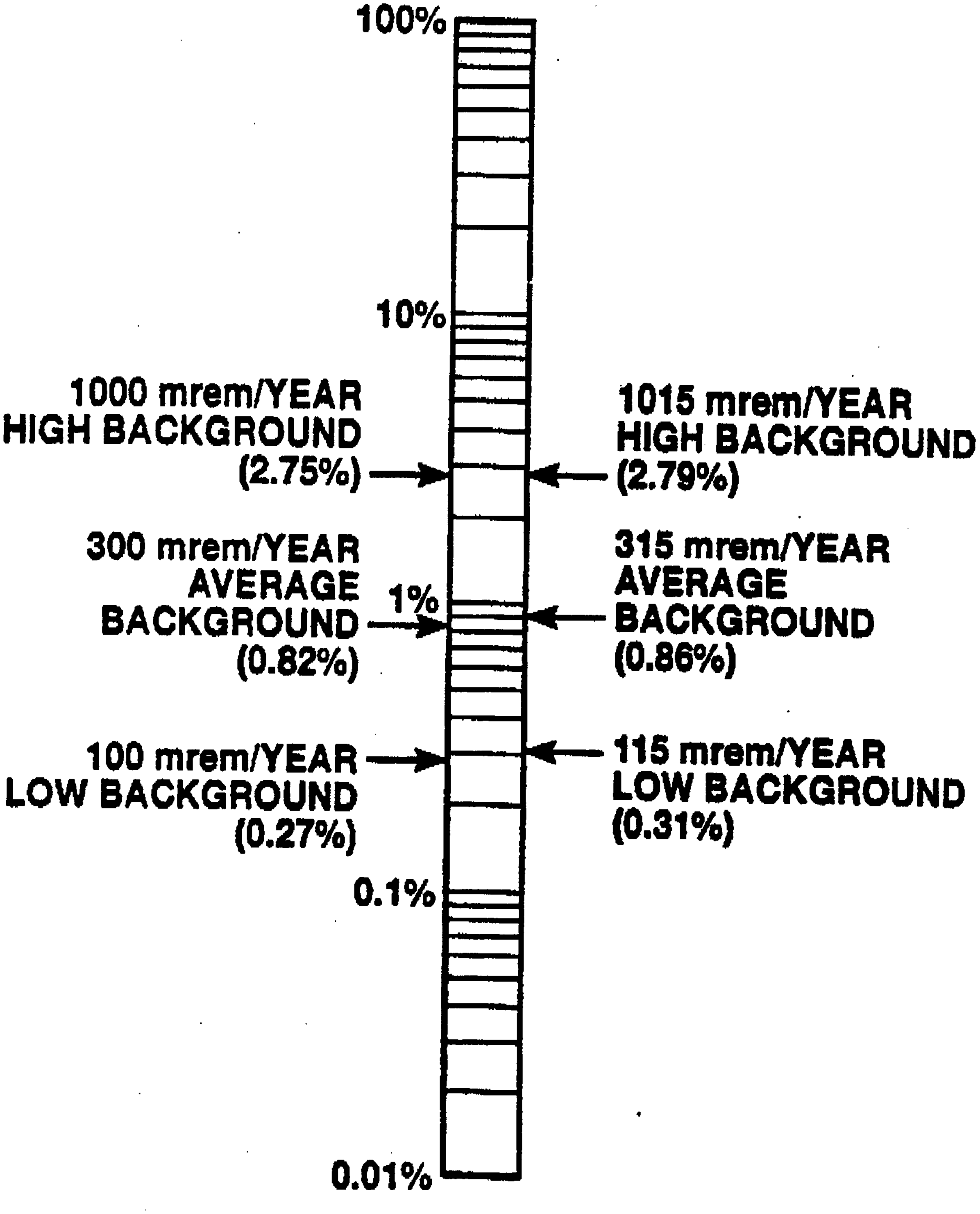


FIGURE 7

ESTIMATED COSTS OF RADIATION MEASUREMENTS

METHOD	COST PER SAMPLE
ALPHA SPECTROMETRY	$300-1000
BETA ANALYSIS	$50-750
EXTERNAL GAMMA EXPOSURE SURVEY	$50
EXTERNAL GAMMA TLD MEASUREMENT	$20
GAMMA SPECTROMETRY	$100-300
RADON MEASUREMENT	$10-20
SOIL SAMPLE COLLECTION	$100-200
SOIL SAMPLE PROCESSING	$100-400
THERMAL IONIZATION MASS SPECTROMETRY	$1000

FIGURE 8

ESTIMATED COST PER MEASUREMENT OF CESIUM-137 IN SOIL

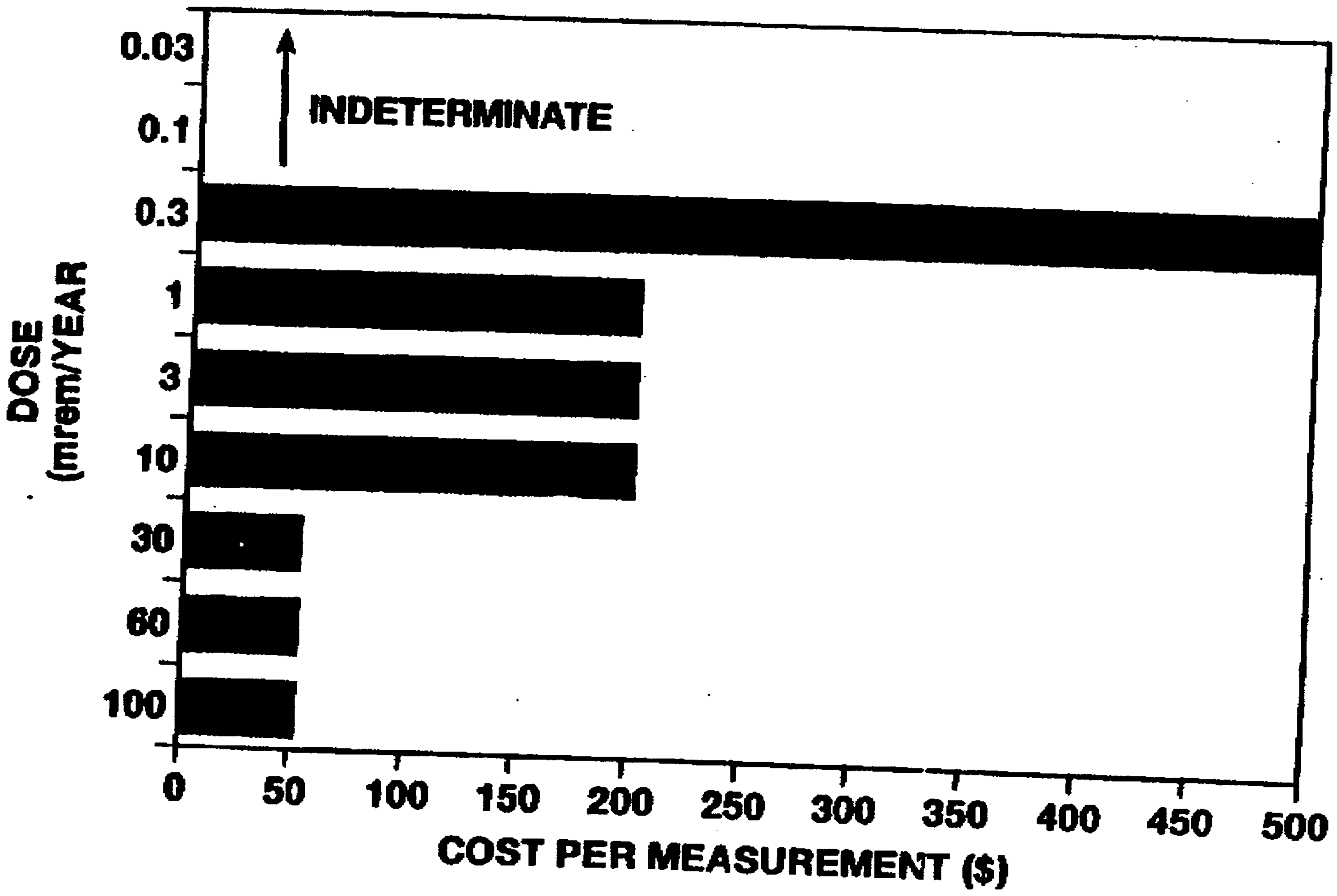


FIGURE 9

Appendix 18

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF RADIOLOGICAL PROTECTION

J. Radiol. Prot. **23** (2003) 247–262 PII: S0952-4746(03)65204-3

Cancer mortality in a Texas county with prior uranium mining and milling activities, 1950–2001

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Received 7 February 2003, in final form 6 May 2003, accepted for publication 9 May 2003
Published 8 September 2003
Online at stacks.iop.org/JRP/23/247

Abstract

Uranium was discovered in Karnes County, Texas, in 1954 and the first uranium mill began operating in 1961 near Falls City. Uranium milling and surface and *in situ* mining continued in Karnes County until the early 1990s. Remediation of uranium tailings ponds was completed in the 1990s. There were three mills and over 40 mines operating in Karnes County over these years and potential exposure to the population was from possible environmental releases into the air and ground water. From time to time concerns have been raised in Karnes County about potential increased cancer risk from these uranium mining and milling activities. To evaluate the possibility of increased cancer deaths associated with these uranium operations, a mortality survey was conducted. The numbers and rates of cancer deaths were determined for Karnes County and for comparison for four 'control' counties in the same region with similar age, race, urbanisation and socioeconomic distributions reported in the 1990 US Census. Comparisons were also made with US and Texas general population rates. Following similar methods to those used by the National Cancer Institute, standardised mortality ratios (SMRs) were computed as the ratio of observed numbers of cancers in the study and control counties compared to the expected number derived from general population rates for the United States. Relative risks (RRs) were computed as the ratios of the SMRs for the study and the control counties. Overall, 1223 cancer deaths occurred in the population residing in Karnes County from 1950 to 2001 compared with 1392 expected based on general population rates for the US. There were 3857 cancer deaths in the four control counties during the same 52 year period compared with 4389 expected. There was no difference between the total cancer mortality rates in

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Karnes County and those in the control counties (RR = 1.0; 95% confidence interval 0.9–1.1). There were no significant increases in Karnes County for any cancer when comparisons were made with either the US population, the State of Texas or the control counties. In particular, deaths due to cancers of the lung, bone, liver and kidney were not more frequent in Karnes County than in the control counties. These are the cancers of *a priori* interest given that uranium might be expected to concentrate more in these tissues than in others. Further, any radium intake would deposit primarily in the bone and radon progeny primarily in the lung. Deaths from all cancers combined also were not increased in Karnes County and the RRs of cancer mortality in Karnes County *before* and in the early years of operations (1950–64), shortly after the uranium activities began (1965–79) and in two later time periods (1980–89, 1990–2001) were similar, 1.0, 0.9, 1.1 and 1.0, respectively. No unusual patterns of cancer mortality could be seen in Karnes County over a period of 50 years, suggesting that the uranium mining and milling operations had not increased cancer rates among residents.

1. Introduction

In Karnes County, Texas, concern has been expressed that cancer rates might be greater than expected due to uranium mining and milling activities that began in the 1950s (Brender 1987, 1989). The concerns were related to potential environmental releases into the air and ground water from operating the three mills and over 40 uranium mines, including the transport of uranium ore. The activities associated with uranium extraction from ore would produce solid and liquid wastes. The wastes, called tailings, contain most of the radionuclides present in the ore, including thorium, radium and other decay products. Radon and radon progeny are a secondary source of possible exposure in mines, mills and tailings ponds. The tailings ponds, surface mines, runoff collection ponds, ore transport and the mills (extraction facilities) are the potential exposure pathways to humans (NCRP 1993).

A small cytogenetic study in Karnes County (Au *et al* 1995) and a recent exploratory geographical correlation study in Spain (López-Abente *et al* 2001) have suggested that uranium operations might increase cancer risk, but both investigations had methodologic deficiencies that limited interpretation. Studies of cancer mortality (1979–88) and cancer incidence (1976–80) conducted previously by the Texas Department of Health, provided no indication of unusually high cancer rates in populations living in Karnes County (Brender 1987, 1989) but it is possible that the time between potential exposure and occurrence of disease may have been too short to demonstrate an effect. To provide additional information over a longer time period than previously possible, we conducted a county mortality study contrasting cancer rates in Karnes County before, during and after the uranium operations began. The current investigation includes more calendar years than previously possible, over 50 years, and incorporates a comparison with nearby counties with similar demographic characteristics. The investigative methods followed are similar to those used by the National Cancer Institute in a study of nuclear installations throughout the United States (Jablon *et al* 1990, 1991).

2. Methods

2.1. Uranium mining, transportation, milling and waste disposal activities

Karnes County is south of San Antonio, Texas, in the central coastal plain area in the southern part of the state. The uranium mining activities around Karnes County began in 1959 and the first uranium mill began operating in 1961. The uranium ore was transported from surface mines to mills where the uranium concentrate U_3O_8 (yellowcake) was produced. There were three conventional uranium mills and over 40 *in situ* and surface mines operating in Karnes County for several decades. *In situ* or solution mining is a method where a leaching solution is injected through wells into the ore body to dissolve the uranium. Production wells are then pumped to bring the uranium-bearing solution to the surface for eventual extractions. There were no underground mines. After the uranium ore was processed, the waste material, called tailings, was placed in tailings piles or ponds. The tailings contain unrecovered uranium and amounts of other radionuclides including thorium and radium (Ruttenber *et al* 1984, Eisenbud 1987, Ibrahim *et al* 1990, Veska and Eaton 1991, Thomas 2000). Radon gas released from the decay of radium would be dispersed and diluted into the atmosphere. Remediation of the Falls City mill site was completed in 1994 (DoE 2002). The Conquista mill was decommissioned in the early 1980s and the tailings pond was capped and closed by the early 1990s. The Panna Maria mill was decommissioned in the early 1990s and the tailings pond was capped and closed in the late 1990s.

Because the uranium mining and milling processes in Karnes County did not involve any uranium enrichment, workers and the public were not exposed to enriched radioactive materials or wastes. Natural uranium ores are not generally considered to present an external radiation hazard (NCRP 1993, Priest 2001). Exposure to airborne ore dust is a principal source of potential exposure. The Texas Department of Health began monitoring the environment around uranium mines and recovery facilities in 1961 and in 1988–89 instituted a sampling programme in response to public concerns about possible exposure to radioactive materials from the uranium recovery activities (Meyer 1990). The sampling programme included private water supplies, radon in homes, radon in schools and radioactivity in milk and meat. There was no evidence for increased levels of radioactive materials in Karnes County compared with other parts of Texas; if anything, the average radon concentrations in homes ($0.8\ \mathrm{pCi\ l^{-1}}$) was lower than in other parts of the state. The concentration of uranium in milk samples was also below the minimum detectable level of the measurement equipment.

2.2. *Cancers considered in the study*

After ingestion or inhalation, uranium distributes within the body to tissues depending on its chemical properties and route of intake (ICRP 1995a, 1995b). Inhalation of uranium would result in deposition within the lung and pulmonary lymph nodes. The bone, kidney and liver are the other most probable sites of deposition and exposure, albeit at a lower level than for the lung. In general, the solubility of natural uranium is very high (ICRP 1995a, 1995b, Priest 2001) which implies a relatively short residence time within the body before being eliminated by normal processes. The kidney is also an organ of interest because of possible damage related to the chemical properties of uranium, a heavy metal.

The following kinds of cancer were studied on the basis of the likely deposition of uranium in body tissue mentioned above: cancers of the lung, bone, liver and kidney. In addition, it is known that substantial ingestion of radium has increased the risk of bone cancer among dial painters (Fry 1998) and extensive exposure to radon and its progeny has increased the risk of lung cancer among underground miners (Lubin *et al* 1995, NRC 1999). On the basis of the knowledge of cancers found increased after high dose and high dose rate external exposures to gamma or x-rays, cancers of the stomach, colon, female breast and thyroid gland and leukemia were studied (Boice *et al* 1996, UNSCEAR 2000). For completeness, other cancers were included, including those not frequently found to be increased in exposed populations, such as cancers of the oesophagus, pancreas, cervix uteri and corpus uteri and prostate, malignant melanoma of the skin, Hodgkin's disease, non-Hodgkin's lymphoma and multiple myeloma.

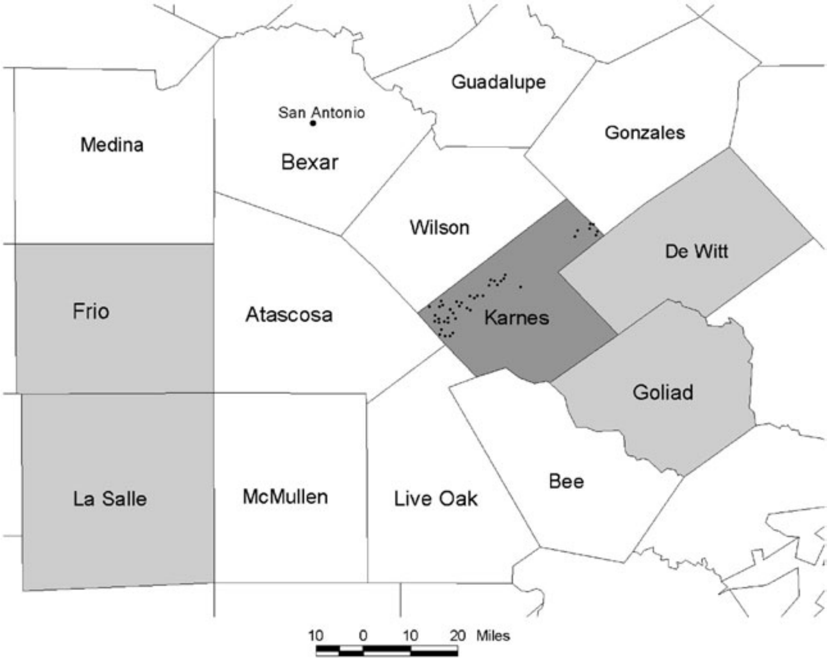

Figure 1. A map of South Texas containing Karnes County and the four control counties (Frio, La Salle, DeWitt and Goliad). The dots in Karnes County represent the prior location of 43 mines and 3 mills (Railroad Commission of Texas, Surface Mining and Reclamation Division map).

2.3. Mortality data

Counties are the smallest areas for which both population estimates and annual counts of the number of deaths for specific causes are readily available back to 1950 from the National Center for Health Statistics and the US Census Bureau (NCI 1999). Cancer mortality data for Texas at the county level were available from the National Cancer Institute from 1950 to 1995 (NCI 1999) and from the Texas Department of Health from 1996 to 2001 (TDH 2002).

2.4. Study county (figure 1)

Karnes County constituted the study county where the residing population had the potential for exposure to uranium ore and its decay products from the surface and *in situ* mining and milling activities, including transportation and any possible exposures from tailings ponds.

2.5. Control counties

Four comparison counties were selected (table 1). Control counties were matched to Karnes County by the following characteristics: percentages of persons in the population that were white, Hispanic, urban, rural, employed in manufacturing, below the poverty level, over age 64, and high school graduates, and mean family income and population size. Data were obtained from the 1990 census (USDC 1992). Data on diet, smoking and other potential cancer risk factors are not readily available at the county level, but choosing control counties from the same region as the study counties, i.e., South Central Texas, helps minimise differences in these and other factors.

Table 1. Selected characteristics of residents in Karnes County and in four control counties in South Central Texas.

County	Total population 1990	Percentages (%)									Median household income ($10 000)
		Male	White	Black	Hispanic	Rural	>64 y	Below poverty	High school graduate	Employed	
Study county											
Karnes	12 455	48	97	3	47	46	16	36	51	50	16.2
Control counties											
DeWitt	18 840	47	89	11	24	53	19	25	55	49	18.0
Frio	13 472	49	98	1	72	29	10	38	50	53	14.1
Goliad	5 980	48	93	7	36	100	16	18	63	53	21.4
La Salle	5 254	50	99	0	75	29	14	37	45	51	15.6
All control											
	43 546	48	93	6	47	49	15	29	56	51	18.5

2.6. Statistical analyses

Counts of deaths by cause, sex, race and five year age group were obtained for each of the five selected counties for each year from 1950 to 2001. Estimated annual county populations by sex, race and age group were obtained by interpolation in census counts for 1950–69 and for later years decennial censuses prepared by the Bureau of the Census (NCI 1999, Jablon *et al* 1990). Population data for counties in Texas were also available from the Texas Department of Health (TDH 2002). For each type of cancer and each county the ‘expected’ number of deaths, based on concurrent US experience, was calculated for the 52 year study period (NCI 1999, Marsh *et al* 1998). The expected numbers were obtained by multiplying annual US cancer death rates by the estimated populations, stratified by five year age group and sex. Counts were then summed for Karnes County and for all four of the corresponding control counties. Counts of observed and expected deaths were then summed over the following time periods: 1950–64 (before and just after the uranium operations began), 1965–79, 1980–89 and 1990–2001, thus producing numbers of deaths observed and expected generally *before, during* and *after* uranium activities began. This approach is the same as what was done previously in the United States by the National Cancer Institute (NCI) using similar databases and statistical programs (Jablon *et al* 1990, NCI 1999). Comparisons with Texas cancer death rates were also made but are not presented because computed RRs, described below, did not differ appreciably from those based on US general population rates.

The ratio of the actual number of deaths observed to the number expected at US rates is the standardised mortality ratio (SMR). Ratios of the SMRs for the study and control counties were called RRs. The difference between each RR and 1.00 was assessed by calculation of the probability that a difference of the observed magnitude, or larger, might have arisen by chance (Breslow and Day 1987, Jablon *et al* 1990, Mantel and Ederer 1985). A 95% confidence interval that contains 1.00 indicates that chance is a likely explanation for any observed differences in cancer mortality rates between Karnes County and the control counties.

Strata containing three or fewer cancer deaths are not presented but are listed as LT4 to denote ‘less than four’. This is to abide by the confidentiality requirements for using the NCI and National Center for Health Statistics database. The concern is the possibility that individuals with certain characteristics might be identified if the number of deaths were small.

Table 2. The number of cancer deaths occurring in Karnes County and in the four control counties in South Central Texas, 1950–2001. 'LT4' denotes 'less than 4'.

	Number of deaths	
Cancer (ICD-9)	Karnes County	Control counties
Oesophagus (150)	20	58
Stomach (151)	72	207
Colon/rectum (153, 154)	168	456
Pancreas (157)	69	217
Lung (162)	224	653
Melanoma/skin (172)	21	58
Female breast (174)	79	246
Cervix uteri (180)	18	72
Corpus uteri (182)	5	27
Ovary (183)	28	97
Prostate (185)	76	257
Urinary bladder (188)	17	87
Kidney/renal pelvis (189)	19	105
Liver (155)	27	109
Bone (170)	11	23
Connective tissue (171)	LT4	15
Brain and CNS (191, 192)	24	78
Thyroid (193)	LT4	20
Non-Hodgkin's lymphoma (200, 202)	38	121
Hodgkin's disease (201)	12	22
Multiple myeloma (203)	22	52
Leukemia (204–8)	59	161
All cancers (140–208)	1223	3857

3. Results

In 1990, the total number of residents within Karnes County and the four control counties were 12 455 and 43 546, respectively. During the 52 years of study, 1950–2001, nearly 650 000 person-years of observation were accrued by people living in Karnes County and just over 2260 000 person-years among people living in the control counties. The control counties were similar to the study counties with regard to demographic indicators of cancer risk such as age, race and various measures of socioeconomic status (table 1). Over 90% of the population studied were listed on the census as white, including 47% Hispanic, just over 15% were older than 64 years and over 51% had graduated from high school. The median household income in 1990, about $16 200 per year, for the study population was somewhat lower than that for the control population. Both study and control counties were about 50% rural.

Table 2 shows the number of cancer deaths occurring in Karnes County and the control counties over the years 1950–2001. There were 1223 cancer deaths within Karnes County (1392 expected; SMR = 0.88) and 3857 cancer deaths within the four control counties (4389 expected; SMR = 0.88). The RR for total cancer mortality in Karnes County compared to the control counties was 1.00 (95% CI 0.9–1.1). The most frequent cancer deaths were of the lung, colon and rectum, female breast, prostate and stomach. There were 224 lung cancer deaths, 11 bone cancer deaths, 19 kidney cancer deaths, 27 liver cancer deaths, 59 leukemia deaths and 79 deaths due to female breast cancer in Karnes County.

Table 3 shows the SMRs for all types of cancer combined for the time periods 1950–64, 1965–79, 1980–89 and 1990–2001. The SMRs comparing study and control counties

Table 3. Mortality due to all types of cancer, all ages and sexes combined over four time periods, 1950–2001, in Karnes County and in the four control counties. (‘Obs’ stands for ‘Observed’.)

	Calendar years of death									
	1950–64		1965–79		1980–89		1990–2001		All	
	Obs	SMR[a]	Obs	SMR[a]	Obs	SMR[a]	Obs	SMR[a]	Obs	SMR[a]
Karnes County	267	0.9[c]	331	0.9[c]	279	0.9	346	0.9[c]	1223	0.88[c]
Control counties	799	0.8[c]	1102	0.9[c]	818	0.8[c]	1138	0.9[c]	3857	0.88[c]
RR[b]	1.0		0.9		1.1		1.0		1.0	

[a] SMR is the observed number of cancers divided by that expected based on rates within the general population of the United States.

[b] Estimated RR taken as the ratio of the SMR in Karnes County with that in the four control counties.

[c] $p < 0.05$.

with the general population of the United States were slightly below 1.00 for each of the four time periods. The RRs contrasting total cancer mortality in Karnes County with that in control counties before and after uranium operations began were similar and varied between 0.9 and 1.1.

Table 4 concerns specific causes of death for both children and adults and shows very little difference in cancer mortality rate between study and control counties over the four time periods. There were three statistically significant RRs. Colon and rectal cancer was increased significantly overall (RR 1.17) which was due to a significant elevation (RR 1.6) in 1950–64 and prior to the major onset of uranium operations. Cancer of the kidney was significantly low (RR 0.58). Lung cancer (RR 1.08), leukemia (RR 1.15), bone cancer (RR 1.35), female breast cancer (RR 1.01), liver cancer (RR 0.81) and non-Hodgkin’s lymphoma (RR 1.04) occurrences were close to expectation and were not statistically distinguishable from no risk (RR 1.0). Of the 23 RRs presented in table 4 for 1950–2001, nine were slightly above 1.0, ten were slightly below 1.0 and four were essentially equal to 1.0—a distribution consistent with the random variations commonly seen in population statistics. There was no suggested pattern for increasing risks over time for any specific cancer.

For childhood cancer mortality, including leukemia, the RR comparing Karnes County with the control counties was 1.2 ($n = 7$) before most uranium operations began (1950–64) and 1.3 ($n = 8$) after the onset of the mining and milling activities (1965–2001) (data not shown). Overall in Karnes County, there were 6 deaths due to leukemia in children versus 5.1 expected based on general population rates. Based on a total of 59 leukemia deaths, there were no significant elevations in any time interval or overall (RR 1.15; 95% CI 0.9–1.1). Only 2 deaths from thyroid cancer were observed versus 2.7 expected.

4. Discussion

Compared to similar counties in South Central Texas, no increase in cancer mortality was found in Karnes County where there was potential for radiation exposures from uranium mining and milling activities, including potential exposures from transportation of ore and from tailings ponds. No significant excess deaths were found for cancers of the lung, bone, liver or kidney, or non-Hodgkin’s lymphoma, i.e., in those tissues where deposition of uranium might have been anticipated had there been intake (ICRP 1995a, 1995b). Any intake of radium would have lodged primarily in bone and radon decay products would have deposited primarily in lung.

Table 4. RR of mortality due to selected cancers in Karnes County versus the four control counties for four time periods during 1950–2001. ('Obs' denotes the observed cancer deaths within Karnes County, 'LT4' denotes that the observed number of deaths is less than 4 and 'RR' denotes the estimated relative risk taken as the ratio of the SMR in Karnes County to that in the four control counties.)

	Calendar year of death										
	1950–64		1965–79		1980–89		1990–2001		Total 1950–2001		
Cancer (ICD-9)	Obs	RR	Obs	RR	Obs	RR	Obs	RR	Obs	RR	95% CI
Oesophagus (150)	5	1.4	4	0.7	LT4	1.1	9	1.1	20	1.06	(0.6–1.8)
Stomach (151)	29	1.3	19	1.0	11	0.9	13	1.0	72	1.08	(0.8–1.4)
Colon/rectum (153, 154)	45	1.6[a]	40	0.9	35	1.1	48	1.2	168	1.17[a]	(1.0–1.4)
Pancreas (157)	14	1.0	22	1.1	20	1.3	13	0.7	69	1.01	(0.8–1.3)
Lung (162)	0	0.0	59	1.0	73	1.2	92	1.0	224	1.08	(0.9–1.3)
Melanoma/skin (172)	5	2.0	9	1.7	LT4	0.8	4	0.7	21	1.23	(0.7–2.0)
Female breast (174)	21	1.3	21	0.9	14	0.9	23	1.0	79	1.01	(0.8–1.3)
Cervix uteri (180)	9	1.1	4	0.5	LT4	0.8	LT4	0.6	18	0.76	(0.5–1.3)
Corpus uteri (182)	0	0.0	0	0.0	4	1.8	LT4	0.3	5	0.72	(0.3-1.9)
Ovary (183)	LT4	0.3	13	1.7	4	0.7	8	1.0	28	0.90	(0.6–1.4)
Prostate (185)	15	0.9	15	0.7	16	1.0	30	1.2	76	0.95	(0.7–1.2)
Urinary bladder (188)	5	0.7	4	0.5	4	1.1	4	0.6	17	0.64	(0.4–1.1)
Kidney/renal pelvis (189)	LT4	0.4	6	0.6	5	0.9	5	0.5	19	0.58[a]	(0.4–1.0)
Liver (155)	0	0.0	11	1.0	6	0.8	10	0.7	27	0.81	(0.5–1.2)
Bone (170)	5	2.2	LT4	0.3	LT4	—	LT4	0.9	11	1.35	(0.7–2.8)
Connective tissue (171)	LT4	0.7	0	0.0	0	0.0	LT4	1.2	LT4	0.44	(0.1–1.5)
Brain and CNS (191, 192)	5	0.8	5	0.6	8	1.8	6	0.9	24	0.92	(0.6–1.4)
Thyroid (193)	0	0.0	LT4	0.4	0	0.0	LT4	0.8	LT4	0.31	(0.1–1.3)
Non-Hodgkin's lymphoma (200, 202)	LT4	0.7	13	0.9	8	1.2	14	1.1	38	1.00	(0.7–1.4)
Hodgkin's disease (201)	4	1.8	5	1.5	LT4	—	0	0.0	12	1.79	(0.9–3.6)
Multiple myeloma (203)	LT4	0.7	4	1.0	6	1.1	11	2.0	22	1.37	(0.8–2.3)
Leukemia (204–208)	9	0.7	20	1.3	17	1.7	13	1.0	59	1.15	(0.9–1.6)
All cancers (140–208)	267	1.0	331	0.9	279	1.1	346	1.0	1223	1.00	(0.9–1.1)

[a] $p < 0.05$.

Knowledge about radiation carcinogenesis has accumulated during the past 50 years and is helpful in interpreting the study findings (UNSCEAR 1994, 2000, IARC 2000, 2001). Although radiation-induced leukemia may occur as soon as two years after exposure, other cancers such as those of the lung and breast develop more slowly and are unlikely to be identified in mortality data for ten years or more after radiation exposures. Because mortality data were available for over 40 years after the uranium mining activities began in 1959, residents of the surrounding area could be evaluated for a long enough period of time to accumulate sufficient exposure to detect any increase in mortality due to cancer if one were present. Comparing Karnes County with the four nearby control counties, the RR for all cancer mortality ranged from 0.9 to 1.1 over the 52 years of study. The fact that significant differences were not found in our survey for the periods *before, during* or *after* the uranium mining and milling activities began provides evidence that the mining and milling operations have not adversely affected the occurrence of cancer among County residents. Our survey is thus consistent with other studies of persons living near uranium processing facilities in the US (Jablon *et al* 1990, Boice *et al* 2003a, 2003b), and also with studies of workers heavily exposed to uranium during processing activities (CRS 2001) where no increased cancer risks were observed.

Because many workers involved in uranium mining and milling activities lived in Karnes County, their inclusion within the study population probably enhances our power to detect a radiation association given that worker exposures would be expected to be much greater than residential exposures. Studies of over 120 000 workers at uranium milling, fabrication and processing facilities, however, have not found any consistent links between uranium exposures and increases in any cancer or leukemia (McGeoghegan and Binks 2000a, 2000b, CRS 2001, IOM 2001, IARC 2001). Specifically, no increases in cancers of the lung, liver or bone or lymphoma were observed among these uranium workers, i.e., in those tissues where the probable distribution of uranium was highest (ICRP 1995a, 1995b, IARC 2001). Uranium, similar to radium or plutonium, would deposit primarily in bone and not bone marrow, minimising the likelihood of a leukemogenic exposure to the uncommitted stem cells that reside more centrally in the marrow (Priest 1989, 2001). Thus the absence of a leukemia risk is not surprising. A recent geographical correlation study in Finland also found no evidence for increased leukemia rates among communities with high levels of uranium in their water supplies (Auvinen *et al* 2002). Radon and its decay products have caused lung cancer among underground miners (Lubin *et al* 1995, NRC 1999) but no other cancer or leukemia has been found elevated among the over 64 000 heavily exposed miners studied (Darby *et al* 1995). Substantial intake of radium has caused excess bone cancers among dial painters, but no risk was seen at low to moderately high doses (<10 Gy skeletal dose) and no other cancers were associated with radium intake except a rare carcinoma of the sinuses attributable to the build-up of radon from the radium decay (Rowland *et al* 1978, Polednak *et al* 1978, Fry 1998, Priest 2001).

Reports of small clusters of childhood leukemia around nuclear installations in the United Kingdom in the 1980s prompted several large scale systematic surveys around the world (UNSCEAR 1994). Subsequent surveys in other counties failed to confirm a link between childhood leukemia or any other cancer and proximity to nuclear installations (Doll *et al* 1994, Doll 1999). Several geographical correlation studies around nuclear installations in Spain have been published recently suggesting an increase in cancer mortality in areas containing uranium processing facilities, including one that also contained a nuclear waste storage facility, but not in areas with nuclear power plants (López-Abente *et al* 1999, 2001). However, the cancer mortality rates in the towns near the uranium operations were below expectation based on general population rates (SMR 0.88) and it was the even lower rates among the more distant towns (50–100 km) used as control that produced the apparent elevation. The areas with uranium facilities, then, did not experience elevated cancer rates but rather the control areas experienced unusually low cancer rates. This suggests that the residents of the control areas may not have been similar to the residents of towns near uranium processing facilities and such non-comparability tempers interpretation (Laurier *et al* 2002). Further, cancer risks overall and for lung cancer and kidney cancer in particular were lower in the towns nearest (<15 km) to the uranium facilities than in the towns located further away (15–30 km), which is just the opposite to what would be expected if radiation were a contributing factor. In addition, the elevated mortality rates were gender specific in that lung cancer increases were seen only in males and not females, whereas kidney cancer increases were seen only in females and not males. Such differences are also not consistent with a possible effect of environmental exposures, because any exposures common to both sexes would be expected to affect both males and females and not just one or the other. Similarly, a slight increase in leukemia reported in the Spanish study (López-Abente *et al* 1999) is not in accord with what is known about the distribution of uranium in the body after intake, i.e., exposure to the leukemia-producing cells is minuscule (Bender *et al* 1988, Priest 1989). Further a radiation link between leukemia and living near nuclear installations has been discounted after extensive epidemiologic study (UNSCEAR 1994, Laurier *et al* 2002). Finally, uranium processing facilities in the US have not been correlated with increased cancer mortality (Jablon *et al* 1990, Boice *et al* 2003a) or cancer incidence in nearby populations (Boice *et al* 2003b). Thus the exploratory correlation studies in Spain must be interpreted with caution, since the mortality excesses and deficits may be attributable to bias if control area residents were not comparable to study area residents in terms of cancer risk factors or, as mentioned by the authors, to chance when so many hundreds of comparisons are made (11 different cancers, 8 installations and 3 distances).

A cross-sectional cytogenetic analysis has also been conducted among a small number of Karnes County residents to investigate whether living near uranium mining and milling activities might be associated with chromosome aberrations in circulating lymphocytes and also with abnormal DNA repair processes (Au *et al* 1995). Bloods were analysed for 24 persons, primarily women, potentially exposed to uranium and other radionuclides and for 24 persons presumably non-exposed. The participation rate was very low, about 30% of those initially selected, and only 6 of the 48 participants were males, indicating the possibility of selection bias. Although the frequency of all types of chromosome aberration combined was slightly increased among those presumably exposed to radiation, the difference was not statistically significant. Further, dicentrics, a type of unstable chromosome aberration found to be increased in populations continuously exposed to environmental radioactivity (Wang *et al* 1990, Upton 1990), was actually higher among the presumed non-exposed and this difference approached statistical significance ($p = 0.06$). Thus there was no evidence that radiation exposure from uranium mining and milling operations resulted in increased levels of chromosome breakage among residents of Karnes County.

An abnormal DNA repair response was also reported among the exposed subjects based on a 'challenge assay' developed by the authors who concluded that prior radiation exposure caused these DNA repair problems (Au *et al* 1995). In addition to the substantial uncertainties associated with small numbers, poor participation rates and the potential for selection bias, the study has other serious deficiencies. First, there was no attempt to estimate radiation exposure to any group, so it is uncertain whether the exposed group actually received more exposure than the non-exposed. Second, the assay, which apparently has not been validated by other laboratories, appears to have been misapplied. The potential exposure is from uranium, an alpha particle emitting radionuclide that deposits energy mainly in the lung and bone. Because alpha particles have little penetrating power, circulating lymphocytes would be expected to demonstrate little if any damage since the stem cells within the bone marrow would not be reached (Bender *et al* 1988, Priest 1989, Lloyd *et al* 2001). Third, the results are not internally consistent. It is not logical that chromosomal aberrations would not be increased in a radiation-exposed group characterised by an abnormal DNA repair processes (somehow associated with this same radiation). For example, in patients with severely defective DNA repair mechanisms, such as ataxia telangiectasia, exposure to radiation results in substantial elevations in chromosome aberrations (IARC 2000). Fourth, cytogenetic studies are substantially limited in their ability to detect any effect from low protracted environmental exposures. In addition, several experimental cellular studies have found that low dose radiation can enhance the repair capabilities of cellular DNA subsequently exposed to higher doses (adaptive response) (UNSCEAR 1994); and not damage them as postulated by (Au *et al* 1995). Finally the authors' claim that their assay results indicate that residents have increased health risks from uranium exposures (Au *et al* 1998) is speculative and unproven. Chromosome aberrations, including dicentrics, have been reported to be increased in areas of high natural background radiation due to thorium contaminated soil (similar to the postulated exposure conditions associated with the uranium mining and milling activities), yet no health effects have been identified in large populations residing their entire lives in such areas in China (Wang *et al* 1990, Wei *et al* 1997, Boice 2002). Thus radiation-associated damage in circulating lymphocytes is considered a marker of prior exposure but has not been linked to increased health risks (Upton 1990). The Au *et al* (1995) cytogenetics study thus provides no evidence for either increased radiation exposure or adverse health effects among residents of Karnes County.

4.1. Strengths and limitations

This community study covered a long time frame, over 50 years, which enabled detailed analyses of several specific cancers. For Karnes County, comparisons of cancer rates before and after uranium mining and milling activities began could be made. Further comparisons with similar control counties in South Central Texas and with the entire United States were possible. The numbers of total cancer deaths between 1950 and 2001, over 1200, was such that any differences between Karnes County and the control counties could be identified, if they were present. The methodology used was the same as that employed by the National Cancer Institute in a similar, but larger scale investigation of mortality in counties throughout the United States with nuclear facilities: electrical utilities, uranium processing plants and weapons production laboratories (Jablon *et al* 1990, 1991). Like us, the National Cancer Institute concluded that increased cancer risks were not associated with living in counties with nuclear facilities and associated radiation activities.

The cancer data reported herein resulted from routinely collected mortality statistics, but were not from an experimental study where individuals would be randomly assigned exposures and followed forward in time. Information on uranium or other radionuclide exposures, if any, was not known for individuals countywide. Although counties were matched using available data concerning racial composition, urban–rural mix, income and other factors, it is not possible to choose control counties that are exactly comparable with the study county. Counties, for example, can vary with respect to industries, occupations, and lifestyle. Cancer deaths in each county were also compared with the numbers expected on the basis of concurrent US and Texas mortality rates. However, the similarity in cancer rates between Karnes County and the proximal control counties and the Texas and US population for practically all cancers suggest very little incompatibility. The absence of any significant trends in cancer risk over time indirectly addresses the possibility of differences arising solely from inadequate comparison populations.

This study relied mainly on mortality data. Although the accuracy of the cause of death information on death certificates is variable, this inaccuracy is less for cancer than other causes even during the early years of this study (Percy *et al* 1981). Further, the quality of death certificate information would be expected to be similar for Karnes County and the neighbouring counties which comprised the comparison population. Mortality data, however, are not optimal for monitoring such cancers as those of the thyroid or childhood leukemia, for which improved therapy has markedly lowered death rates in recent years while not affecting incidence. The numbers of deaths due to thyroid cancer ($n = 2$) and childhood leukemia ($n = 6$) did not differ from expectation but were too small to be informative in the current study other than to indicate a low mortality risk for these cancers. On the other hand, mortality and incidence rates are highly correlated and mortality nearly equals incidence for many cancers which have high fatality rates, such as cancers of the lung, stomach, bone, connective tissue and liver and adult leukemia. Further, the mortality data are consistent with the available incidence data from 1976 to 1980 in finding no significant increases for these or any other cancers in Karnes County (Brender 1987). These findings are also consistent with a study of cancer incidence in small geographical areas around two uranium processing facilities in the US which also found no increased cancer rates (Boice *et al* 2003a, 2003b).

Mortality rates have changed over time for a number of reasons including improvements in treatment and changes in lifestyle. For example, mortality rates for childhood leukemia have decreased in the entire United States during the study time period, whereas mortality rates for lung cancer have increased (Jemal *et al* 2003). Our study compares mortality rates in Karnes County with those in nearby control counties by calendar year to account for such changes over time to the extent possible. The increases in lung cancer rates in Karnes County, for example, were similar to the increases seen in the control counties and throughout the nation. The absence of lung cancer deaths in the 1950s reflects both the low death rate during these years and the small numbers at risk of dying.

Data were available only for counties and some residents may have lived at some distance from the uranium mining and milling operations. Local effects might be difficult to detect using county death rates because of any dilution resulting from the inclusion of the populations living far from the uranium mining and milling activities. However, over the years there were over 40 uranium mines, mills and tailings piles and ponds in Karnes County (figure 1) and it also has been suggested that the transport of ore on various county roads might have resulted in some population exposure. Thus, the potential for population exposure was greater than in counties with only one operating facility. Further, the county residents also included workers who probably received higher exposures than were possible from environmental circumstances and their inclusion would probably have increased the chance of finding an effect had there been one.

This was an ‘ecological’ survey in which the exposures, if any, of individuals are not known. Persons who lived in particular counties at the time of death may not have been long term residents. Some residents will have moved elsewhere and died in another part of the country. Although there have been population changes within Karnes County over the years, e.g., with young people going to college and seeking employment elsewhere or with some workers leaving the area when the mining and milling activities ceased, there has been some relative stability as suggested by the population census. In 1960, for example, the population was 14 995 in contrast to 12 455 in 1990 and 15 446 in 2000 (Website, US Census Bureau).

Despite the limitations inherent in an ecological study of cancer mortality in the counties with and without uranium operations, the methods used have been applied effectively in the past to identify environmental carcinogens when exposures were high and long term. For example, on the basis of findings from the ‘cancer maps’ constructed from county mortality statistics by the National Cancer Institute (Devesa *et al* 1999a, 1999b), counties with shipyard industries were found to have elevated lung cancer death rates, particularly among men. Subsequent case-control studies in the high risk areas linked the excess lung cancer deaths to occupational exposures to asbestos (Blot *et al* 1978). It might be noted that the NCI cancer maps, similar to our community study, do not indicate that cancer mortality in Karnes County is higher than in the rest of the US or that changes in cancer rates over time differ from those of the rest of the US (Devesa *et al* 1999b).

5. Conclusions

The cancers that might possibly be increased following high exposures to uranium and its decay products, i.e., cancers of the lung, bone, kidney and liver, were not elevated, nor was leukemia, a sensitive indicator of excessive exposure to external gamma radiation. This survey then provides no evidence that the mining and milling activities increased the rate of any cancer in Karnes County. The ecological nature of the study design, however, tempers the strength of these conclusions.

Acknowledgments

We thank the National Cancer Institute for providing the statistical program and databases used for these analyses, the Texas Department of Health for providing county mortality data for the years 1996–2001 and the Texas Uranium mining industry for providing financial support. Dr Boice has been an expert witness regarding the relationship between uranium exposure and cancer in Karnes County, Texas.

Résumé

De l'uranium fut découvert en 1954 dans le comté de Karnes, Texas. Le premier broyeur d'uranium commença à fonctionner en 1961, près de Falls City. Le broyage de l'uranium, son extraction en surface et *in situ* continuèrent, dans ce comté, jusqu'au premières années 90. Dans les années 90, on élimina les dépôts de résidus de broyage. Il existait trois usines de broyage et plus de 40 mines, fonctionnant dans le comté de Karnes, durant ces années; l'irradiation potentielle de la population venait de rejets possibles dans l'environnement, air et eaux souterraines. De temps à autre, il naissait, dans le comté de Karnes, le souci d'une augmentation potentielle du risque de cancers, venant de ces activités d'extraction et de broyage d'uranium. On a établi le relevé de la mortalité pour évaluer la possibilité d'une augmentation des décès par cancer, associée aux opérations sur l'uranium. On a déterminé le nombre et le taux de décès par cancer, pour le comté de Karnes, et on les a comparés aux valeurs pour quatre comtés 'de contrôle' de la même région, présentant des âges, des races, une urbanisation et des distributions socio-économiques semblables, données dans l' US Census de 1990. On fit aussi des comparaisons avec les taux pour la population générale des Etats Unis et du Texas. Par des méthodes semblables à celles employées par l'Institut national du cancer, on a calculé les rapports normalisés de mortalité (SMR); il s'agit du rapport du nombre de cancers dans les comtés, étudié ou de contrôle, au nombre attendu, déduit du taux pour la population globale des Etats Unis. Les risques relatifs (RR) calculés, sont les rapports des SMR pour le comté étudié à celui pour les comtés de contrôle. Au total, il y a eu 1223 décès par cancer dans la population résidant dans le comté de Karnes, entre 1950 et 2001; le nombre attendu en partant de la population générale des Etats Unis était de 1392. Il y eut 3857 décès par cancers dans les quatre comtés de contrôle durant la même période de 52 ans, à comparer aux 4389 attendus. Il n'y a pas de différence entre les taux totaux de mortalité par cancer, dans le comté de Karnes et ceux dans les comtés de contrôle (RR = 1,0; probabilité de 95% pour l'intervalle 0,9–1,1). Quand on a comparé à la population des Etats Unis, à celle du Texas, à celle des comtés de contrôle, on n'a observé aucune augmentation significative dans le comté de Karnes. En particulier, les décès dus à des cancers du poumon, des os, du foie et du rein n'étaient pas plus fréquents dans le comté de Karnes que dans les comtés témoins. Ce sont les cancers à prendre en compte, *à priori*, compte tenu que l'on peut penser que l'uranium se concentre plus dans ces tissus que dans les autres; De plus, toute absorption de radium se déposerait principalement dans les os, et son descendant, le radon, principalement dans les poumons. Les décès venant de l'ensemble de tous les cancers n'avaient pas augmenté dans le comté de Karnes; les RR de mortalité par cancer dans le comté de Karnes *avant* et dans les premières années des opérations (1950–64), peu de temps après que ne commencent les activités sur l'uranium (1965–79) et dans les deux dernières périodes de temps (1980–95, 1990–2001) étaient semblables; 1,0, 0,9, 1,1, 1,0, respectivement. On n'a vu aucun schéma inhabituel de mortalité par cancer dans le comté de Karnes, sur une période de 50 ans; cela suggère que les opérations d'extraction et de broyage d'uranium n'ont pas augmenté les taux de cancers chez les résidents.

Zusammenfassung

Uran wurde in Karnes County, Texas im Jahre 1954 entdeckt und das erste Uranwerk nahm 1961 in der Nähe von Falls City den Betrieb auf. Uranverarbeitung sowie Tagebau und *in situ* Bergbau wurden in Karnes County bis in die frühen 1990iger fortgesetzt. Die Beseitigung der Uranabfälle in Teichen wurde in den 1990igern abgeschlossen. In diesen Jahren waren drei Werke und mehr als 40 Zechen in Karnes County in Betrieb und die potenzielle Bestrahlung der Bevölkerung wurde durch mögliche Freisetzungen umweltschädlicher Stoffe in die Luft und das Grundwasser verursacht. Von Zeit zu Zeit wurden in Karnes County Bedenken über ein mögliches erhöhtes Krebsrisiko aufgrund dieser Uranabbau- und Verarbeitungsaktivitäten zum Ausdruck gebracht. Zur Bewertung der Möglichkeit einer erhöhten Zahl von Krebstoten aufgrund dieser Uranverarbeitung wurde eine Sterblichkeitsstudie durchgeführt. Die Anzahl der Krebstode wurde für Karnes County ermittelt und im US-Census 1990 verglichen mit vier 'Kontroll'-Counties in derselben Region mit Personen ähnlichen Alters, Rasse, Urbanisierung und soziökonomischen Verteilungen. Weitere Vergleiche wurden angestellt mit allgemeinen Bevölkerungsraten in den USA und Texas. Unter Verwendung ähnlicher Methoden, wie sie vom National Cancer Institute eingesetzt werden, wurden standardisierte Sterblichkeitsverhältnisse (SMRs) berechnet, d.h. die beobachteten Zahlen von Krebsfällen im Studien-und in den Kontroll-Counties wurden mit der Anzahl der zu erwartenden Anzahl verglichen, die aus den allgemeinen Bevölkerungsraten in den USA abgeleitet wurden. Die relativen Risiken (RR) wurden berechnet als Verhältnisse der SMRs für die Studien- und Kontroll-Counties. Insgesamt gab es zwischen 1950 und 2001 1223 Krebstote in der Bevölkerung in Karnes County, verglichen mit 1392, die auf der Grundlage der allgemeinen Bevölkerungsraten in den USA erwartetet worden waren. In den vier Kontroll-Counties gab es im selben Zeitraum über 52 Jahre 3857 Krebstote, verglichen mit 4389 erwarteten. Es gab keinen Unterschied zwischen den gesamten Krebssterblichkeitsraten in Karnes County und denen in den Kontroll-Counties (RR = 1,0; 95% Konfidenzintervall 0,9–1,1). Es gab keine signifikante Zunahme in Karnes County für irgendeine Krebsart, als Vergleiche entweder mit der US-Bevölkerung, dem Staat Texas oder den Kontroll-Counties angestellt wurden. Insbesondere waren Todesfälle aufgrund von Lungen-, Knochen-, Leber- und Nierenkrebs in Karnes County nicht häufiger als in den Kontroll-Counties. Diese Krebsarten sind deshalb von besonderem Interesse, weil sich Uran in diesen Geweben stärker konzentriert als in anderen. Außerdem würde sich jede Radiumaufnahme primär im Knochen ablagern und Radon-Folgeprodukte primär in der Lunge. Die Zahl der Toten aus allen Krebsarten kombiniert lag in Karnes County ebenfalls nicht höher. Die RRs der Krebssterblichkeit in Karnes County *vor* und in den ersten Jahren des Betriebs (1950–64), kurz nach Beginn der Uranaktivitäten (1965–79) und in den beiden Zeiträumen (1980–89, 1990–2001) waren ähnlich: 1,0, 0,9, 1,1 bzw. 1,0. Keine ungewöhnlichen Muster der Krebssterblichkeit wurden in Karnes County über einen Zeitraum von 50 Jahren beobachtet; dies deutet darauf hin, dass Uranabbau und—verarbeitung nicht zu einer Zunahme der Krebsraten unter den Bewohnern führte.

References

Au W W, Lane R G, Legator M S, Whorton E B, Wilkinson G S and Gabehart G J 1995 Biomarker monitoring of a population residing near uranium mining activities *Environ. Health Perspect.* **103** 466–70

Au W W, McConnell M A, Wilkinson G S, Ramanujam V M and Alcock N 1998 Population monitoring: experience with residents exposed to uranium mining/milling waste *Mutat. Res.* **405** 237–45

Auvinen A, Kurttio P, Pekkanen J, Pukkala E, Ilus T and Salonen L 2002 Uranium and other natural radionuclides in drinking water and risk of leukemia: a case-cohort study in Finland *Cancer Causes Control* **13** 825–9

Blot W J, Harrington J M, Toledo A, Hoover R, Heath C W Jr and Fraumeni J F Jr 1978 Lung cancer after employment in shipyards during World War II *New Engl. J. Med.* **299** 620–4

Boice J D Jr 2002 Study of health effects in areas of high background radiation in China *J. Radiol. Prot.* **22** 102–4

Boice J D Jr, Bigbee W L, Mumma M T and Blot W J 2003a Cancer mortality in counties near two former nuclear processing facilities in Pennsylvania, 1950–95 *Health Phys.* **85** at press

Boice J D Jr, Bigbee W L, Mumma M T and Blot W J 2003b Cancer incidence in municipalities near two former nuclear processing facilities in Pennsylvania *Health Phys.* **85** at press

Boice J D Jr, Land C E and Preston D L 1996 Ionizing radiation *Cancer Epidemiology and Prevention* 2nd edn, ed D Schottenfeld and J F Fraumeni Jr (New York: Oxford University Press) pp 319–54

Brender J D 1987 Cancer and adverse reproductive outcomes in Karnes County *Inter-Office Memorandum 10 July 1987* (Austin, TX: Texas Department of Health, Environmental Epidemiology Program)

Brender J D 1989 Update: cancer and adverse reproductive outcomes in Karnes County *Inter-Office Memorandum 18 December 1989* (Austin, TX: Texas Department of Health, Environmental Epidemiology Program)

Bender M A, Awa A A, Brooks A L, Evans H J, Groer P G, Littlefield L G, Pereira C, Preston R J and Wachholz B W 1988 Current status of cytogenetic procedures to detect and quantify previous exposures to radiation *Mutat. Res.* **196** 103–59

Breslow N E and Day N E 1987 *Statistical Methods in Cancer Research* vol 2 *(IARC Scientific Publication 82)* (Lyons: International Agency for Research on Cancer)

CRS (Council of the Royal Society) 2001 *The Health Hazards of Depleted Uranium Munitions Part 1* (London: Science Advice Section, The Royal Society)

Darby S C *et al* 1995 Radon and cancers other than lung cancer in underground miners: a collaborative analysis of 11 studies *J. Natl Cancer Inst.* **87** 378–84

Devesa S S, Grauman D J, Blot W J and Fraumeni J F Jr 1999a Cancer surveillance series: changing geographic patterns of lung cancer mortality in the United States, 1950 through 1994 *J. Natl Cancer Inst.* **91** 1040–50

Devesa S S, Grauman D, Blot W J, Pennello G A, Hoover R N and Fraumeni J F Jr 1999b Atlas of cancer mortality in the United States: 1970–94 *NIH Publication No* 99-4564 (Washington, DC: DHHS, PHS, NIH)

DoE (Department of Energy) 2002 [online] Falls City Mill Site, Karnes County Texas (Energy Information Administration) available from: http://www.eia.doe.gov/cneaf/nuclear/page/umtra/fallscity_title1.html

Doll R 1999 The Seascale cluster: a probable explanation *Br. J. Cancer* **81** 3–5

Doll R, Evans H J and Darby S C 1994 Paternal exposure not to blame *Nature* **367** 678–80

Eisenbud M 1987 *Environmental Radioactivity from Natural, Industrial, and Military Sources* 3rd edn (Orlando, FL: Academic Press) pp 178–82

Fry S A 1998 Studies of US radium dial workers: an epidemiological classic *Radiat. Res.* **150** S21–9

IARC (International Agency for Research on Cancer) 2000 IARC monographs on the evaluation of carcinogenic risks to humans *Ionizing Radiation, Part 1: X- and Gamma (γ)-Radiation, and Neutrons* vol 75 (Lyon, France: IARC)

IARC (International Agency for Research on Cancer) 2001 IARC monographs on the evaluation of carcinogenic risks to humans *Ionizing Radiation, Part 2: Some Internally Deposited Radionuclides* vol 78 (Lyon, France: IARC)

Ibrahim S A, Whicker F W and Simon S L 1990 Ground distribution patterns of selected radioactive, chemical, and physical contaminants from dispersion of U mill tailings *Health Phys.* **58** 321–8

ICRP 1995a Age-dependent doses to members of the public from intake of radionuclides: part 3. Ingestion dose coefficients *ICRP Publication 69* (*Ann. ICRP* **25** (1))

ICRP 1995b Age-dependent doses to members of the public from intake of radionuclides: part 4. Inhalation dose coefficients *ICRP Publication 71* (*Ann. ICRP* **25** (3–4))

IOM (Institute of Medicine) 2001 Committee on the health effects associated with exposures during the Gulf war *Depleted Uranium, Pyridostigmine Bromide, Sarin, Vaccines* (*Gulf War and Health* vol 1) (Washington, DC: National Academy Press)

Jablon S, Hrubec Z and Boice J D Jr 1991 Cancer in populations living near nuclear facilities. A survey of mortality nationwide and incidence in two states *J. Am. Med. Assoc.* **265** 1403–8

Jablon S, Hrubec Z, Boice J D Jr and Stone B J 1990 Cancer in populations living near nuclear facilities *NIH Publication* 90-874 (Bethesda, MD: Public Health Service, Department of Health and Human Services)

Jemal A, Murray T, Samuels A, Ghafoor A, Ward E and Thun M 2003 Cancer statistics, 2003 CA *Cancer J. Clin.* **53** 5–28

Laurier D, Grosche B and Hall P 2002 Risk of childhood leukaemia in the vicinity of nuclear installations—findings and recent controversies *Acta Oncol.* **41** 14–24

Lloyd D C *et al* 2001 A study to verify a reported excess of chromosomal aberrations in blood lymphocytes of Namibian uranium miners *Radiat. Res.* **155** 809–17

López-Abente G, Aragonés N and Pollán M 2001 Solid-tumor mortality in the vicinity of uranium cycle facilities and nuclear power plants in Spain *Environ. Health Perspect.* **109** 721–9

López-Abente G, Aragonés N, Pollán M, Ruiz M and Gandarillas A 1999 Leukemia, lymphomas, and myeloma mortality in the vicinity of nuclear power plants and nuclear fuel facilities in Spain *Cancer Epidemiol. Biomarkers Prev.* **8** 925–34

Lubin J H, Boice J D Jr, Edling C, Hornung R W, Howe G R, Kung E, Kusiak R A, Morrison H I, Radford E P, Samet J M, Tirmarche M, Woodard A, Yao S X and Pierce D A 1995 Lung cancer in radon-exposed miners and estimation of risk from indoor exposure *J. Natl Cancer Inst.* **87** 817–27

Mantel N and Ederer F 1985 Exact limits for the ratio of two SMR values *J. Epidemiol. Community Health* **39** 367–8

Marsh G M *et al* 1998 OCMAP-PLUS: a program for the comprehensive analysis of occupational cohort data *Occup. Environ. Med.* **40** 351–62

McGeoghegan D and Binks K 2000a The mortality and cancer morbidity experience of workers at the Springfields uranium production facility, 1946–95 *J. Radiol. Prot.* **20** 111–37

McGeoghegan D and Binks K 2000b The mortality and cancer morbidity experience of workers at the Capenhurst uranium enrichment facility 1946–95 *J. Radiol. Prot.* **20** 381–401

Meyer C R 1990 Summary of environmental monitoring activities in Karnes County requested by Dr Bernstein *Inter-Office Memorandum 26 March 1990* (Austin, TX: Texas Department of Health)

NCI 1999 RateCalc mortality rate generator version 3.2 *Users Guide* (Bethesda, MD: Division of Cancer Epidemiology and Genetics, National Cancer Institute)

NCRP 1993 Radiation protection in the mineral extraction industry *NCRP Report No* 118 (Bethesda, MD: National Council on Radiation Protection and Measurements)

NRC (National Research Council) 1999 *Committee on the Biological Effects of Ionizing Radiations. Radon (BEIR VI)* (Washington, DC: National Academy Press)

Percy C, Stanek E and Gloeckler L 1981 Accuracy of cancer death certificates and its effect on cancer mortality statistics *Am. J. Public Health* **71** 242–520

Polednak A P, Stehney A F and Rowland R E 1978 Mortality among women first employed before 1930 in the US radium dial-painting industry. A group ascertained from employment lists *Am. J. Epidemiol.* **107** 179–95

Priest N D 1989 Alpha-emitters in the skeleton: an evaluation of the risk of leukaemia following intakes of plutonium 239 *Risks from Radium and Thorotrast (Report* 21*)* ed D M Taylor, C W Mays, G B Gerber and R G Thomas (London: British Institute of Radiology) pp 159–65

Priest N D 2001 Toxicity of depleted uranium *Lancet* **357** 244–6

Rowland R E, Stehney A F and Lucas H F Jr 1978 Dose–response relationships for female radium dial workers *Radiat. Res.* **76** 368–83

Ruttenber A J Jr, Kreiss K, Douglas R L, Buhl T E and Millard J 1984 The assessment of human exposure to radionuclides from a uranium mill tailings release and mine dewatering effluent *Health Phys.* **47** 21–35

TDH (Texas Department of Health) 2002 Texas Health Data—Population available from: http://soupfin.tdh.state.tx.us/people.htm

Thomas P A 2000 Radionuclides in the terrestrial ecosystem near a Canadian uranium mill—:Part III. Atmospheric deposition rates (pilot test) *Health Phys.* **78** 633–40

UNSCEAR 1994 *Sources and Effects of Ionizing Radiation E.94.IX11* (Report to the General Assembly, with Scientific Annexes) (New York: United Nations)

UNSCEAR 2000 *Sources and Effects of Ionizing Radiation Vol I: Sources, Vol II: Effects E.00.IX.4* (Report to the General Assembly, with Scientific Annexes) (New York: United Nations)

Upton A C 1990 Carcinogenic effects of low-level ionizing radiation *J. Natl Cancer Inst.* **82** 448–9

USDC (US Department of Commerce) 1992 1990 Census of the population. Characteristic of the population *PC 90-1-B40* (Washington, DC: Bureau of the Census)

Veska E and Eaton R S 1991 Abandoned Rayrock uranium mill tailings in the northwest territories: environmental conditions and radiological impact *Health Phys.* **60** 399–409

Wang Z, Boice J D Jr, Wei L, Beebe G W, Zha Y, Kaplan M M, Tao Z, Maxon H R III, Zhang S, Schneider A B, Tan B, Wesseler T A, Chen D, Ershow A G, Kleinerman R A, Littlefield L G and Preston D 1990 Thyroid nodularity and chromosome aberrations among women in areas of high background radiation in China *J. Natl Cancer Inst.* **82** 478–85

Wei L, Sugahara T and Tao Z (ed) 1997 High levels of natural radiation *Radiation Dose and Health Effects* (Amsterdam: Elsevier)

Comments on “Cancer mortality in a Texas county with prior uranium mining and milling activities, 1950-2001”

Note: This document was prepared by Dr. Standler for discussion with the Colorado Medical Society (CMS) who were considering recommending a complete ban on all in-situ and open pit uranium mining in Colorado with part of the proposal being a request that the American Medical Association (AMA) approve a similar ban nationwide.

This current and important paper compared mortality rates in the important uranium producing area of Karnes County, Texas, to those in four similar control counties that were not uranium producers. Karnes County has had extensive uranium milling, uranium surface mining, and uranium in situ mining from 1954 to the early 1990s.

A very detailed analysis of mortality statistics both overall cancer rates and by specific cancers was performed, with the following results:

- The total numbers of cancer deaths evaluated (1223 in Karnes County and 3857 deaths in the four control counties) are large enough to make the study statistically valid.
- The overall cancer rates in Karnes County and in the control counties were *both* 87% of the overall cancer rate expected based on the general population rates for the US.
- There were no statistically significant increases in Karnes County cancer deaths of *any type of cancer* when Karnes County was compared to the US population, the State of Texas, or the control counties.
- More specifically, there was no increase in cancers of the lung, bone, liver, or kidney. These are clinically important sites because uranium and its daughter product radon can concentrate in these areas.
- No unusual patterns of cancer mortality were seen in Karnes County over a period of 50 years.

The uranium industry is very highly and closely regulated by a variety of state and federal government agencies. To me these findings go a long ways toward offering convincing evidence that our current tight regulatory practices *are* effective in protecting both the general public and the employees who might have been occupationally exposed, both of whom would have lived in Karnes County.

Nancy Standler MD, PhD

Appendix 19

DIATION RESEARCH 167, 711–726 (2007)
3-7587/07 $15.00

Cancer and Noncancer Mortality in Populations Living Near Uranium and Vanadium Mining and Milling Operations in Montrose County, Colorado, 1950–2000

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Boice, J. D., Jr., Mumma, M. T. and Blot, W. J. Cancer and Noncancer Mortality in Populations Living Near Uranium and Vanadium Mining and Milling Operations in Montrose County, Colorado, 1950–2000. *Radiat. Res.* 167, 711–726 (2007).

Mining and milling of uranium in Montrose County on the Western Slope of Colorado began in the early 1900s and continued until the early 1980s. To evaluate the possible impact of these activities on the health of communities living on the Colorado Plateau, mortality rates between 1950 and 2000 among Montrose County residents were compared to rates among residents in five similar counties in Colorado. Standardized mortality ratios (SMRs) were computed as the ratio of observed numbers of deaths in Montrose County to the expected numbers of deaths based on mortality rates in the general populations of Colorado and the United States. Relative risks (RRs) were computed as the ratio of the SMRs for Montrose County to the SMRs for the five comparison counties. Between 1950 and 2000, a total of 1,877 cancer deaths occurred in the population residing in Montrose County, compared with 1,903 expected based on general population rates for Colorado (SMR_{CO} 0.99). There were 11,837 cancer deaths in the five comparison counties during the same 51-year period compared with 12,135 expected (SMR_{CO} 0.98). There was no difference between the total cancer mortality rates in Montrose County and those in the comparison counties (RR = 1.01; 95% CI 0.96–1.06). Except for lung cancer among males (RR = 1.19; 95% CI 1.06–1.33), no statistically significant excesses were seen for any causes of death of *a priori* interest: cancers of the breast, kidney, liver, bone, or childhood cancer, leukemia, non-Hodgkin lymphoma, renal disease or nonmalignant respiratory disease. Lung cancer among females was decreased (RR = 0.83; 95% CI 0.67–1.02). The absence of elevated mortality rates of cancer in Montrose County over a period of 51 years suggests that the historical milling and mining operations did not adversely affect the health of Montrose County residents. Although descriptive correlation analyses such as this preclude definitive causal inferences, the increased lung cancer mortality seen among males but not females is most likely due to prior occupational exposure to radon and cigarette smoking among underground miners residing in Montrose County, consistent with previous cohort studies of Colorado miners and of residents of the town of Uravan in Montrose County. © 2007 by Radiation Research Society

INTRODUCTION

Uranium and vanadium oxides were extracted from carnotite ore as early as 1900 in Montrose County, CO (*1*). In 1912, carnotite ore was mined and radium was extracted at one of the first mills in what later became the town of Uravan, Montrose County, on the Western Slope of Colorado (*2, 3*). By 1919, the mining of uranium was well established as an ongoing industry in Montrose Country (*1*). Between 1925–1945, carnotite ore was mined to extract vanadium for use as a hardening component of steel. Some uranium was also extracted for use in ceramic and chemical industries. In the mid to late 1930s, the U.S. Vanadium Corporation built a mill at Uravan, named from the first three letters of the elements uranium and vanadium. During the 1940s ore was mined and milled in Montrose County to extract uranium for use in the Manhattan Project to produce the first atomic weapons (*2*). According to the U.S. Geological Survey (*5*), there were more uranium mines located in Montrose County (*n* = 223) than in any other county in Colorado. The average density of about one mine per 10 square miles was also the highest in Colorado. Mining and milling activities were substantially curtailed by the 1980s for economic reasons (*2, 4*).

The extraction of uranium from ore produced solid and liquid wastes, called tailings. The wastes contained the naturally occurring radionuclides present in the ore, including thorium, radium and other decay products. Tailing piles, runoff collection ponds, ore transport, and airborne and liquid effluents from the mills (extraction facilities) were potential sources of environmental exposure to humans (*6*). Historical milling and mining activities have raised questions over the years about possible increased exposure of milling and mining communities to ionizing radiation from

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uranium and its decay products, possible contamination of groundwater and vegetation, and possible increased levels of indoor radon.

The primary occupational exposures in uranium mills were to airborne uranium, silica and vanadium. NIOSH conducted a comprehensive study of 1,484 men who worked at one of seven uranium mills on the Colorado Plateau on or after January 1, 1940 (*7*). Increased numbers of deaths were found for nonmalignant respiratory diseases, lung cancer, lymphoma and kidney disease. The authors were unable to show conclusively whether these deaths resulted from working in the mills because length of employment was not associated with increased risks. Studies of other "non-mining" uranium workers have provided little to no evidence of increased cancer risks among occupationally exposed workers (*8–10*). Environmental studies of populations residing in areas near uranium mining, milling or processing facilities similarly have not shown increased cancer risks (*11–13*). Studies of populations with increased levels of uranium, radium, radon and other radionuclides in drinking water also have not found associations with any cancers, overt kidney disease or bone disease (*14–19*).

An earlier cohort study of over 3,500 residents of the town of Uravan in Montrose County (which contained one of the earliest uranium and vanadium mills in the country) found no statistically significant increases in cancer mortality or cancer incidence except for male lung cancer, which was attributed to prior employment of some residents in underground uranium mines and increased tobacco use (*20*). This explanation was plausible since underground miners working on the Colorado Plateau are known to have been exposed to high cumulative levels of radon gas and radon decay products during their working careers and to have been heavy smokers (*21, 22*). While underground miner studies have linked radon exposures and tobacco use to increased lung cancer risks, no other cancer has been reported to be significantly linked to radon concentrations among underground miners (*23–25*). Studies of underground miners of the Colorado Plateau, however, have reported significant elevations of noncancer deaths from tuberculosis, nonmalignant respiratory disease and accidents (*24*).

Radium (which naturally occurs in carnotite ore but is not extracted during the milling of uranium and vanadium) is a component of mill tailings. Excessive ingestion of radium has been linked to bone cancer in occupational studies, although only at extraordinarily high levels, and no other cancer excesses were observed except for a rare carcinoma of the paranasal sinuses (*26, 27*). Radium decays into radon, and radon levels are increased near mill tailings. Case-control studies of indoor radon suggest increased lung cancer rates in long-term residents of homes with high radon concentrations (*25, 28, 29*) but have not found increased rates of childhood leukemia or childhood cancer (*30–32*). Radium also decays by emitting γ radiation, and excessive exposure to such external penetrating radiation is a known cause of breast cancer, leukemia and other malignancies (*33–35*). Cohort studies of uranium processors, millers and miners, however, have revealed no significant increases in leukemia, nor have descriptive studies of communities living near uranium milling and processing facilities revealed significant increases (*7, 8, 11, 12, 25*). Some ecological studies have reported correlations between radon levels and leukemia, but results are not consistent, and some studies appeared methodologically flawed (*25, 36*). Two cohort studies of underground miners have reported increases in leukemia, but the risks were not significant, nor were they correlated with cumulative radon exposures (*37, 38*). A recent case-control study of leukemia among Czech uranium miners reported a significant association with radon concentrations for chronic lymphocytic leukemia, a cancer that is not considered inducible by radiation (*39*), suggesting that aspects in the mining environment other than radon might be involved (*37, 40*).

Vanadium also was extracted from carnotite ore and is another source of potential exposure. No human study has linked vanadium to increased cancer rates (*41*), but recent animal experiments have found significant elevations of lung cancer in rats (*42*).

An earlier cancer mortality study of counties in the Western Slope of Colorado by the National Cancer Institute revealed no unusual patterns of death compared to the rest of Colorado (*43*). A later tabulation of county cancer mortality rates for 1950–1979 suggested increased rates of male lung cancer in Montrose County compared to the state of Colorado, but female lung and breast cancer rates were decreased, as were leukemia rates (*44*). Because of the long history of uranium and vanadium milling and mining activities and the large number of uranium mines in Montrose County, we extended the previous county cancer mortality studies by 20 years and compared the mortality risks in Montrose County with the mortality risks seen in demographically similar counties in Colorado as well as with the state of Colorado and the United States. Further, we evaluated noncancer causes of death in Montrose County, which had not previously been done.

METHOD

Cancer and noncancer mortality rates among Montrose county residents were compared with rates among residents in five other counties in Colorado that were selected because of similar demographic and socioeconomic characteristics. Mortality rates in Montrose County also were compared to the mortality rates in the general populations of Colorado and the United States, and standardized mortality ratios (SMRs) were computed. Following an approach taken by the National Cancer Institute (NCI) in a nationwide study of cancer mortality in counties with nuclear installations, relative risks were estimated as the ratio of the SMRs for Montrose County to the SMRs for the comparison counties (*45*). Similar approaches have been used to evaluate cancer risk in communities living in areas near uranium mining, milling and processing operations in Colorado, Pennsylvania and Texas (*11, 13, 43*).

TABLE 1
Demographic and Socioeconomic Characteristics of Montrose County, the Comparison Counties[a] and the State of Colorado

					Percentage							
County	Total score[a]	Total persons	Area (square miles)	Population density	Male	White	Rural	High school graduate	Age 65+	Employed	Below poverty	Median household income ($)
Study county												
Montrose	—	24,423	2,242	10.9	48.4	96.0	63.7	73.4	16.4	57.2	14.0	22,610
Comparison counties[a]												
Montezuma	177	18,672	2,040	9.2	48.6	85.1	61.0	73.6	12.3	57.3	20.0	22,491
Delta	181	20,980	1,148	18.4	49.1	96.0	81.9	72.4	22.3	45.3	17.4	18,532
Yuma	186	8,954	2,369	3.8	48.9	98.5	69.6	77.7	16.8	59.9	13.1	22,249
Logan	204	17,567	1,845	9.6	48.5	95.8	41.0	79.1	15.4	64.1	14.5	22,065
Mesa	214	93,145	3,341	28.0	48.4	94.9	18.4	79.0	14.4	58.2	14.8	23,698
Total comparison counties	—	159,318	10,743	14.9	48.5	94.2	37.1	77.4	15.4	57.1	15.6	22,570
State of Colorado		3,294,394	103,718	31.8	49.5	88.3	17.6	83.8	10.0	66.4	11.4	30,140

[a] As described in the Methods, a simple rank-sum algorithm was applied to all Colorado counties contrasting demographic and socioeconomic characteristics with those of Montrose County. A low score signifies close similarity to Montrose County. The five counties most similar to Montrose County (i.e., with the lowest scores) were selected as comparison counties.

Mortality Data

Counties are the smallest areas for which both population estimates and annual counts of the number of deaths from specific causes are readily available back to 1950 from the National Center for Health Statistics (*46*). Cancer mortality data for all counties in the state of Colorado from 1950 to 2000 were obtained from the National Cancer Institute (*46*). Noncancer mortality rates for counties in Colorado from 1960 to 1999 were obtained from the University of Pittsburgh (*47*). The number of deaths from noncancer causes was not available and was estimated by multiplying the cause-specific mortality rates by the corresponding age, sex, race and calendar year population data available from the National Cancer Institute (*46*).

Selection of Comparison Counties

Mining and milling activities in Montrose County began in the early 1900s; this county had many more uranium mines and mills than any other Colorado county (*5*). Accordingly, Montrose County was chosen as the study county. Comparison counties were selected based on similar population characteristics. All 62 of Colorado's other counties were eligible for selection as comparison counties. Census Bureau demographic data on nine socioeconomic variables were obtained for all counties, i.e., population density (total residents divided by county area), percentage male, percentage white, percentage rural, percentage high school graduate, percentage over age 64 years, percentage employed, percentage below poverty, and median household income (*48*). For each of these characteristics, counties were sorted and ranked based on their similarity to Montrose County. The rank values for the nine socioeconomic variables were then summed, with a low sum (or score) representing more similarity to Montrose than a high sum (or score). The five counties with the lowest scores (Montezuma, Delta, Yuma, Logan and Mesa) were chosen as the comparison counties (Table 1, Fig. 1). The determination of a socioeconomic score based on area-level characteristics is similar to that done in other studies (*49*). Data on diet, smoking and other potential risk factors for disease are not readily available at the county level, but use of comparison counties in proximity to Montrose County (Montezuma, Delta and Mesa) should help minimize differences in these unknown factors, assuming that factors such as diet would be similar in neighboring areas. Montrose County had the highest number of uranium mines (n = 223) of any county in Colorado. Delta and Yuma Counties did not have any uranium mines, Logan had one, Montezuma had eight, and Mesa had 55 (*5*). The average density of mines in the five comparison counties was about six per 1000 square miles or 600 times less than Montrose County. Montrose County had two operating uranium mills, Mesa Country had one, and the other comparison counties had none. Supplemental analyses excluding Mesa County were conducted to reduce the likelihood that these mining and milling activities had affected the mortality rates in the comparison counties.

Statistical Analyses

Mortality rates for the general populations of Colorado and the United States were used for calculating expected numbers of deaths and SMRs among the Montrose County and comparison county populations. Counts of cancer deaths by cause, sex, race and 5-year age group were obtained for Montrose County and the five comparison counties for each year from 1950 to 2000. For each type of cancer and each county, the expected number of deaths, based on concurrent Colorado and U.S. experience, was calculated for the 51-year study period (*46, 47*). Expected numbers were obtained by multiplying annual Colorado and U.S. cancer death rates by the estimated populations, stratified by 5-year age group, race and sex. Counts of observed and expected deaths were then summed over the periods 1950–1969, 1970–1984 and 1985–2000. These intervals were selected to be of similar size, and consideration was given to the fact that practically all milling and mining activities had ceased by 1985.

The standardized mortality ratio was calculated by dividing the number of deaths observed among the Montrose County population by the number of deaths that would be expected using U.S. (SMR_{US}) or Colorado (SMR_{CO}) rates. Relative risks (RRs) were computed as the ratios of the SMRs for Montrose County to the comparison counties, and 95% confidence intervals were calculated following the methods applied in the NCI nationwide study of nuclear facilities (*45*). A 95% confidence interval that contains 1.00 means that chance cannot be ruled out as a possible explanation for any observed differences in mortality rates between Montrose County and the comparison counties. When a 95% confidence interval does not contain 1.00, the difference in mortality rates is called "statistically significant" and means that chance is not a likely explanation for the observed results (*50*).

SMRs and RRs for noncancer deaths between 1960 and 1999 were computed in a similar manner as for cancer deaths. Although counts of noncancer deaths were not available, they could be estimated accurately

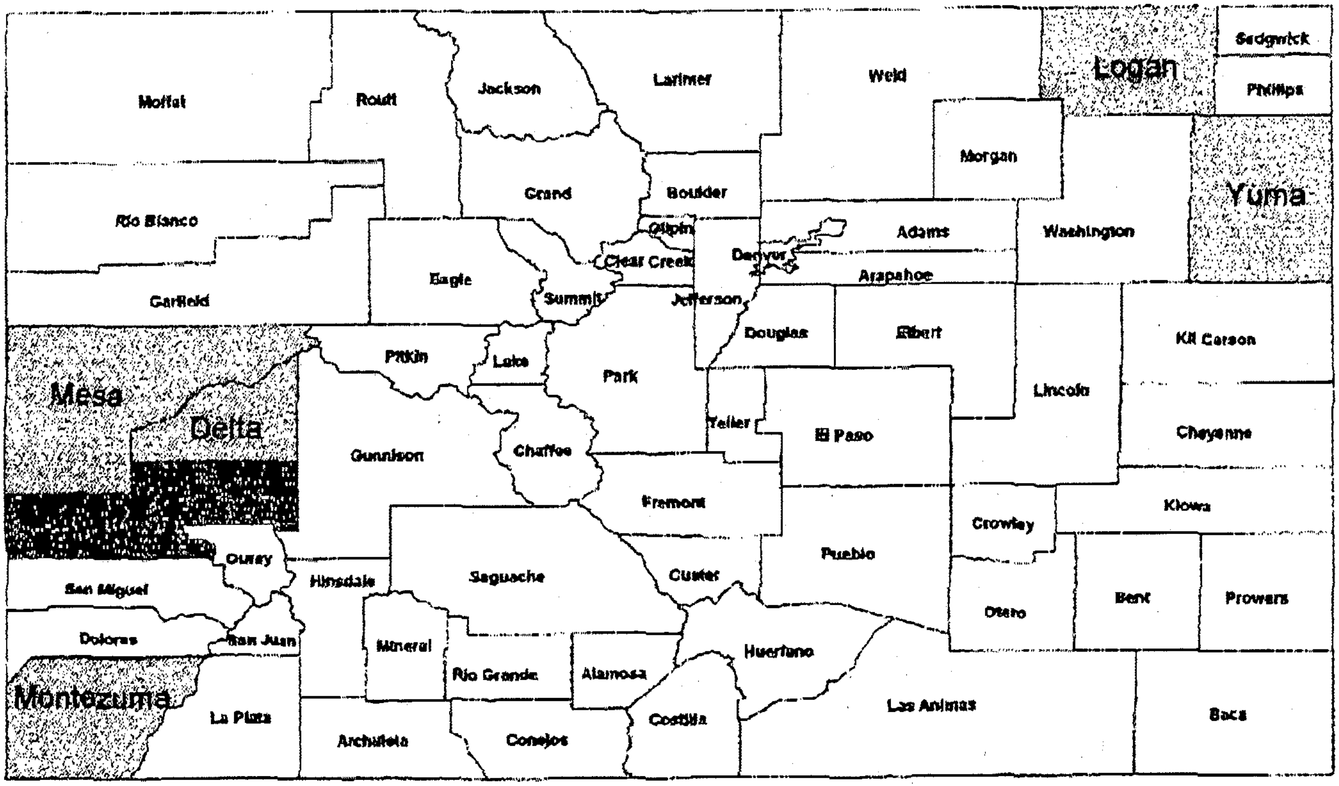


FIG. 1. County map of Colorado indicating the study county (Montrose) and the comparison counties (Mesa, Delta, Montezuma, Logan and Yuma) selected to be similar to Montrose County on demographic and socioeconomic characteristics.

by multiplying the age, calendar year, sex, race and site-specific mortality rates times the corresponding population data obtained from the NCI. This procedure was validated by comparing the estimated counts for cancer deaths with the actual counts of cancer deaths available from the NCI data files (*46*).

While the study uses existing databases that contain no identifying information, strata containing two or fewer deaths are not presented but are listed as LT3 to denote "less than three". This is to abide by the confidentiality requirements for using the NCI and National Center for Health Statistics databases. The concern is the possibility that individuals with certain characteristics might be identified if the number of deaths were small.

RESULTS

The number of residents in Montrose County and the five comparison counties totaled 24,423 and 159,318, respectively, in 1990 (Table 1). Residents in the comparison counties were similar to residents in Montrose County with regard to demographic indicators of cancer risk such as age, race and various accepted measures of socioeconomic status such as educational level and median household income. Most of the population studied was white with few black or Asian citizens; 15.4% of the comparison county residents were older than 64 years compared to 16.4% for Montrose County residents; most graduated from high school (77.4% compared to 73.4%), and most were employed (57.1% compared to 57.2%). The median household incomes of Montrose County ($22,610) and the comparison counties ($22,570) were also similar. Comparison counties were less rural (37.1% compared to 63.7%) than Montrose County, but residents were similar with regard to poverty level (15.6% compared to 14.0%). Montrose and the comparison counties differed from the state of Colorado in being more rural, less educated, older and much less affluent. Because certain diseases are known to be associated with low socioeconomic status (*51, 52*), any differences in mortality risks based on Colorado comparisons may be related in part to differences in socioeconomic factors and not environmental factors. Any bias associated with differences in socioeconomic status would be in the direction of producing higher SMRs. Some variations in characteristics were also seen among the comparison counties (e.g., Yuma has a relatively low population density and Mesa has a high population density). Such differences, however, are balanced by closer similarities in other characteristics (e.g., Yuma is similar to Montrose in rural characteristics and Mesa is similar in poverty characteristics).

Table 2 presents the total number of cancer deaths, SMRs based on Colorado and U.S. rates, and RRs comparing Montrose County with the comparison counties, for all cancers and for specific cancers, during 1950–2000. There were no significantly increased or significantly decreased RRs for any cancer or combination of cancers. No significant differences were seen for all cancers (RR 1.01; 95% CI 0.96–1.06), lung cancer (RR 1.08; 95% CI 0.98–1.19), kidney and liver cancer (RR 0.92; 95% CI 0.74–1.15), breast cancer (RR 0.86; 95% CI 0.71–1.03), non-Hodgkin lymphoma (RR 1.05; 95% CI 0.82–1.34), leukemia (RR 0.78; 95% CI 0.60–1.01), or childhood cancer (RR 0.73; 95% CI 0.43–1.25).

Overall, results based on Colorado population rates were generally similar to results based on the comparison counties (e.g., the SMR_{CO} for all cancer deaths was 0.99 based on Colorado rates, whereas the RR was 1.01 contrasting cancer rates in Montrose with the comparison counties). There were 1,877 cancer deaths in Montrose County (SMR_{CO} 0.99) and 11,837 cancer deaths in the comparison counties (SMR_{CO} 0.98). The most frequent causes of death in Montrose County and the comparison counties were cancer of the lung (SMR_{CO} 1.14 compared to. 1.06), breast (SMR_{CO} 0.80 compared to 0.93), colon and rectum (SMR_{CO} 0.88 compared to 0.93), and prostate (SMR_{CO} 1.07 compared to 1.00). Leukemia deaths occurred below expectation in both Montrose County and the comparison counties (SMR_{CO} 0.73 compared to 0.94). There were five childhood leukemia deaths in Montrose County and 58 in the comparison counties (SMR_{CO} 0.57 compared to 1.14). The SMRs based on U.S. rates were generally lower than those based on Colorado rates (e.g., the all-cancer SMR_{US} of 0.85 was significantly lower than the all-cancer SMR_{CO} of 0.99 based on Colorado rates). Similarly, the lung cancer SMR_{US} of 0.85 based on U.S. rates was significantly low, whereas the SMR_{CO} of 1.14 based on Colorado rates was significantly high.

Contrasting cancer rates in Montrose with the comparison counties revealed no significantly high or significantly low relative risks for any cancer of *a priori* interest. Slight elevations were seen for cancers of the lung (RR 1.08; 95% CI 0.98–1.19), bone (RR 1.36; 95% CI 0.63–2.91), and non-Hodgkin lymphoma (RR 1.05; 95% CI 0.82–1.34). Slight deficits were seen for cancers of the kidney (RR 0.80; 95% CI 0.56–1.14), breast (RR 0.87; 95% CI 0.72–1.04), thyroid (RR 0.82; 95% CI 0.32–2.07), leukemia other than CLL (RR 0.80; 95% CI 0.61–1.06), and childhood cancer (RR 0.73; 95% CI 0.43–1.25).

Of the 28 relative risks presented, 16 were less than 1.00 and 12 were greater than 1.00, a distribution about the overall value of 1.01 for all cancers combined that is consistent with the play of chance when evaluating so many individual cancers. SMRs based on comparisons with the Colorado population were similar to the RRs in magnitude and direction (i.e., above or below 1.00). For all cancers taken together, the SMR_{CO} for men and women combined was 0.99 (95% CI 0.94–1.03) based on Colorado rates and similar to the RR of 1.01 (95% CI 0.96–1.06) based on the comparison counties.

With regard to sex-specific risks, there were no significantly high or significantly low RRs for female residents of Montrose County (Table 3). Overall, female cancer mortality rates in Montrose County were the same as those in the comparison counties (RR 1.00; 95% CI 0.93–1.08). Lung cancer (RR 0.83; 95% CI 0.67–1.02) and breast cancer (RR 0.86; 95% CI 0.72–1.04) risks were notably low, with the deficits approaching statistical significance. The overall cancer rates for males in Montrose County were also similar to those in the comparison counties (RR 1.02; 95% CI 0.95–1.09). Lung cancer, however, was significantly increased (RR 1.19; 95% CI 1.06–1.33), whereas kidney cancer (RR 0.60; 95% CI 0.37–0.99), liver and kidney cancer (RR 0.70; 95% CI 0.50–0.97), and leukemia (RR 0.63; 95% CI 0.44–0.90) were significantly decreased. The SMRs based on Colorado rates were extremely similar to the RRs based on the comparison counties, indicating that the choice of the referent made little difference.

Table 4 presents, for both sexes combined, the SMRs and RRs of mortality for selected cancers in Montrose County for three periods during 1950–2000. Overall, cancer rates in Montrose County were similar to those in the comparison counties. No RR for any cancer was significantly above or below expectation for any time interval. There were no increasing patterns of risk over the 51-year period of observation. There was a tendency for the SMRs and the RRs to be lower in the last interval, 1985–2000.

Table 5 presents SMRs and RRs for noncancer causes of death for the years 1960–1999. A slightly increased RR for all causes of death (RR 1.03; 95% CI 1.01–1.06) compared to the five comparison counties was due largely to a significant increase in deaths from accidents other than automobile accidents (RR 1.15; 95% CI 1.02–1.30). Deaths due to tuberculosis were also significantly increased (RR 1.89; 95% CI 1.10–3.48). Significantly low RRs were seen for hypertension but not for heart disease. Of the 23 RRs presented in Table 5, 10 were below, 11 were above, and two were equal to the central value of 1.03, which is consistent with the play of chance when many comparisons are made.

SMRs based on U.S. rates tended to be lower than those based on Colorado rates. The all-causes-of-death SMR_{US} for Montrose County residents based on U.S. rates, for example, was significantly low. Lower SMRs based on U.S. rates were also seen for heart disease and cerebrovascular disease, but significantly higher mortality rates were seen for nonmalignant respiratory disease, accidents and suicides. These differences were also apparent among residents of the five comparison counties and may reflect differences in socioeconomic factors between the study counties and the general populations of the state of Colorado and the United States (*52*).

Table 6 presents, for both sexes combined, the SMRs and RRs for selected noncancer causes of death in Montrose County for three periods during 1960–1999. There was little tendency for any cause of death to increase over time. The RRs tended to be higher in the earliest interval, 1960–1969, than in any other interval. The all-cause RR was significantly high during 1960–1969 (RR 1.14) whereas it was close to expectation during 1970–1984 (RR 1.02) and 1985–1999 (RR 1.01). The significantly high all-cause RR during 1960–1969 was due to significantly high risks for

TABLE 2
Observed (Obs) and Expected (Exp)[a] Numbers of Cancer Deaths and Standardized Mortality Ratios (SMRs) for Montrose County and the Five Comparison Counties during 1950–2000, and the Estimates of Relative Risk (RR)[b]

	Montrose County				
Cancer (ICD 9)	Obs	Exp_{US}	Exp_{CO}	SMR_{US}	SMR_{CO}
All cancers (140–208)	1,877	2,201.4	1,903.2	0.85*	0.99
Esophagus (150)	22	39.4	31.3	0.56*	0.70
Stomach (151)	87	88.6	80.3	0.98	1.08
Colon/rectum (153, 154)	207	279.7	234.0	0.74*	0.88
Pancreas (157)	121	111.8	107.0	1.08	1.13
Lung (162)	454	531.0	397.5	0.85*	1.14*
Skin (172, 173)	37	38.0	37.7	0.97	0.98
Malignant melanoma of the skin (172)	25	26.7	27.7	0.94	0.90
Breast (174)	126	175.5	158.2	0.72*	0.80*
Cervix uteri (180)	15	26.8	25.0	0.56*	0.60
Corpus uteri (182)	34	29.7	24.4	1.15	1.39
Ovary (183)	49	56.2	54.0	0.87	0.91
Prostate (185)	148	136.3	138.2	1.09	1.07
Urinary bladder (188)	44	57.1	48.4	0.77	0.91
Kidney (189)	34	45.1	41.9	0.75	0.81
Liver and kidney (155, 189)	88	106.3	95.9	0.83	0.92
Bone (170)	8	8.4	6.4	0.95	1.25
Connective tissue (171)	12	11.9	12.0	1.01	1.00
Brain & CNS (191, 192)	44	52.1	49.3	0.84	0.89
Thyroid (193)	5	5.7	5.6	0.88	0.89
Non-Hodgkin lymphoma (200, 202)	75	76.4	72.6	0.98	1.03
Hodgkin lymphoma (201)	15	12.8	11.1	1.17	1.35
Multiple myeloma (203)	33	32.3	32.9	1.02	1.00
Leukemia (204–208)	65	91.4	88.6	0.71*	0.73*
Leukemia, CLL (204.1)[c]	10	13.3	13.1	0.75	0.76
Leukemia, not CLL	55	77.3	74.8	0.71*	0.74*
Childhood leukemia (<20 years)	5	9.0	8.8	0.55	0.57
Childhood cancer (<20 years)	15	21.9	20.1	0.68	0.75

[a] Expected numbers based on U.S. rates (Exp_{US}) and on Colorado rates (Exp_{CO}).

[b] RR is taken as the SMR_{CO} for Montrose County divided by the SMR_{CO} for the comparison counties.

[c] CLL denotes chronic lymphocytic leukemia.

* $P < 0.05$.

tuberculosis (RR 3.07), diabetes (RR 1.90), cerebrovascular disease (RR 1.22), cirrhosis of the liver (RR 1.91), and all external causes of death (RR 1.20). Except for tuberculosis, none of these causes of death were significantly elevated overall or during 1970–1984 or 1985–1999. For the interval 1970–1984, the RR (1.04) and estimated number of all-cancer deaths ($n = 508$) were the same as those computed in Table 4 based on exact cancer counts; this concordance supports the validity of the approach used to estimate RRs for the noncancer deaths.

DISCUSSION

Cancer and noncancer mortality rates among residents of Montrose County were similar to those of residents in the state of Colorado as well as residents in five comparison counties in Colorado selected as comparable based on a wide range of demographic and socioeconomic characteristics. Notably, no significant increases were seen for either men or women for all cancers combined, kidney cancer or kidney disease, liver cancer or bone cancer, leukemia, lymphoma or nonmalignant respiratory disease. These causes of death were of an *a priori* interest because of associations reported previously in studies of uranium mill workers and uranium miners of the Colorado Plateau (*7*, *24*) or because they are the most biologically plausible tissues to be affected by any deposition of uranium and its decay products after possible ingestion or inhalation (*53*, *54*). Significant increases among men but not women, however, were seen for lung cancer, tuberculosis and accidental injuries. These causes of death were also previously reported to be significantly increased among male miners of the Colorado Plateau (*24*) and suggest that the mortality rates in Montrose County were influenced by occupational rather than environmental factors since it is implausible that environmental exposures would affect the mortality rates of these three causes of death in one sex but not in the other. Tobacco use likely contributed to this risk of lung cancer since miners of the Colorado Plateau are known to be heavy smokers (*22*). Although there were increases and decreases in other causes of death over time, there were no consistent patterns to suggest that living in Montrose County increased the risk

TABLE 2
Extended

Comparison counties						
Obs	Exp_{US}	Exp_{CO}	SMR_{US}	SMR_{CO}	RR[a]	95% CI
11,837	13,981.4	12,135.3	0.85*	0.98	1.01	0.96–1.06
196	247.1	195.4	0.79*	1.00	0.70	0.45–1.09
496	581.0	527.4	0.85*	0.94	1.15	0.92–1.45
1,416	1,814.8	1,519.7	0.78*	0.93	0.95	0.82–1.10
705	715.3	685.6	0.99	1.03	1.10	0.91–1.33
2,612	3,282.0	2,472.7	0.80*	1.06	1.08	0.98–1.19
218	237.0	235.3	0.92	0.93	1.06	0.75–1.50
171	164.5	171.4	1.04	1.00	0.90	0.59–1.38
951	1,133.7	1,025.9	0.84*	0.93	0.86	0.71–1.03
136	176.5	165.6	0.77*	0.82	0.73	0.43–1.24
168	197.4	163.4	0.85	1.03	1.35	0.94–1.96
337	363.6	350.3	0.93	0.96	0.94	0.70–1.27
881	865.6	882.1	1.02	1.00	1.07	0.90–1.28
281	369.2	312.9	0.76*	0.90	1.01	0.74–1.39
270	282.8	264.9	0.95	1.02	0.80	0.56–1.14
613	679.8	615.2	0.90	1.00	0.92	0.74–1.15
38	53.9	41.3	0.70	0.92	1.36	0.63–2.91
58	73.9	75.6	0.78	0.77	1.30	0.70–2.42
291	320.0	302.7	0.91	0.96	0.93	0.68–1.28
40	37.2	36.7	1.07	1.09	0.82	0.32–2.07
451	479.9	457.4	0.94	0.99	1.05	0.82–1.34
55	80.9	70.0	0.68*	0.79	1.72	0.97–3.04
217	204.0	209.5	1.06	1.04	0.97	0.67–1.39
530	578.9	560.9	0.92	0.94	0.78	0.60–1.01
90	84.1	83.2	1.07	1.08	0.71	0.37–1.36
434	489.8	473.8	0.89	0.92	0.80	0.61–1.06
58	52.3	50.7	1.11	1.14	0.50	0.20–1.24
120	128.8	117.6	0.93	1.02	0.73	0.43–1.25

of cancer or other fatal diseases other than those related to employment as an underground miner and increased tobacco use. This is one of the few descriptive county mortality studies that included both cancer and noncancer mortality, and the male excess of specific cancer and noncancer diseases that have been associated with underground mining (i.e., lung cancer, tuberculosis and accidental deaths) strengthens the inference made that occupational exposures and cigarette smoking were responsible for the observed county excesses.

Lung Cancer

Given the statistically significant increase in lung cancer rates among men living in Montrose County, we considered the possibility that environmental exposures from uranium and vanadium milling and mining activities might be contributing factors. This is unlikely, however, because the risk of lung cancer was decreased in women (RR 0.82), and it is implausible that an environmental exposure would increase the risk of lung cancer among men and decrease the risk of lung cancer among women. Further, it has been known for some time that working as an underground miner in the Colorado Plateau is associated with an increased rate of lung cancer due to high-level exposure to radon and its decay products, increased tobacco use and possibly other mine exposures such as silica, diesel exhaust and blasting fumes (*21, 22, 24*). It has also been reported that radon exposures and cigarette smoking among underground miners of the Colorado Plateau have interacted in a synergistic or nearly multiplicative fashion to increase lung cancer risks. It is noteworthy that a previous study of persons living in the town of Uravan in Montrose County found a significant increase in lung cancer among men but not women, which was also attributed to employment in underground mines and smoking and not to environmental exposures (*20*).

Because workers with a specific occupation usually make up only a small percentage of all persons residing in a county, it is often difficult to identify occupational risks based on county mortality studies. However, there are notable examples where this has been possible [e.g., occupational exposure to asbestos from shipyard work during World War II was identified as a risk factor for lung cancer based on county mortality data and later confirmed in analytic studies (*55*)]. Indirect support for the likelihood that our county mortality study identified an occupational rather than environmental cause of male lung cancer also comes from the similarities in other causes of death that were elevated both

TABLE 3
Observed (Obs)[a] Numbers of Cancer Deaths and Standardized Mortality Ratios (SMRs) for Montrose County for Males and Females during 1950–2000, and the Estimates of Relative Risk (RR)[b]

	Males					Females				
Cancer (ICD 9)	Obs[a]	SMR_{US}	SMR_{CO}	RR[b]	95% CI	Obs[a]	SMR_{US}	SMR_{CO}	RR[b]	95% CI
All cancers (140–208)	1,068	0.85*	1.02	1.02	0.95–1.09	809	0.85*	0.95	1.00	0.93–1.08
Esophagus (150)	16	0.52*	0.65	0.63	0.37–1.05	6	0.69	0.87	1.01	0.43–2.38
Stomach (151)	63	1.10	1.21	1.30	0.99–1.70	24	0.77	0.85	0.89	0.58–1.37
Colon/rectum (153, 154)	108	0.72*	0.90	0.97	0.79–1.19	99	0.76*	0.86	0.93	0.75–1.14
Pancreas (157)	64	1.02	1.08	0.99	0.76–1.28	57	1.16	1.20	1.26	0.95–1.67
Lung (162)	353	0.94	1.27*	1.19*	1.06–1.33	101	0.66*	0.84	0.83	0.67–1.02
Skin (172, 173)	24	0.98	1.00	1.06	0.69–1.64	13	0.96	0.95	1.05	0.59–1.89
Malignant melanoma of the skin (172)	16	0.97	0.94	0.97	0.57–1.64	9	0.90	0.84	0.81	0.40–1.62
Breast (174)	—	—	—	—	—	126	0.72*	0.80*	0.86	0.72–1.04
Cervix uteri (180)	—	—	—	—	—	15	0.56*	0.60*	0.73	0.43–1.24
Corpus uteri (182)	—	—	—	—	—	34	1.15	1.39	1.35	0.94–1.96
Ovary (183)	—	—	—	—	—	49	0.87	0.91	0.94	0.70–1.27
Prostate (185)	148	1.09	1.07	1.07	0.90–1.28		—	—	—	—
Urinary bladder (188)	29	0.70	0.84	0.97	0.65 1.43	15	0.97	1.09	1.12	0.65–1.93
Kidney (189)	17	0.58*	0.64	0.60*	0.37–0.99	17	1.08	1.10	1.16	0.69–1.94
Liver and kidney (155, 189)	39	0.63*	0.72*	0.70*	0.50–0.97	49	1.11	1.17	1.23	0.91–1.67
Bone (170)	6	1.19	1.55	1.74	0.71–4.29	LT3	0.60	0.79	0.82	0.19–3.56
Connective tissue (171)	5	0.80	0.79	1.06	0.41–2.75	7	1.27	1.23	1.55	0.68–3.53
Brain and CNS (191, 192)	23	0.76	0.81	0.83	0.54–1.29	21	0.96	1.00	1.06	0.67–1.69
Thyroid (193)	LT3	0.44	0.46	0.42	0.06–3.15	4	1.19	1.16	1.07	0.37–3.08
Non-Hodgkin lymphoma (200, 202)	32	0.75	0.82	0.81	0.56–1.18	43	1.28	1.29	1.33	0.96–1.85
Hodgkin lymphoma (201)	7	0.89	0.98	1.49	0.65–3.41	8	1.63	2.00	1.99	0.90–4.40
Multiple myeloma (203)	18	1.00	0.99	0.92	0.56–1.50	15	1.05	1.02	1.03	0.60–1.78
Leukemia (204–208)	32	0.59*	0.61*	0.63*	0.44–0.90	33	0.89	0.92	1.01	0.70–1.46
Leukemia, CLL (204.1)[c]	6	0.73	0.72	0.61	0.26–1.41	4	0.80	0.84	0.91	0.32–2.59
Leukemia, not CLL	26	0.57*	0.59*	0.64*	0.43–0.96	29	0.92	0.94	1.03	0.70–1.53
Childhood leukemia (<20 years)	LT3	0.19	0.20	0.19	0.03–1.37	4	1.07	1.05	0.86	0.30–2.45
Childhood cancer (<20 years)	6	0.47	0.52	0.51	0.22 1.17	9	0.97	1.06	1.03	0.51–2.10

[a] Observed number of cancer deaths in Montrose County. LT3 denotes less than 3 deaths.

[b] RR is taken as the SMR_{CO} for Montrose County divided by the SMR_{CO} for the comparison counties.

[c] CLL denotes chronic lymphocytic leukemia.

* $P < 0.05$.

among miners of the Colorado Plateau and among Montrose County residents (i.e., tuberculosis and accidental deaths were significantly increased among miners and also among male, but not female, residents of Montrose County).

Smoking

Cigarette smoking is the predominant cause of lung cancer and is responsible for more than 87% of all lung cancers diagnosed in the United States (*56*). It is thus possible that men in Montrose County used tobacco products to a greater extent than men who lived in other counties in Colorado. This supposition seems possible since miners of the Colorado Plateau are known to be heavy smokers (*22*). Females residing in Montrose County had a lower risk of lung cancer than females residing in the comparison counties or the state of Colorado. Although this suggests that they may have smoked proportionally less than females in the comparison counties, the lower risk was not significant and thus chance cannot be ruled out. Further, the risk of other smoking-related sites among females, such as the bladder and pancreas, was slightly elevated and in the opposite direction expected if they were infrequent smokers.

External Radiation

The potential for environmental exposures to penetrating radiation, such as γ rays, to have contributed to the risk of cancer in Montrose County residents is also unlikely because of the deficits seen for leukemia, female breast cancer and childhood cancer. Leukemia and female breast cancer are the cancers most frequently observed to be increased in comprehensive epidemiological studies of populations exposed to excessive amounts of ionizing radiation, and, in addition, children are considered to be at higher risk of radiation-induced cancers than adults (*33–35*). Living in areas of high natural background radiation, which primarily would include exposure to external radiation, also has not been convincingly linked to elevations in cancer risk or thyroid disease (*57, 58*).

Uranium Ingestion

Uranium from the environment can enter the body by ingestion of food and water or by inhalation of uranium

TABLE 4
Standardized Mortality Ratios (SMR) and Relative Risks (RRs) for Selected Cancer Deaths in Montrose County for Three Times during 1950–2000 for Both Sexes Combined

	1950–1969			1970–1984			1985–2000		
Cancer (ICD 9)	Obs[a]	SMR_{co}	RR[b]	Obs[a]	SMR_{co}	RR[b]	Obs[a]	SMR_{co}	RR[b]
All cancers (140–208)	470	1.03	1.10	508	0.99	1.04	899	0.96	0.94
Esophagus (150)	5	0.94	1.04	6	0.87	1.15	11	0.58	0.51
Stomach (151)	45	1.22	1.23	23	1.18	1.47	19	0.80	0.81
Colon/rectum (153, 154)	55	0.89	1.03	53	0.78	0.81	99	0.94	0.98
Pancreas (157)	33	1.27	1.04	25	0.86	0.88	63	1.21	1.27
Lung (162)	67	1.14	1.28	133	1.22*	1.18	254	1.11	0.98
Skin (172, 173)	16	2.07*	1.96	8	0.83	0.87	13	0.64	0.71
Malignant melanoma of the skin (172)	11	2.49*	1.97	4	0.52	0.50	10	0.64	0.71
Breast (174)	35	0.91	1.08	32	0.71	0.72	59	0.79	0.84
Cervix uteri (180)	9	0.69	0.91	3	0.51	0.63	3	0.49	0.50
Corpus uteri (182)	7	0.86	0.75	10	1.50	2.07	17	1.77*	1.52
Ovary (183)	14	1.05	1.15	14	0.94	0.91	21	0.82	0.85
Prostate (185)	36	1.14	1.04	44	1.26	1.32	68	0.95	0.96
Urinary bladder (188)	12	0.87	1.01	12	0.92	0.92	20	0.93	1.08
Kidney (189)	6	0.63	0.54	9	0.79	0.91	19	0.90	0.86
Liver and kidney (155, 189)	28	1.07	0.89	22	0.89	1.10	38	0.84	0.86
Bone (170)	3	1.06	0.98	LT3	1.14	1.19	3	1.64	2.65
Connective tissue (171)	LT3	0.91	2.16	3	0.97	1.02	7	1.04	1.29
Brain and CNS (191, 192)	4	0.36*	0.41	13	0.95	0.91	27	1.10	1.15
Thyroid (193)	LT3	1.03	0.86	LT3	1.53	1.49	LT3	0.42	0.41
Non-Hodgkin lymphoma (200, 202)	14	0.95	0.89	16	0.92	1.04	45	1.11	1.11
Hodgkin lymphoma (201)	7	1.28	1.70	3	0.94	1.06	5	2.01	2.81
Multiple myeloma (203)	3	0.59	0.73	13	1.48	1.49	17	0.89	0.79
Leukemia (204–208)	21	0.83	0.87	14	0.58*	0.60	30	0.77	0.84
Leukemia, CLL (204.1)	0	0.00	0.00	LT3	0.50	0.53	8	0.93	0.81
Leukemia, not CLL	21	0.85	0.89	12	0.59	0.61	22	0.74	0.88
Childhood leukemia (<20 years)	LT3	0.39	0.30	LT3	0.85	0.89	LT3	0.81	0.89
Childhood cancer (<20 years)	7	0.65	0.57	6	1.06	1.17	LT3	0.56	0.66

Notes. SMRs based on rates in Colorado population. RRs based on comparison counties.
[a] Observed number of cancer deaths in Montrose County. LT3 denotes less than three deaths.
[b] RR is taken as the SMR_{co} in Montrose County divided by the SMR_{co} in the comparison counties.
* $P < 0.05$.

containing dust. Uranium is ubiquitous and is distributed throughout the Earth's crust. Environmental exposures to uranium, however, have not been linked to any detrimental effects (*59*), and the IARC has concluded that there is inadequate evidence to classify uranium as a human carcinogen (*27*). Because uranium has such a long half-life, it is not very radioactive. Chemical toxicity (especially of the kidney) is considered more important for human health than the risk of cancer from uranium's radioactive properties (*59*). Nevertheless, even with respect to chemical toxicity, studies of workers exposed to uranium have failed to demonstrate overt kidney disease (*24*, *60*) including end stage renal disease (*7*). Among Montrose County residents, deaths associated with kidney disease were not significantly increased, again suggesting that any environmental exposures to uranium milling products were likely too low to result in toxic effects.

Occupational Studies

Workers exposed to uranium dust during milling, processing and manufacturing have not shown significant or consistent increases in lung cancer, kidney cancer or any other cancer in large-scale occupational studies (*8–10*, *27*, *61*, *62*), so it is not surprising that lower-level environmental exposures are not found to increase cancer risks. One study of uranium processing reported a significant dose response for kidney cancer based on four high-dose cases, but the SMR for kidney cancer was not significantly increased, and the authors concluded that chance was a possible explanation (*63*). Studies of uranium mill workers have reported significant increases of nonmalignant respiratory disease and nonsignificant increases of lymphoma, but the associations were not considered causal because increased risks were not seen among the workers who were employed for the longest time (*7*). Residents of Montrose County were not found to be at significant risk of dying from nonmalignant respiratory disease or from lymphoma.

Radon and Radium

While occupational exposures to high radon levels in underground mines have been shown to increase lung cancer risks, employment in underground mines has not been con-

TABLE 5
Observed (Obs) and Expected (Exp)[a] Numbers of Noncancer Deaths and Standardized Mortality Ratios (SMRs) for Montrose County and the Five Comparison Counties during 1960–1999, and the Estimates of Relative Risk (RR)[b]

	Montrose County				
Cause of death (ICD 9)	Obs[c]	Exp_{US}	Exp_{CO}	SMR_{US}	SMR_{CO}
All causes of death (001–999)	8,617	8,941.7	8,330.3	0.96*	1.03*
Tuberculosis (010–018)	15	12.1	10.7	1.24	1.40
All malignant neoplasms (140–208)	1,610	1,888.0	1,620.1	0.85*	0.99
Diabetes mellitus (250)	152	173.9	139.8	0.87	1.09
Cerebrovascular disease (430–438)	720	755.2	659.2	0.95	1.09*
All heart disease (390–398, 404, 410–429)	2,638	3,316.8	2,705.9	0.80*	0.97
Hypertension with heart disease (402, 404)	58	104.4	71.7	0.56*	0.81
Hypertension without heart disease (401, 403, 405)	23	38.1	35.3	0.60*	0.65*
Non-malignant respiratory disease (460–519)	897	708.5	903.0	1.27*	0.99
Influenza and pneumonia (480–487)	318	300.2	356.7	1.06	0.89
Bronchitis, emphysema, asthma (490–493)	188	133.3	181.3	1.41*	1.04
Bronchitis (490, 491)	37	34.5	43.3	1.07	0.85
Emphysema (492)	126	83.7	116.3	1.51*	1.08
Asthma (493)	25	15.1	21.7	1.65*	1.15
Ulcer of stomach and duodenum (531–533)	44	33.1	39.1	1.33	1.12
Cirrhosis of liver (571)	97	114.7	109.2	0.85	0.89
Nephritis and nephrosis (580–589)	68	69.8	59.7	0.97	1.14
All external causes of death (800–999)	810	572.6	667.8	1.41*	1.21*
Accidents (850–949)	595	399.7	446.7	1.49*	1.33*
Motor vehicle accidents (810–825)	270	186.6	197.9	1.45*	1.36*
All other accidents (800–807, 826–949)	325	213.1	248.8	1.53*	1.31*
Suicides (950–959)	174	115.7	162.6	1.50*	1.07
Homicides and other external causes (960–978, 980–999)	41	57.2	58.5	0.72*	0.70*

[a] Expected numbers based on U.S. rates (Exp_{US}) and on Colorado rates (Exp_{CO}).

[b] RR is taken as the SMR_{CO} for Montrose County divided by the SMR_{CO} for the comparison counties.

[c] The observed numbers were estimated by applying the age, calendar year, sex and cause-specific mortality rates for Montrose County for 1960–1999 to the corresponding Montrose County population data. All cancer deaths were accurately known and comparison with these known values validated the estimation procedure. Slight differences might occur, however, due to rounding.

* $P < 0.05$.

vincingly associated with any other cancer (*23, 25*). Again, were environmental (as opposed to occupational) radon exposure the cause of elevated lung cancer rates observed in males living in Montrose County, a corresponding increase should have been observed in females, but it was not. Risk of leukemia has been investigated in case-control studies of residential radon exposures, but no significant associations were found (*27, 30, 31*). Leukemia and childhood leukemia did not occur at elevated rates among Montrose County residents in the current or previous county mortality studies (*43, 44*).

Vanadium

Carnotite ore also was processed to extract vanadium in addition to uranium and is another source of potential exposure. No human study has linked vanadium to increased cancer rates (*41, 64*), but one animal study recently reported significant elevations of lung cancer in rats, although not mice, after 2 years of continuous inhalation of vanadium pentoxide (*42*). There is some evidence that very large exposures to vanadium could result in kidney damage (*64*). Thus, if vanadium exposures were to result in adverse health effects among residents of Montrose County, they would likely involve damage to the lungs and/or kidney. Similar to the discussion of uranium and radiation exposure, it would be implausible that environmental exposure to vanadium would increase the risk of lung cancer among males while decreasing the risk among females. Further, kidney cancer and kidney disease were not significantly increased among Montrose county residents.

Strengths and Limitations

Strengths of our geographical correlation study include the availability of mortality data that spanned over 50 years, the long history of milling and mining operations in Montrose County from the early 1900s to after 1970, the large number of uranium mines ($n = 223$) and mills ($n = 2$), the availability of several comparison populations, the use of previously accepted methodologies, and the insights provided by previous county, occupational and residential studies of Colorado Plateau populations. Evaluation of both cancer and noncancer mortality is another unique strength of this county investigation.

The minimum latent period for the development of solid cancer after radiation exposure is approximately 5 to 10 years and for leukemia approximately 2 years (*33–35*).

TABLE 5
Extended

Comparison counties						
Obs[c]	Exp_{us}	Exp_{co}	SMR_{us}	SMR_{co}	RR[b]	95% CI
54,125	58,381.1	54,392.5	0.93*	1.00	1.04*	1.02–1.00
51	80.7	71.2	0.63*	0.72*	1.96*	1.10–3.49
10,117	12,004.8	10,315.8	0.84*	0.98	1.01	0.96–1.07
968	1,134.3	910.8	0.85*	1.06	1.02	0.86–1.21
4,600	5,176.4	4,515.5	0.89*	1.02	1.07	0.99–1.16
17,912	21,996.4	18,019.4	0.81*	0.99	0.98	0.94–1.02
557	712.4	495.3	0.78*	1.12*	0.72*	0.55–0.94
240	256.4	238.9	0.94	1.00	0.65*	0.42–0.99
5,548	4,570.2	5,842.4	1.21*	0.95*	1.05	0.97–1.12
2,085	1,990.5	2,386.4	1.05	0.87*	1.02	0.91–1.15
1,128	855.3	1,168.1	1.32*	0.97	1.07	0.92–1.25
262	218.1	273.5	1.20*	0.96	0.89	0.63–1.26
742	540.0	755.1	1.37*	0.98	1.10	0.91–1.33
124	97.2	139.5	1.28*	0.89	1.30	0.84–1.99
242	218.9	261.6	1.11	0.93	1.22	0.88–1.68
540	709.7	676.1	0.76*	0.80*	1.11	0.90–1.38
404	451.1	386.5	0.90*	1.05	1.09	0.84–1.41
5,033	3,662.5	4,249.6	1.37*	1.18*	1.02	0.95–1.10
3,678	2,559.1	2,853.8	1.44*	1.29*	1.03	0.95–1.13
1,866	1,187.7	1,256.2	1.57*	1.49*	0.92	0.81–1.04
1,812	1,371.4	1,597.6	1.32*	1.13*	1.15*	1.02–1.30
1,026	725.5	1,017.8	1.41*	1.01	1.06	0.90–1.25
329	377.8	377.9	0.87*	0.87*	0.80	0.58–1.11

Thus, because uranium and vanadium mining and milling activities in Montrose Country began in the early 1900s, there was ample time for any environmental exposures to accumulate and any effects on resident populations to be detected during 1950–2000. Mortality occurring before 1950 could not be evaluated because county mortality data are not readily available before then.

Comparing the mortality experience of residents of Montrose County with that of demographically similar counties in Colorado followed the methods used by the National Cancer Institute in similar studies (*43, 45*). The use of local comparison populations rather than the state of Colorado or the entire United States minimizes biases possibly associated with different demographic and socioeconomic features that cannot be easily controlled for in analyses. For example, an early report of an excess of chronic renal disease among miners of the Colorado Plateau based on comparisons with U.S. rates was not apparent when comparisons were made based on rates in the corresponding four-state area (*24*). Finally, the Montrose County mortality analyses could be interpreted in light of findings from previous studies; e.g., the excess of lung cancer in men but not women was consistent with an occupational exposure to radon and tobacco use in underground mines previously reported in Uravan and Montrose County (*20, 44*). The excess of tuberculosis and accidental deaths among men but not women was similarly consistent with findings from studies of underground miners of the Colorado Plateau (*24*).

Common to all ecological or geographic correlation studies, however, our study could not assign exposure levels to individuals or directly control for potential confounding factors such as cigarette smoking (*65*). However, because the milling and mining operations in Montrose County began many years before 1950, and because there were many more uranium mines in Montrose County than any other county in Colorado, it is reasonable to assume that the residents of Montrose County experienced more environmental exposures over time than residents of other counties, albeit at presumably low levels. The comparison counties were selected to have similar demographic and socioeconomic characteristics so that personal habits such as use of tobacco products and diet or other potentially confounding factors might be as similar as possible to those of residents of Montrose County. The slightly lower socioeconomic status among Montrose Country residents than the comparison county residents and Colorado state residents suggests that this selection process was not perfect. However, the lower measures of socioeconomic status would act in the direction of increasing the SMRs and RRs in Montrose County, and no consistent increases were seen.

Common to all geographical correlation studies, the comparison counties also could not be perfectly matched on all characteristics. Mesa County, for example, had a higher population density than Montrose County and included some residents who had engaged in uranium mill and mine activities, which might have reduced the magnitude of any

TABLE 6
Standardized Mortality Ratios (SMRs) and Relative Risks (RRs) for Selected Noncancer Deaths in Montrose County for Three Time Periods during 1960–1999 for Both Sexes Combined

	1960–1969			1970–1984			1985–1999		
Cause of death (ICD 9)	Obs[a]	$\mathrm{SMR}_{\mathrm{co}}$	RR[b]	Obs[a]	$\mathrm{SMR}_{\mathrm{co}}$	RR[b]	Obs[a]	$\mathrm{SMR}_{\mathrm{co}}$	RR[b]
All causes of death (001–999)	1,816	1.10*	1.14*	2,817	1.01	1.02	3,984	1.03	1.01
Tuberculosis (010–018)	11	1.89	3.07*	LT3	0.66	0.76	LT3	1.11	1.39
All malignant neoplasms (140–208)	255	1.05	1.12	508	0.99	1.04	846	0.98	0.97
Diabetes mellitus (250)	47	2.24*	1.90*	43	1.01	1.01	62	0.81	0.76*
Cerebrovascular disease (430–438)	215	1.31*	1.22*	265	1.14	1.05	239	0.91	1.00
All heart disease (390–398, 404, 410–429)	599	1.01	1.05	890	0.89*	0.94	1,149	1.03	0.97
Hypertension with heart disease (402, 404)	28	1.05	0.77	17	0.97	0.93	13	0.47*	0.52*
Hypertension without heart disease (401, 403, 405)	8	1.00	1.31	7	0.80	0.76	8	0.43*	0.39*
Non-malignant respiratory disease (460–519)	119	0.83*	0.96	295	1.13	1.24*	483	0.97	0.97
Influenza and pneumonia (480–487)	56	0.67*	0.94	123	1.13	1.39*	139	0.85	0.84
Bronchitis, emphysema, asthma (490–493)	45	1.04	0.95	48	0.88	0.89	95	1.14	1.30*
Bronchitis (490, 491)	9	1.43	1.95	8	0.84	0.95	20	0.73	0.70
Emphysema (492)	28	0.86	0.73	36	0.90	0.87	61	1.40*	1.84*
Asthma (493)	8	1.82	2.00	4	0.81	0.99	13	1.05	1.16
Ulcer of stomach and duodenum (531–533)	18	1.39	1.66	16	1.32	1.21	10	0.71	0.83
Cirrhosis of liver (571)	26	1.17	1.91*	30	0.72	0.94	42	0.92	1.00
Nephritis and nephrosis (580–589)	13	1.52	1.30	27	1.65*	1.52	28	0.81	0.81
All external causes of death (800–999)	205	1.34*	1.20*	290	1.16*	0.92	315	1.19*	1.03
Accidents (850–949)	170	1.50*	1.23*	212	1.27*	0.90	213	1.29*	1.07
Motor vehicle accidents (810–825)	77	1.55*	1.09	104	1.34*	0.83	89	1.27*	0.91
All other accidents (800–807, 826–949)	93	1.45*	1.37*	108	1.21	0.96	124	1.30*	1.22*
Suicides (950–959)	29	0.91	1.16	58	0.99	0.98	87	1.21	1.09
Homicides and other external causes (960–978, 980–999)	5	0.62	0.75	20	0.82	1.08	15	0.58*	0.58*

Notes. SMRs based on rates in the Colorado population. RRs based on comparison counties.

[a] Observed deaths of deaths in Montrose County. See footnote 3 in Table 5 for explanation of estimation procedure. LT3 denotes less than 3.

[b] RR is taken as the $\mathrm{SMR}_{\mathrm{co}}$ for Montrose County divided by the $\mathrm{SMR}_{\mathrm{co}}$ for the comparison counties.

* $P < 0.05$.

observed associations. Analyses excluding Mesa County (and also Yuma and Logan counties) produced similar results as those based on all five comparison counties (Table 7). Comparisons with the general populations of Colorado and the United States also yielded similar results [e.g., based on Colorado rates, significant increases in lung cancer mortality among men (but not women) were seen only among residents of Montrose County and not the residents of the comparison counties]. The advantages of the five-county analyses over the two-county analyses include statistical precision due to larger numbers and likely validity given the closer similarity of essentially all cancer rates with those of the state of Colorado.

While the fact of death within the study counties is known with certainty, length of residence and migration into and from the counties are not known for individuals. There was in general population growth throughout the years, although there may have been some migration out of Montrose County when the uranium industry became less active in the 1980s. Nonetheless, there would have been ample opportunity for any environmental exposures from milling or mining activities to occur and accumulate from the late 1930s to the 1970s in Montrose County so that any increase in mortality from 1950 to about 1984 related to such exposures could have been observed. Further, there was little evidence that Montrose County experienced population changes different from those of the comparison counties over the years 1950 to 2000. The percentage increase in population growth, for example, was essentially the same for each decade over this period [e.g., the population of Montrose County grew from 15,220 in 1950 to 24,423 in 1990 (or 60%), whereas the population growth in the comparison counties was from 94,341 to 159,318 (or 68%)]. Although immigration of "nonexposed" persons might be expected to reduce somewhat the magnitude of the risk associated with possible environmental exposures, much of the increase in Montrose County was related to employment opportunities in the uranium industry and associated occupational and environmental exposures.

Our study is of mortality and not incidence. However, because reporting of deaths is likely to be similar within Montrose County and the comparison counties, and many of the diseases of interest (e.g., lung cancer), have a high fatality rate, mortality would be expected to reflect incidence fairly closely. The current 5-year survival rate for

TABLE 7
Observed (Obs) and Expected (Exp)[a] Numbers of Cancer Deaths and SMRs Occurring in the Two Most Similar Comparison Counties (Delta and Montezuma) during 1950–2000, and the Estimates of Relative Risk (RR)[b] Comparing Montrose County with These Two Counties

	Delta and Montezuma						
Cancer (ICD 9)	Obs	$\mathrm{Exp}_{\mathrm{us}}$	$\mathrm{Exp}_{\mathrm{co}}$	$\mathrm{SMR}_{\mathrm{us}}$	$\mathrm{SMR}_{\mathrm{co}}$	RR[b]	95% CI
All cancers (140–208)	3,254	3,981.4	3,467.5	0.82*	0.94*	1.05	0.99–1.11
Esophagus (150)	45	71.3	56.8	0.63*	0.79	0.89	0.53–1.48
Stomach (151)	142	168.6	153.0	0.84*	0.93	1.17	0.89–1.52
Colon/Rectum (153, 154)	384	518.6	435.0	0.74*	0.88*	1.00	0.85–1.19
Pancreas (157)	195	204.6	196.8	0.95	0.99	1.14	0.91–1.43
Lung (162)	710	940.8	713.6	0.75*	0.99	1.15*	1.02–1.29
Skin (172, 173)	79	66.0	65.6	1.20	1.20	0.82	0.55–1.21
Malignant melanoma of the skin (172)	60	45.3	47.3	1.33*	1.27	0.71	0.45–1.13
Breast (174)	240	312.9	284.3	0.77*	0.84*	0.94	0.76–1.17
Cervix uteri (180)	47	48.8	45.9	0.96	1.02	0.58	0.33–1.05
Corpus uteri (182)	60	55.3	45.8	1.08	1.31	1.06	0.70–1.62
Ovary (183)	92	100.9	97.4	0.91	0.94	0.96	0.68–1.36
Prostate (185)	264	255.2	261.7	1.03	1.01	1.06	0.87–1.30
Urinary bladder (188)	61	106.7	90.6	0.57*	0.67*	1.35	0.92–1.99
Kidney (189)	68	80.5	75.7	0.84	0.90	0.90	0.60–1.36
Liver and kidney (155, 189)	178	195.0	176.4	0.91	1.01	0.91	0.70–1.17
Bone (170)	6	14.9	11.2	0.40*	0.54	2.33	0.81–6.73
Connective tissue (171)	10	20.4	21.1	0.49*	0.47*	2.10	0.91–4.87
Brain and CNS (191, 192)	97	88.4	83.8	1.10	1.16	0.77	0.54–1.10
Thyroid (193)	5	10.6	10.5	0.47	0.48	1.86	0.54–6.43
Non-Hodgkin lymphoma (200, 202)	111	135.3	129.4	0.82*	0.86	1.20	0.90–1.61
Hodgkin lymphoma (201)	12	21.9	19.0	0.55*	0.63	2.14	0.99–4.57
Multiple myeloma (203)	75	58.3	60.4	1.29*	1.24	0.81	0.54–1.21
Leukemia (204–208)	133	162.7	158.1	0.82*	0.84	0.87	0.65–1.17
Leukemia, CLL (204.1)[c]	20	24.0	23.9	0.83	0.84	0.91	0.43–1.95
Leukemia, not CLL	111	137.2	133.1	0.81*	0.83	0.88	0.64–1.22
Childhood leukemia (<20 years)	15	13.8	13.5	1.08	1.11	0.51	0.19–1.42
Childhood cancer (<20 years)	24	33.9	31.2	0.71	0.77	0.97	0.51–1.85

[a] Expected numbers based on U.S. rates ($\mathrm{Exp}_{\mathrm{us}}$) and on Colorado rates ($\mathrm{Exp}_{\mathrm{co}}$).

[b] RR is taken as the $\mathrm{SMR}_{\mathrm{co}}$ for Montrose County divided by the $\mathrm{SMR}_{\mathrm{co}}$ for the two comparison counties (see Table 2 for the observed numbers of cancer deaths and $\mathrm{SMR}_{\mathrm{co}}$ for Montrose County).

[c] CLL denotes chronic lymphocytic leukemia.

* $P < 0.05$.

lung cancer is 17% (*66*), whereas in years past, survival was much worse; e.g., in 1960–1973, the median survival time was only 5.4 months (*67*). Diseases that have a low fatality rate can also be evaluated, although the statistical power to identify an effect would be lower than for an incidence survey because of the smaller number of events. Improvement in treatment would also be expected to be similar between Montrose and the comparison counties so that it is unlikely that study findings would reflect differences in medical care over time. Cancer incidence data exist for Colorado for recent years, 1990–2002. Similar to the patterns for cancer mortality, there were essentially no differences in cancer incidence rates for all cancers over this 13-year period among the residents of Montrose County, the five comparison counties, and the State of Colorado (Fig. 2). Comparable findings are seen for childhood leukemia in that cancer incidence between 1990 and 2002 gave a similar picture as the mortality data [i.e., the rate of leukemia (2.6 per 100,000) was lower than the state of Colorado (4.0 per 100,000) and the difference was not statistically significant].

Finally, the entire county rather than smaller areas in the immediate vicinity of specific mining or milling facilities was used as the geographic unit for analysis. This was necessitated because mortality data extending back to 1950 are available only at the county level. However, mining and milling facilities were widespread throughout large parts of western Montrose County so that the potential for environmental exposure was not limited to any single area. There were 223 uranium mines and two uranium mills in Montrose County, and the average density of about one uranium facility per 10 square miles was much greater than that for the state of Colorado or the comparison counties. Further, a comprehensive cohort study of residents of the town of Uravan from 1937 and followed through May 1984 reached similar conclusions based on both cancer incidence and mortality data (i.e., there was no significant increase in any cancer or disease except lung cancer among men attributed

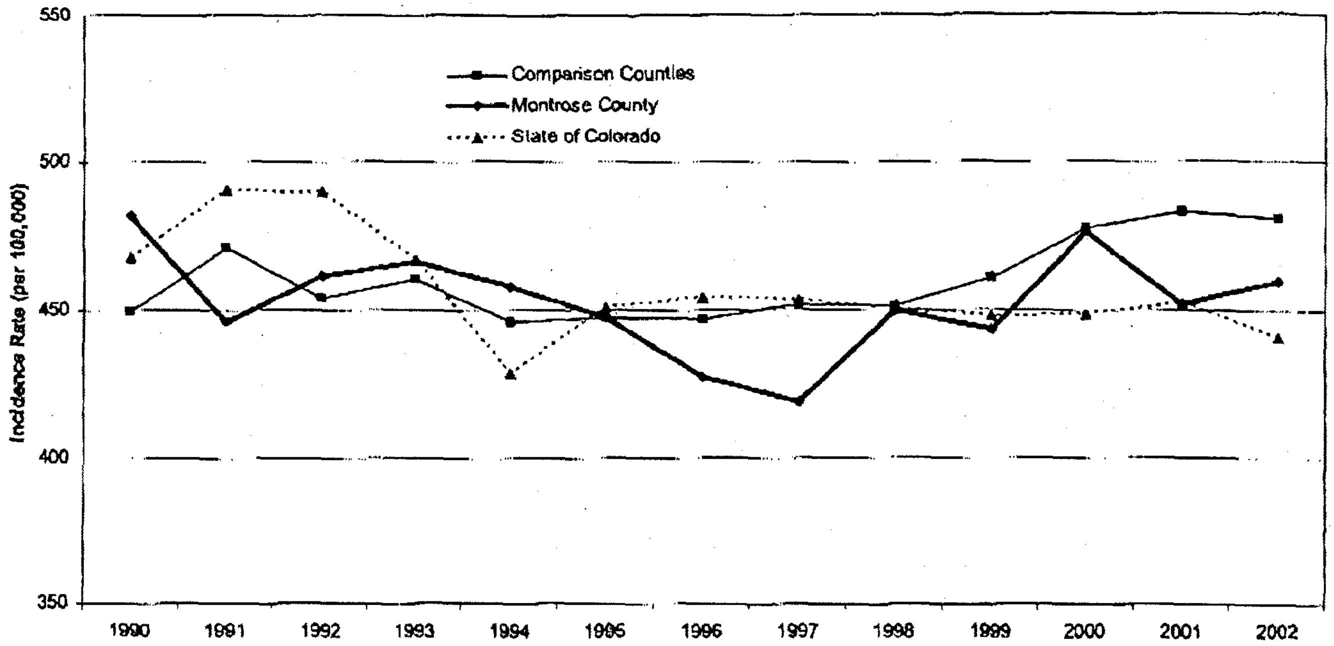


FIG. 2. Age-adjusted cancer incidence rates for all cancers in Montrose County, the five comparison counties, and the state of Colorado from 1990–2002. Except for the first 2 calendar years, 3-year moving averages are presented to smooth fluctuations in rates due to relatively small numbers of cancer cases occurring in a single year for Montrose County and the five comparison counties. Source: Colorado Department of Public Health and Environment (http://www.cdphe.state.co.us/cohid/agreement.html).

to documented employment in underground mines and tobacco use (*20*)].

Summary

In summary, there is no evidence that residents of Montrose County experienced an increased risk of dying of cancer or other diseases because of environmental exposures associated with uranium and vanadium milling and mining activities. Although descriptive correlation analyses such as this preclude definitive causal inferences on their own, an occupational risk of lung cancer due to underground mining exposure to radon and smoking is suggested among males and consistent with previous cohort studies of underground miners of the Colorado Plateau and of residents of a milling and mining community in Montrose County.

ACKNOWLEDGMENTS

We thank the National Cancer Institute and the University of Pittsburgh for providing the statistical programs and databases used for these analyses and Union Carbide Corporation and UMETCO Minerals Corporation who funded the study. Dr. Boice has provided an expert report regarding the possible relationship between cancer and living in the town of Uravan, CO. The results presented herein represent the conclusions and opinions solely of the authors. Its publication does not imply endorsement by any of the acknowledged agencies or individuals.

Received: September 28, 2006; accepted: February 20, 2007

REFERENCES

1. F. J. Hahne, *Early Uranium Mining in the United States*. Presentation at the Fourteenth International Symposium, Uranium Institute, London, September 1989. [Available online at http://www.world-nuclear.org/usumin.htm (last accessed 24 August 2006)].
2. J. S. Hamrick, D. E. Kocis and S. E. Shepard, *Uravan, Colorado—One Hundred Years of History*. Umetco Minerals Corporation, Grand Junction, CO, 2002.
3. U.S. Environmental Protection Agency, Region VIII, *Final Five-Year Review, UMETCO Minerals Corporation. Uravan Superfund Site, Uravan, Colorado. Contract No. 68-W7-0039* (March 13, 2000). Morrison Knudson Corporation, Littleton, CO, 2000. [Available online at http://www.epa.gov/region8/superfund/co/uravan/Five-year_Review.pdf (last accessed 21 July 2006)].
4. U.S. Department of Energy (DOE), *Nuclear Decommissioning—Naturita Mill Site, Montrose County, Colorado* (June 6, 2002), 2002. [Available online at http://www.eia.doe.gov/cneaf/nuclear/page/umtra/naturita_title1.htm (last accessed 21 July 2006)].
5. U.S. Geological Survey, *Mineral Resources Data System: U.S. Geological Survey*, Reston, VA, 2005. [Available online at http://tin.er.usgs.gov/mrds/ (last accessed 05 January 2007)].
6. NCRP, *Radiation Protection in the Mineral Extraction Industry*. Report No. 118, National Council on Radiation Protection and Measurements, Bethesda, MD, 1993.
7. L. E. Pinkerton, T. F. Bloom, M. J. Hein and E. M. Ward, Mortality among a cohort of uranium mill workers: an update. *Occup. Environ. Med.* **61**, 57–64 (2004). [Additional information available online at http://www.cdc.gov/niosh/pgms/worknotify/UraniumMillers.html (last accessed 23 September 2006)].
8. Institute of Medicine, Committee on the Health Effects Associated with Exposures During the Gulf War, *Gulf War and Health. Volume 1. Depleted Uranium, Pyridostigmine Bromide, Sarin, Vaccines*. National Academy Press, Washington, DC, 2001.
9. Council of the Royal Society, *The Health Hazards of Depleted Uranium Munitions*. Part 1. Science Advice Section. The Royal Society, London, 2001.
10. N. H. Harley, E. C. Foulkes, L. H. Hiborne, A. Hudson and C. R. Anthony, *Depleted Uranium: A Review of the Scientific Literature as it Pertains to Gulf War Illness*. RAND, Santa Monica, CA, 1999.
11. J. D. Boice, Jr., W. L. Bigbee, M. T. Mumma and W. J. Blot, Cancer

mortality in counties near two former nuclear materials processing facilities in Pennsylvania, 1950–1995. *Health Phys.* **85**, 691–700 (2003).

12. J. D. Boice, Jr., W. L. Bigbee, M. T. Mumma and W. J. Blot, Cancer incidence in municipalities near two former nuclear materials processing facilities in Pennsylvania. *Health Phys.* **85**, 678–690 (2003).

13. J. D. Boice, Jr., M. Mumma, S. Schweitzer and W. J. Blot, Cancer mortality in a Texas county with prior uranium mining and milling activities, 1950–2001. *J. Radiol. Prot.* **23**, 247–262 (2003).

14. A. Auvinen, P. Kurttio, J. Pekkanen, E. Pukkala, T. Ilus and L. Salonen, Uranium and other natural radionuclides in drinking water and risk of leukemia: A case-cohort study in Finland. *Cancer Causes Control* **13**, 825–829 (2002).

15. A. Auvinen, L. Salonen, J. Pekkanen, E. Pukkala, T. Ilus and P. Kurttio, Radon and other natural radionuclides in drinking water and risk of stomach cancer: a case-cohort study in Finland. *Int. J. Cancer* **114**, 109–113 (2005).

16. P. Kurttio, A. Auvinen, L. Salonen, H. Saha, J. Pekkanen, I. Makelainen, S. B. Vaisanen, I. M. Penttila and H. Komulainen, Renal effects of uranium in drinking water. *Environ. Health Perspect.* **110**, 337–342 (2002); Erratum, *Environ. Health Perspect.* **111**, 632 (2003).

17. P. Kurttio, H. Komulainen, A. Leino, L. Salonen, A. Auvinen and H. Saha, Bone as a possible target of chemical toxicity of natural uranium in drinking water. *Environ. Health Perspect.* **113**, 68–72 (2005).

18. P. Kurttio, A. Harmoinen, H. Saha, L. Salonen, Z. Karpas, H. Komulainen and A. Auvinen, Kidney toxicity of ingested uranium from drinking water. *Am. J. Kidney Dis.* **47**, 972–982 (2006).

19. P. Kurttio, L. Salonen, T. Ilus, J. Pekkanen, E. Pukkala and A. Auvinen, Well water radioactivity and risk of cancers of the urinary organs. *Environ. Res.* **103**, 333–338 (2006).

20. S. G. Austin, *A Study of the Health Experience of Residents of Uravan, Colorado. Final Report.* Austin Health Consultants, Inc., Fort Collins, CO, 1986.

21. F. D. Lundin, Jr., J. K. Wagoner and V. E. Archer, *Radon Daughter Exposure and Respiratory Cancer. Quantitative and Temporal Aspects.* National Institute for Occupational Safety and Health and National Institute of Environmental Health Sciences Joint Monograph No. 1, U.S. Department of Health, Education, and Welfare, Public Health Service, Washington, DC, 1971.

22. A. S. Whittemore and A. McMillan, Lung cancer mortality among U.S. uranium miners: a reappraisal. *J. Natl. Cancer Inst.* **71**, 489–499 (1983).

23. S. C. Darby, E. Whitley, G. R. Howe, S. J. Hutchings, R. A. Kusiak, J. H. Lubin, H. I. Morrison, M. Tirmarche, L. Tomasek and S. X. Yao, Radon and cancers other than lung cancer in underground miners: a collaborative analysis of 11 studies. *J. Natl. Cancer Inst.* **87**, 378–384 (1995).

24. R. J. Roscoe, An update of mortality from all causes among white uranium miners from the Colorado Plateau Study Group. *Am. J. Ind. Med.* **31**, 211–222 (1997).

25. National Research Council, Committee on the Biological Effects of Ionizing Radiations, *The Health Effects of Exposure to Indoor Radon (BEIR VI).* National Academy Press, Washington, DC, 1999.

26. S. A. Fry, Studies of U.S. radium dial workers: An epidemiological classic. *Radiat. Res.* **150** (Suppl.), S21–S29 (1998).

27. IARC, *Ionizing Radiation, Part 2: Some Internally Deposited Radionuclides.* Vol. 78, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, International Association for Research on Cancer, Lyon, 2001.

28. J. H. Lubin and J. D. Boice, Jr., Lung cancer risk from residential radon: meta-analysis of eight epidemiologic studies. *J. Natl. Cancer Inst.* **89**, 49–57 (1997).

29. S. Darby, D. Hill, H. Deo, A. Auvinen, J. M. Barros-Dios, H. Baysson, F. Bochicchio, R. Falk, S. Farchi and R. Doll, Residential radon and lung cancer—detailed results of a collaborative analysis of individual data on 7148 persons with lung cancer and 14,208 persons without lung cancer from 13 epidemiologic studies in Europe. *Scand. J. Work Environ. Health* **32** (Suppl. 1), 1–83 (2006).

30. J. H. Lubin, M. S. Linet, J. D. Boice, Jr., J. Buckley, S. M. Conrath, E. E. Hatch, R. A. Kleinerman, R. E. Tarone, S. Wacholder and L. L. Robison, Case-control study of childhood acute lymphoblastic leukemia and residential radon exposure. *J. Natl. Cancer Inst.* **90**, 294–300 (1998).

31. UK Childhood Cancer Study Investigators, The United Kingdom Childhood Cancer Study of exposure to domestic sources of ionizing radiation: 1: radon gas. *Br. J. Cancer* **86**, 1721–1726 (2002).

32. UK Childhood Cancer Study Investigators, The United Kingdom Childhood Cancer Study of exposure to domestic sources of ionizing radiation: 2: gamma radiation. *Br. J. Cancer* **86**, 1727–1731 (2002).

33. IARC, *Ionizing Radiation, Part 1: X- and Gamma (γ)-Radiation, and Neutrons.* Vol. 75, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, International Association for Research on Cancer, Lyon, 2000.

34. UNSCEAR, *Sources and Effects of Ionizing Radiation, Vol. I: Sources, Vol. II: Effects.* 2000 Report to the General Assembly, with Scientific Annexes. United Nations, New York, 2000.

35. National Research Council, Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, *Health Risks from Exposure to Low Levels of Ionizing Radiation (BEIR VII).* National Academies Press, Washington, DC, 2006.

36. D. Laurier, M. Valenty and M. Tirmarche, Radon exposure and the risk of leukemia: A review of epidemiological studies. *Health Phys.* **81**, 272–288 (2001).

37. L. Tomasek, S. C. Darby, A. J. Swerdlow, V. Placek and E. Kunz, Radon exposure and cancers other than lung cancer among uranium miners in West Bohemia. *Lancet* **341**, 919–923 (1993).

38. M. Mohner, M. Lindtner, H. Otten and H. G. Gille, Leukemia and exposure to ionizing radiation among German uranium miners. *Am. J. Ind. Med.* **49**, 238–248 (2006).

39. V. Rericha, M. Kulich, R. Rericha, D. L. Shore and D. P. Sandler, Incidence of leukemia, lymphoma, and multiple myeloma in Czech uranium miners: a case-cohort study. *Environ. Health Perspect.* **114**, 818–822 (2006).

40. R. J. Sram, B. Binkova, L. Dobias, P. Rossner, J. Topinka, D. Vesela, D. Vesely, J. Stejskalova, H. Bavorova and V. Rericha, Monitoring genotoxic exposure in uranium miners. *Environ. Health Perspect.* **99**, 303–305 (1993).

41. Agency for Toxic Substances and Disease Registry (ATSDR), *Toxicological Profile for Vanadium.* U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA, 1995. [Updated on November 22, 2004; available online at http://www.atsdr.cdc.gov/tfacts58.html (last accessed 24 August 2006)].

42. N. B. Ress, B. J. Chou, R. A. Renne, J. A. Dill, R. A. Miller, J. H. Roycroft, J. R. Hailey, J. K. Haseman and J. R. Bucher, Carcinogenicity of inhaled vanadium pentoxide in F344/N rats and B6C3F1 mice. *Toxicol. Sci.* **74**, 287–296 (2003).

43. T. J. Mason, J. F. Fraumeni, Jr. and F. W. McKay, Jr., Uranium mill tailings and cancer mortality in Colorado. *J. Natl. Cancer Inst.* **49**, 661–664 (1972).

44. W. B. Riggan, J. Van Bruggen, J. F. Acquavella, J. Beaubier and T. J. Mason, *U.S. Cancer Mortality Rates and Trends—1950–1979.* Report EPA-600/1-83-015a, U.S. Environmental Protection Agency, Washington, DC, 1983.

45. S. Jablon, Z. Hrubec and J. D. Boice, Jr., Cancer in populations living near nuclear facilities. A survey of mortality nationwide and incidence in two states. *J. Am. Med. Assoc.* **265**, 1403–1408 (1991).

46. *RateCalc Mortality Rate Generator, Version 3.7.1 Users Guide.* Division of Cancer Epidemiology and Genetics, National Cancer Institute, Bethesda, MD, 2004.

47. G. M. Marsh, A. O. Youk, R. A. Stone, S. Sefcik and C. Alcorn, OCMAP-PLUS: a program for the comprehensive analysis of occupational cohort data. *J. Occup. Environ. Med.* **40**, 351–362 (1998).

48. U.S. Department of Commerce, *1990 Census of the Population, Characteristics of the Population PC 90-1-B40.* Bureau of the Census, Washington, DC, 1992.

49. K. Steenland, J. Henley, E. Calle and M. Thun, Individual- and area-

level socioeconomic status variables as predictors of mortality in a cohort of 179,383 persons. *Am. J. Epidemiol.* **159**, 1047–1056 (2004).

50. J. C. Bailar, III and F. Ederer, Significance factors for the ratio of a Poisson variable to its expectation. *Biometrics* **20**, 639–643 (1964).
51. I. Kawachi and K. Lochner, Socioeconomic status. In *Cancer Prevention: The Causes and Prevention of Cancer—Volume 1* (G. A. Colditz and D. Hunter, Eds.), pp. 87–100. Kluwer Academic Publishers, Netherlands, 2000.
52. K. Steenland, J. Henley and M. Thun, All-cause and cause-specific death rates by educational status for two million people in two American Cancer Society cohorts, 1959–1996. *Am. J. Epidemiol.* **156**, 11–21 (2002).
53. ICRP, *Age-dependent Doses to Members of the Public from Intake of Radionuclides, Part 3, Ingestion Dose Coefficients.* Publication 69, *Annals of the ICRP*, Vol. 25, No. 1, Pergamon Press, Oxford, 1995.
54. ICRP, *Age-dependent Doses to Members of the Public from Intake of Radionuclides, Part 4, Inhalation Dose Coefficients.* Publication 71, *Annals of the ICRP*, Vol. 25, No. 3–4, Pergamon Press, Oxford, 1995.
55. W. J. Blot, J. M. Harrington, A. Toledo, R. Hoover, C. W. Heath, Jr. and J. F. Fraumeni, Jr., Lung cancer after employment in shipyards during World War II. *N. Engl. J. Med.* **299**, 620–624 (1978).
56. *Cancer Facts and Figures 2006.* American Cancer Society, Atlanta, GA, 2006.
57. J. D. Boice, Jr., Study of health effects in areas of high background radiation in China. *J. Radiol. Prot.* **22**, 102–104 (2002).
58. Z. Y. Wang, J. D. Boice, Jr., L. X. Wei, G. W. Beebe, Y. R. Zha, M. M. Kaplan, Z. F. Tao, H. R. Maxon, III, S. Z. Zhang and D. Preston, Thyroid nodularity and chromosome aberrations among women in areas of high background radiation in China. *J. Natl. Cancer Inst.* **82**, 478–485 (1990).
59. D. M. Taylor and S. K. Taylor, Environmental uranium and human health. *Rev. Environ. Health* **12**, 147–157 (1997).
60. J. J. Russell, R. L. Kathren and S. E. Dietert, A histological kidney study of uranium and non-uranium workers. *Health Phys.* **70**, 466–472 (1996).
61. N. D. Priest, Toxicity of depleted uranium. *Lancet* **357**, 244–246 (2001).
62. E. A. Dupree, J. P. Watkins, J. N. Ingle, P. W. Wallace, C. M. West and W. G. Tankersley, Uranium dust exposure and lung cancer risk in four uranium processing operations. *Epidemiology* **6**, 370–375 (1995).
63. E. Dupree-Ellis, J. Watkins, J. N. Ingle and J. Phillips, External radiation exposure and mortality in a cohort of uranium processing workers. *Am. J. Epidemiol.* **52**, 91–95 (2002).
64. National Academy of Sciences, *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc.* National Academy Press, Washington, DC, 2000. [Available online at http://books.nap.edu/books/0309072794/html/index.htm (last accessed 23 August 2006)].
65. C. Poole, Ecologic analysis as outlook and method. *Am. J. Public Health* **84**, 715–716 (1994).
66. L. A. G. Ries, D. Harkins, M. Krapcho, A. Mariotto, B. A. Miller, E. J. Feuer, L. Clegg, M. P. Eisner, M. J. Horner and B. K. Edwards, Eds., *SEER Cancer Statistics Review, 1975–2003*, National Cancer Institute, Bethesda, MD, 2005. [Available online at http://seer.cancer.gov/csr/1975_2003/, based on November 2005 SEER data submission, (last accessed January 12, 2007)].
67. L. M. Axtell, A. J. Asire and M. H. Myers, Eds., *Cancer Patient Survival. Report Number 5.* DHEW Publication No. (NIH) 77-992, National Cancer Institute, Bethesda, MD, 1976.

Comments on “Cancer and Noncancer Mortality in Populations Living Near Uranium and Vanadium Mining and Milling Operations in Montrose County, Colorado, 1950-2000”

Note: This document was prepared by Dr. Standler for discussion with the Colorado Medical Society (CMS) who were considering recommending a complete ban on all in-situ and open pit uranium mining in Colorado with part of the proposal being a request that the American Medical Association (AMA) approve a similar ban nationwide.

This current (2007) and important paper compares mortality rates in the important uranium and vanadium producing area of Montrose County, Colorado to five similar counties that were not involved with uranium and vanadium. Montrose County had mining and milling of uranium from the early 1900s to the 1980s. Mortality rates from 1950 to 2000 were used for the study. The paper is very carefully put together, and the analysis took into consideration calculating the various expected US and Colorado disease rates based on stratified age groups instead of just using one global number for the calculation. The paper also chose the comparison counties very carefully to match as closely as possible based on population density, percentage male, percentage white, percentage rural, percentage high school graduate, percentage over age 64 years, percentage employed, percentage below poverty, and median household income. In my opinion, this paper is a true attempt to match to the highest of known standards for conduction of serious epidemiologic work. The authors were really trying to ask the right questions without bias about the expected outcomes.

A very detailed analysis of mortality statistics both of overall rates and by specific conditions was performed. The results with respect to overall cancer deaths were the following:

- The total numbers of cancer deaths evaluated (1,877 in Montrose County and 11,837 cancer deaths in five control counties) are large enough to make the study statistically valid.
- The overall cancer rate in Montrose County was 99% of that expected based on the general population rates of the US, and the overall cancer rate of the control counties was 98% of that expected based on the general population rates of the US.
- There was no difference between the total cancer mortality rates in Montrose County and those in control counties.

When one does a very detailed analysis and comparison of large bodies of data, one tends to get a great many small areas with statistically significant differences. This happens partly because 95% significance level means 1 in 20 analyses would be expected to “falsely” produce a statistically significant result, and partly because even “similar” groups tend in real life to have some “real” differences if you look hard enough. (Basically, nothing is ever exactly equivalent to anything else.) The production of a great many areas with small statistically significant differences happened in this paper's analyses, as presented in the various tables, with statistically significant results being indicated by asterisks. Note that in general, because of this tendency for fine grained analyses to produce lots of asterisks, one needs to think carefully about the meaning of the each positive result and ask how it fits into a broader knowledge context.

In the fine grained analyses, SMR (standard mortality rates, with $\mathrm{SMR}_{\mathrm{US}}$ meaning the standard mortality rates in the US and $\mathrm{SMR}_{\mathrm{CO}}$ meaning the standard mortality rates in Colorado) values less than 1 mean less risk and values greater than 1 mean increased risk compared to the appropriate baseline US or Colorado population. Similarly RR (relative rate) values less than 1 mean less risk and greater than 1 mean increased risk. For those of you unfamiliar with the term "relative rate" it is the ratio of the SMR for one patient group over the SMR for a control group. In this paper the RR's for different diseases are calculated as the ratio of the Montrose County $\mathrm{SMR}_{\mathrm{CO}}$ to the comparison counties $\mathrm{SMR}_{\mathrm{CO}}$.

The results for the fine grained analyses were as follows:

- If one looks at the asterisks on the various tables, there are very many more asterisks on SMR and RR numbers that are less than 1 (indicating significantly decreased risks) than are on numbers greater than 1 (indicating significantly increased risks). (Note that some of the tables extend onto the next page, requiring one to count down to find the continuation of the line on the table on the previous page.) This means that most of the statistically significant findings suggest a level of comparative protection for the population of Montrose County compared to other groups. This could have been for a great many reasons, most of which have nothing to do with the uranium activity in the area. The overall impression that there is more "protective effect" than "hurting effect" is important (and real) because it substantiates that overall impression that the uranium industry in Montrose county has not been overall hurting the residents. (Incidentally, one would expect the aquifers under the naturally occurring uranium to be at risk of contamination just from rain water dripping through the natural uranium beds, and so this overall data offers the added insight that the regulation of the public water supply that is in place is working well enough to protect the population.)
- We need to think very carefully about the relatively few places where the asterisks are on values greater than 1, indicating increased risk, for whatever reason.
- One area is which stars on numbers greater than 1 appear is in the area of lung disease:
    - Table 2 on page 716 shows a lung cancer observed rate (for all types of people in Montrose) in Montrose County of 454 cases when the expected US rate was 531 and the expected Colorado rate was 397.5. The observed cancer rate corresponds to a $\mathrm{SMR}_{\mathrm{US}}$ of 0.85, that is statistically significantly *lower* than the expected value of 1 for this measure. The observed cancer rate also corresponds to a $\mathrm{SMR}_{\mathrm{CO}}$ of 1.14, that is statistically significantly *higher* than the expected value of 1 for this

measure. This means that Montrose count had 15% less lung cancer deaths than a similar population in the US would be expected to have, and 14% more lung cancer deaths than Colorado would be expected to have. Note also that the observed rate of lung cancer being higher than the Colorado expected rate is the *only* statistically significant *adverse* result in table 2, and there are 12 stars on values less than 1 in the table, indicating statistically significant *beneficial* results.

- The comparison counties (shown on Table 2 extended page 717) have a lung cancer observed rate of 2612, when the expected US was 3,282.0 and the expected Colorado rate was 2472.7. These values correspond to SMR_{US} of 0.80 (statistically significantly lower than the US) and a SMR_{CO} of 1.06 (greater but not significantly different from the Colorado value). This means that the comparison counties had about 20% *fewer* (and statistically significant) total lung cancer deaths than expected in the US and about 6% greater (but not statistically significant) total lung cancer deaths than expected in Colorado. An additional interesting point is that we can argue that features common (and thus not related to uranium) to both Montrose county and the comparison counties may account for 6% (the comparison county value) of the 14% of the elevation of Montrose county total lung cancer deaths compared to Colorado. The difference between the 14% and 6% values is 8%, and this means both that Montrose county differs by 8% from the control counties, and that only 8% of the 14% elevation when Montrose is compared to Colorado generally is unaccounted for. Incidentally, the relative rate line for lung cancer in that table (which is the ratio of the SMR_{CO} for Montrose County to the SMR_{CO} for the comparison counties) for gives RR=1.08, which is *not* statistically different, substantiating the argument that Montrose County is not different in this respect from similar Colorado counties. All of this goes to argue that we do not at this point have compelling evidence for a real effect on lung cancer in the area related to the uranium.
- This paper's analysis goes farther. Tables 3 (p. 718) and 4 (p. 719) look at the Montrose County cancer deaths by type stratified for males vs females (Table 3) and for both sexes at different time periods (Table 4, 1950-1969 cases vs 1970-1984 cases vs 1985-2000 cases). In these tables is additional data about lung cancer.
- If you look at the lung cancer deaths line on Table 3, you can see that females were protected, with SMR_{US} of 0.66 (statistically significantly less than expected in US generally), SMR_{CO} of 0.84 (less than expected in Colorado but not statistically significant), and RR of 0.83 (less than in comparison counties, but not statistically significant). In contrast, we see the situation with males is different. In male lung cancer cases, the SMR_{US} was 0.94 (less than but not statistically different from general US population), the SMR_{CO} was 1.27 (statistically more lung cancer deaths than expected in Colorado generally), and the relative rate was 1.19 (statistically more lung cancer deaths than comparison counties). This means that there was likely to have been a real, but small, increased lung

cancer rate in the men compared to the Colorado general population and the population in comparison counties, but that this rate was still less than that seen nationally. Of interest, the text of the paper notes (p.718) that "miners of the Colorado Plateau are known to be heavy smokers." The fairly small effect we are seeing therefore might be due to just different smoking incidences, since, as the paper mentions on p. 718, "Cigarette smoking is the predominant cause of lung cancer and is responsible for more than 87% of all lung cancers diagnosed in the United States."

- In Table 4, the question of lung cancer is again picked up, this time from the perspective of cancer rates for different time periods with the data for both sexes combined. [However, since we know from table 3 that the women were relatively protected, you should be thinking that we are actually talking here about the lung cancer rates in the men.] What the data shows is that the only time there was a statistically significant effect on lung cancer rates was in the middle 1970-1984 period, and that no statistically significant effect was seen in either the early 1950-1969 period or in the recent 1985-2000 period. In the 1970-1984 period, the SMR_{CO} was statistically significantly increased to 1.22 (Montrose County saw 22 percent more lung cancer deaths than expected by Colorado general population statistics) and the RR was 1.18 (Montrose County had 18% more lung cancer deaths than control counties, but this was not statistically significant). This data suggests several things to me. There may have been a small, but real, increase in male cancer deaths in the 1970-1984 period, but whatever caused it has since gone away. In this context, the comment in the paper about the known increased smoking among the miners is pertinent, because 1970-1984 was before the big push to get people to stop smoking, and would be when the peak would be expected to be. The fact that the peak passed and the more recent lung cancer rates are not statistically different would be consistent with a public response to the heavy pressure for smoking cessation we have seen over the last twenty years. My personal guess, that cannot be definitely proven, is that these increased deaths were related to the smoking.
- Table 5 looks at noncancer deaths. (Note that the table extends onto the next page as Table 5 extended, and that because of the way the tables were printed, you have to count down on Table 5 extended to find the rest of the line that corresponds to the one in the original Table 5.) Part of the table looks specifically at non-malignant respiratory disease, and does a careful analysis with independently evaluated data for influenza and pneumonia; bronchitis, emphysema, and asthma together; bronchitis alone; emphysema alone; and asthma alone. Overall in the non-malignant respiratory disease, Montrose County had a SMR_{US} of 1.27 (statistically significantly increased rate compared to general US) with SMR_{CO} of 0.99 (virtually equal to the expected rate in Colorado) and RR of 1.05 (not significantly different rate from comparison counties). This says to me that the overall effect on total non-malignant respiratory disease of living in

Colorado was more important than the effect of living specifically in Montrose County.

  - Let’s look at the subcategories of nonmalignant respiratory disease next. Influenza and pneumonia deaths are clearly not a problem in the data, which makes sense, as you would not be expecting a problem in these areas. The combined group of bronchitis, emphysema, and asthma shows a pattern similar to that seen with all non-malignant respiratory disease: SMRUS of 1.41 (statistically significantly more bronchitis, emphysema, and asthma than US generally), SMRCO of 1.04 (not statistically different from Colorado generally), and RR of 1.07 (not statistically different from comparison counties). Living in Colorado is a bigger effect than living in Montrose County. When the bronchitis, emphysema, and asthma group is subdivided, bronchitis turns out to not be of concern. Emphysema and asthma both show the same pattern as both all non-malignant respiratory disease and the combined bronchitis, emphysema, and asthma group: the SMRUS for emphysema is 1.51 and for asthma is 1.65 (both statistically significantly increased compared to US generally); SMRCO for emphysema is 1.08 and for asthma is 1.15 (both not statistically different from Colorado); and RR for emphysema is 0.89 and for asthma is 1.10 (both not statistically different from comparison counties). Again, living in Colorado has a much bigger effect than living in Montrose County.

- In summary with respect to the lung disease, a very detailed analysis suggests that the only “real” effect seen was an small increase in lung cancer in male adults in between 1970 and 1984, with the magnitude of the risk being such that more lung cancers were seen than expected in the general Colorado population, but still less than what were expected in the general US population. The miners of the Colorado Plateau were known to have been heavy smokers, and the smoking appears to be the most likely cause of the increased lung cancer.
- Another area that collected a few asterisks of statistically significant results in the detailed analyses of the Montrose data were skin cancers (presumably excluding melanoma) and melanoma. In the broad data analysis of Table 2 and Table 2 extended, there were no significant differences between rates of deaths due to skin cancers and melanomas when Montrose County was compared to the general US population (SMR_{US} for skin cancers of 0.97 and SMR_{US} for melanoma of 0.94, both not statistically significant), to the general Colorado population (SMR_{CO} for skin cancers of 0.98 and SMR_{CO} for melanoma of 0.90, both not statistically significant), or comparison counties (RR for skin cancers of 0.90 and RR for melanoma of 0.80, both not statistically significant). The analysis in Table 3 of the data by sex also shows no statistically significant effect for skin cancer or for melanoma. The analysis in Table 4 when stratified by age, does show a statistically significant effect for both skin cancer deaths and melanoma deaths. This effect occurs only in the 1950 to 1969 earliest time span, and has cleared completely by the 1970-1984 and 1985-2000 time spans. Specifically, in the 1950-1969 group, the SMR_{CO} for skin cancer was 2.07 and the SMR_{CO} for melanoma was 2.49 (both statistically significant, and I believe “real” because of the large values of the changes). When Montrose is compared to comparison

counties, the RR for skin cancer was 1.96 and that for melanoma was 1.97. Both these numbers are large, but were not statistically significant, probably because of the small numbers of cases involved by the time the data was split heavily for the detailed analysis. I personally believe that this increase in fatal skin cancer and increase in melanoma was probably “real”. Its cause is a little less clear: It might have been due to uranium; it might have been due to differences in sun exposure (known to be the most obvious cause skin cancers and melanoma, and my best guess); it might have been due to other unknown causes; or it might have been multifactorial in cause. In any event, it is very reassuring that by the 1970-1984 period and the most recent 1985-2000 period, the effect had gone away completely, with both the SMR$_{CO}$’s and RR’s for both skin cancer and melanoma in both time periods being consistently well under 1 (ranging from 0.50 to 0.87, depending upon which measure you look at). Whatever caused the original bump in incidence of these cancers has convincing been cleared for nearly 40 years, and Montrose County now has strikingly low death rates from skin cancers and melanoma. (Did people learn to use sunscreen reliably? Are they getting suspicious lesions biopsied early due to aggressive management by their doctors?)

- Potentially “real” asterisks also show up in some of the cancers of the uterine corpus data. No statistically significant results with respect to uterine corpus cancer show up in the broad analyses of Tables 2 and 3. *However, I find the data about cancers of the uterine corpus presented in Table 4 to be very worrisome for a real, current problem*, *whose cause I do not know, but I think is not related to the uranium in Montrose for reasons I will discuss shortly*. What this data showed was a trend toward higher SMR$_{CO,}$ with 1950-1969 value of 0.86 (not statistically significant), 1970-1984 value of 1.50 (quite a bit large but not statistically significant), and 1985-2000 value of 1.77 (large and statistically significant). The RR values (comparison to other counties) are also large in the 1970-1984 (RR = 2.07) and 1985-2000 (RR = 1.52), but are not statistically significant, probably because of the small numbers involved by the time the data of the study is subdivided this far. To me this data suggests that you really are seeing too many cancers of the uterine corpus, but I don’t know what is causing the problem. Uterine corpus cancer to the best of my knowledge is not known to be linked to uranium elsewhere in the literature. There is no more data in the Montrose paper specifically about the uterine corpus cancer, so I went to the sister study “Cancer mortality in a Texas County with prior uranium mining and milling activities, 1950-2001” published by the same group as wrote the Montrose paper. This a similar, but somewhat less detailed paper, written about the Karnes County area and comparing their data to general US, general Texas, and comparison counties. In Karnes County, they had no uterine corpus cancers leading to death in 1950-1964 or 1965-1979; they had 4 deaths in 1980-1989, and they had 1 death in 1990-2001. The relative risk taken for the entire period 1950 to 2001 was 0.72 when compared to the control counties in Texas. From this information, I conclude that it is unlikely that the Montrose increased cancer deaths of the uterine corpus is due to the uranium in the county, since we did not see any hint that a similar increase occurred (even though it conceivably might not have been statistically significant) in Karnes County. Other potential contributing factors to uterine cancer are increased estrogen exposure and family history. In many situations due to both these causes, breast cancer is also increased. So I next looked back at the Montrose paper to see if there was any increase in breast cancer in Montrose County. There is not; throughout the whole time period SMR$_{CO}$ and RR values in Table 4 for breast cancer are all low. *From my perspective, the bottom line is that I think you are looking at a real and current cluster of uterine corpus cancer cases in Montrose County, that are probably not related to uranium exposure. From a medical perspective, I think the best strategy is probably to have a high index of suspicion for uterine cancer, and perhaps somebody will figure out what is causing the pattern, if it is still in place currently (the latest data was from 2000)*.

- Non cancerous damage to the kidney is another important parameter to look at, because uranium is a known renal toxin, and some acute deaths in uranium poisoning have been due to renal failure. The Montrose data in Table 6 show that there does seem to have been some early excess deaths due to nephritis and nephrosis in the earliest period (1960-1969, SMRCO that was not significantly significant but large of 1.52 and RR that was not significantly significant but large of 1.30) and middle period (197-1984, SMRCO of statistically significant 1.65 and RR not significantly significant of but large of 1.52). It is quite conceivable to me that uranium may have played a role in these excess deaths. However, fortunately (possibly as a result of improved health standards in the uranium industry) excess renal deaths are not seen in the 1985 to 1999 period, where the SMR$_{CO}$ is nicely low at 0.81 and the RR is also nicely low at 0.81. This says to me that while they may have been a problem with renal toxicity due to uranium in the past, it has not been a problem for more than 20 years.
- The last things that come out of the Montrose data are important negatives: there was no evidence for increased rates of bone cancer, leukemia, liver cancer, kidney cancer, bladder cancer, brain cancer, or childhood cancers. Cancers of these sites were important theoretical concerns because other studies had suggested uranium might concentrate at some of these sites. Montrose county also has more motor vehicle and other accidents than they should, but it seems something of a stretch to assume that this is because of the uranium.

So, what are the bottom lines for all this data you have just waded through?

- The overall data is very reassuring in the Montrose County study that the existence of uranium milling and mining does not contribute to overall mortality.
- While some increased risk was seen in lung diseases (including both cancers and non-cancerous disease), the patterns of increased risk suggest that processes other than uranium mining and milling were at fault.
- In the earlier but not later periods of the study, there was increased skin cancer and melanoma, that was more likely to be related to sun exposure than the uranium.

- That were early excess deaths due to nephritis and nephrosis that might have been tied into uranium exposure. The data from the past 20 years shows fewer deaths of this type than expected rather than more, which suggests that if uranium were a contributing cause in the early deaths, our modern regulatory and company processes for handling uranium are working successfully to protect people.
- Many cancers that would be expected to be increased on theoretical grounds were occurring at normal rates.
- You do have a cluster of excess uterine corpus cancers of unknown cause that look like they are specifically not related to uranium exposure. It will be important to let the Colorado Medical Community be aware of this, so as to increase the index of suspicion for cancer of the uterine corpus.

Thank you for wading through all of this material. I had intended to write a one or two page cover document. Instead my analysis is roughly as long as the paper itself. But the data in this paper are the very best that we have, and they pertain specifically to your state. Consequently I thought I owed you the best analysis I could do, which takes longer than a quicky overview would.

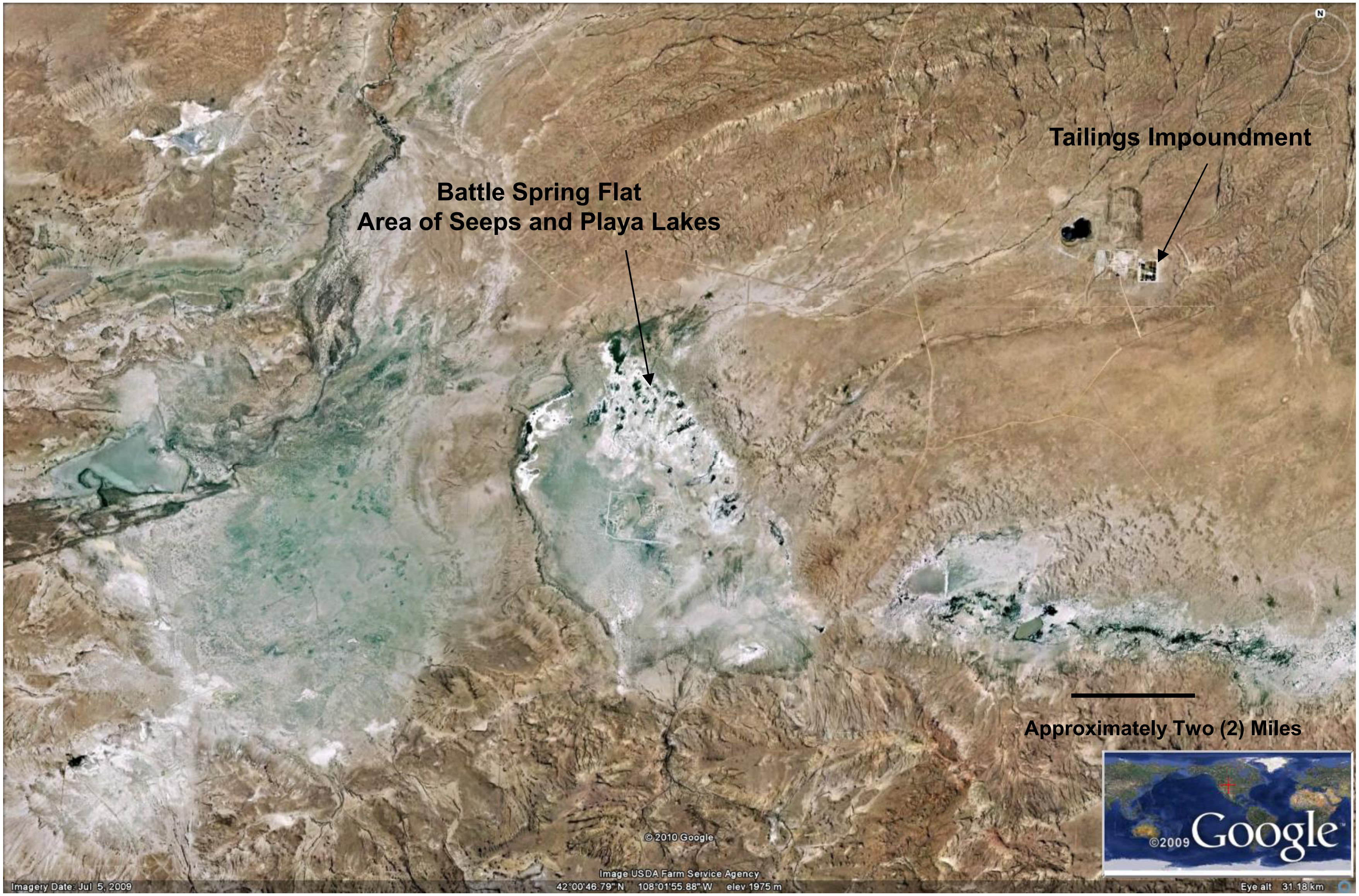
I very much hope that after you study this and other papers you will conclude, as I have, that we have learned a great deal about how to safely handle uranium. We really do very much need the uranium in this country. I hope you will support an effort to use the uranium, but use it carefully and with heavy regulatory oversight, which is already in place and appears to be working adequately.

If I can be of any help, please let me know.

Nancy Standler MD PhD

Appendix 20

Area Around the Sweetwater Uranium Project
Photography – Google Earth July 5, 2009

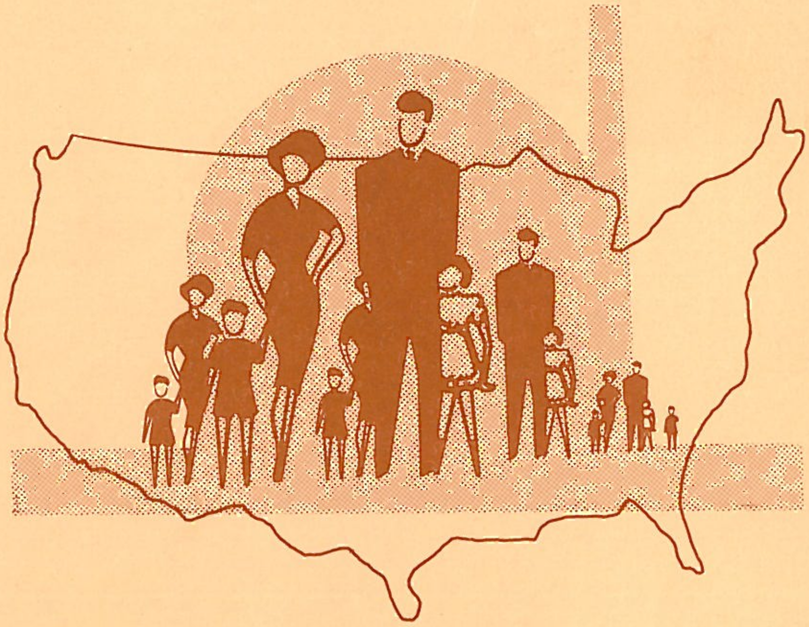


Appendix 21

J. E. ROTHFLEISCH

DER 69-1

EVALUATION OF RADON 222 NEAR URANIUM TAILINGS PILES



U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Consumer Protection and Environmental Health Service

DER 69-1

EVALUATION OF RADON 222 NEAR URANIUM TAILINGS PILES

Final report of joint project of the U. S.
Public Health Service and the U. S. Atomic
Energy Commission in cooperation with the
State Health Agencies of Colorado and Utah

March 1969

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Consumer Protection and Environmental Health Service
Environmental Control Administration
Bureau of Radiological Health
Rockville, Maryland 20852

FOREWORD

A one year research program to evaluate radon 222 near uranium tailings piles was undertaken in June 1967 under a joint agreement between the United States Atomic Energy Commission and the United States Public Health Service in cooperation with the Colorado State Department of Public Health. The objective of this joint project is to provide technical advice and assistance to States and industries in evaluating public health aspects of atmospheric concentrations of radon 222 in the vicinity of uranium tailings piles. The study also was directed to determine the effectiveness of stabilization and containment of uranium tailings piles in controlling radon emanation.

The technical report series of the Division of Environmental Radiation is used to publish the results of research projects and technical evaluations of nuclear facilities. The reports are distributed to State and local radiological health program personnel, Bureau technical staff, Bureau advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press, and other interested individuals. These reports are also included in the collections of the Library of Congress and the Clearinghouse for Federal Scientific and Technical Information.

I encourage the readers of these reports to inform the Bureau of any omissions or errors. Your additional comments or requests for further information are also solicited.

Charles L Weaver

Charles L. Weaver
Director, Division of
Environmental Radiation
Bureau of Radiological Health

Martin B. Biles
Director, Division of
Operational Safety
U.S. Atomic Energy Commission

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TABLES

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Grateful appreciation is expressed by the U.S. Atomic Energy Commission and the U.S. Public Health Service to many individuals of the Foote Mineral Company, Vitro Corporation of America, Climax Uranium Company, Lucius Pitkin, Inc., the health departments of the States of Utah and Colorado, and the Environmental Sciences Services Administration. Without their help, this study would not have been possible.

PREPARATION OF THIS REPORT

This report was prepared at a project review meeting held at the State Division of Health, Salt Lake City, Utah, November 19, 1968, and was based on a technical paper by Dr. S. D. Shearer, Jr., and Dr. C. W. Sill. The following attended the meeting:

- Dr. Grant S. Winn, Utah State Division of Health, Salt Lake City
- Mr. Dennis R. Dalley, Utah State Division of Health, Salt Lake City
- Mr. R. D. Siek, Colorado State Department of Health, Denver
- Dr. R. J. Augustine, Bureau of Radiological Health, PHS, Rockville, Maryland
- Mr. P. B. Smith, BRH, PHS, Region VIII Office, Denver
- Dr. S. D. Shearer, Jr., Southwestern Radiological Health Laboratory, BRH, PHS, Las Vegas
- Mr. Pope A. Lawrence, National Air Pollution Central Administration, Washington, D.C.
- Mr. Frank McGinley, U.S. Atomic Energy Commission, Grand Junction Office, Colorado
- Mr. Warren E. Bush, Lucius Pitkin, Inc., Grand Junction, Colorado
- Dr. Claude W. Sill, Health Services Laboratory, Idaho Operations Office, U.S. Atomic Energy Commission
- Mr. Don F. Harmon, U.S. Atomic Energy Commission, Washington, D.C.
- Mr. Harvey F. Soule, U.S. Atomic Energy Commission, Washington, D.C.

EVALUATION OF RADON 222 NEAR URANIUM TAILINGS PILES

INTRODUCTION

The impact of uranium milling operations on the air and water environment has been studied by a number of Federal and State agencies as well as private industry since the mid-1950's. Most of the investigations to date have been concerned with potential water pollution from milling operations. Increased attention has been focused during the past several years on the atmospheric effects of such operations, particularly the influence of unstabilized mill tailings piles on the atmospheric radioactivity levels in surrounding communities.

Limited atmospheric grab sampling in the vicinity of several uranium mills in 1966 indicated that the radon 222 emanation from the tailings might be increasing environmental levels significantly; however, the sampling program was minimal and the results were limited in their interpretation. Because of increasing public interest, a more elaborate joint study was initiated.

OBJECTIVES

Under a joint agreement between the U.S. Atomic Energy Commission and the U.S. Public Health Service, a project was begun in June 1967, in cooperation with the Colorado Department of Public Health and the Utah State Division of Health to evaluate the public health aspects of atmospheric concentrations of radon 222 in the vicinity of uranium tailings piles. Specific objectives of this project were to:

1. Develop techniques for taking integrated air samples for radon near uranium tailings piles.

2. Evaluate atmospheric concentrations of radon in areas near tailings piles as an index of radiation exposure to the population.
3. Determine the effect of stabilization and covering on the emanation of radon gas from tailings piles.
4. Develop joint recommendations (or guidelines), if necessary, to control exposures based on radon concentrations found.
5. Make the information available to States through technical assistance and published reports.

The National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP) have developed criteria for individuals occupationally exposed to radon 222 (1,2). The maximum permissible concentration (MPC$_a$) of 30 pCi/liter for a 40-hour week and 10 pCi/liter for a 168-hour week have been set for occupational exposure to radon 222 and its daughter products in equilibrium. It is permissible to adjust these concentration limits if it is found that radon 222 is not in equilibrium with its daughter products.

The NCRP (NBS Handbook 69, page 6) states that the maximum permissible average body burden of radionuclides in persons outside of the controlled area and attributable to the operations within the controlled area shall not exceed one-tenth of that for radiation workers (that is, based on continuous occupational exposure for a 168-hour week), and that this recommendation is primarily for the purpose of keeping the average dose to the whole population as low as reasonably possible and not because of the likelihood of specific injury to the individual.

Recommendations of the ICRP state that the annual radiation dose limits for members of the public shall be one-tenth of the corresponding annual occupational values for continuous exposure. Application of these recommendations to the 168-hour value for occupational exposure to radon 222 with daughter products present at equilibrium concentrations leads to a value of 1 pCi/liter for continuous exposure to individuals in the general population. This concentration is in addition to natural background radon levels. Thus, for the purpose of this study, 1 pCi/liter of radon 222 above background in air was used as the screening value below which no further attention would be given to the concentrations involved. Should data obtained from the survey indicate average annual exposures to concentrations of radon 222 in air in excess of 1 pCi/liter above background, it would be necessary to consider the extent of equilibrium between radon and its daughter products.

While Federal regulations generally permit average concentrations of radon 222 up to 3 pCi/liter in air leaving the boundary of a restricted area of a licensed facility, quantities permitted to be released from the restricted area are subject to reduction if it appears that they might result in the exposure of a suitable sample of an exposed population group to average concentrations of radon 222 in excess of 1 pCi/liter (3).

DESCRIPTION OF STUDY

STATION LOCATIONS

In order that the study areas reflect conditions at both operating and inactive uranium mills, locations were chosen initially at Grand Junction, Colo. (operating mill, uncovered tailings); Durango, Colo. (inactive mill, uncovered tailings); and Monticello, Utah (inactive mill, covered tailings). Salt Lake City, Utah was added to the study in October 1967. The Salt Lake City tailings are uncovered, and the mill was closed in July 1968. At each of these study areas, a number of sampling sites were selected that were representative of onpile, near-pile, and general community conditions. Locations were chosen taking into consideration the prevailing wind patterns, population densities, geographical factors, and so forth. At Grand Junction, 25 sampling sites were chosen with five being located directly on the tailings pile: at Durango, eight sites were chosen, two of which were on the tailings pile; at Salt Lake City, 12 sites were chosen with one station being on the tailings pile and another immediately adjacent; and at Monticello, 12 stations were established, four of which were on the tailings area. At the four study areas a total of 57 sampling sites were selected, 12 of which were directly over tailings material, and one immediately adjacent.

SAMPLING TECHNIQUES AND FREQUENCY

The equipment used to collect the samples is described in detail in appendix I. A small aquarium aerator pump forces filtered air through a precision needle valve into a 40-liter laminated Mylar bag at 10 ml/min to give a volume of 30 liters in each 48-hour sampling period. At each sampling location, the pump and bag were placed in a protective weather enclosure. The pump inlet was 3 feet above the ground or the tailings. Sampling was carried out over a 48-hour period in order that 2 diurnal cycles might be covered. The sampling schedule was designed so that each location would be sampled once every 3 weeks over a 12-month period. By sampling in this manner, any bias because of daily or seasonal meteorological variations would be minimized.

ANALYTICAL PROCEDURES

After an extensive intercomparison period, one-half of the samples collected were analyzed at each of the participating laboratories (AEC Health Services Laboratory, Idaho Falls; PHS Southwestern Radiological Health Laboratory, Las Vegas). Samples were shipped to the laboratories by the most expeditious means to minimize corrections for radon decay. The analytical technique consisted of passing a known volume of sample through a gas-separation apparatus and absorbing the radon on activated charcoal at low temperature. The charcoal was then heated and the radon transferred to an alpha-sensitive scintillation cell for subsequent counting. The statistical uncertainty was generally less than 15 percent at the 95 percent confidence level.

In order to determine the agreement between the two laboratories' results, all samples collected during the first 6 weeks of the study were analyzed in duplicate at both laboratories. A paired observation test demonstrated that the differences between the laboratories' results were in agreement, within the uncertainties of the counting statistics involved. After this initial intercomparison, about 5 percent of the remaining samples were analyzed in both laboratories as a continuing cross-check on quality control. All counting data were corrected for radioactive decay to the midpoint of the respective sampling periods; in addition, the concentrations as determined in the laboratory were calculated to the mean annual pressure and temperature at each of the study locations which were: Grand Junction, 638 mm, 11° C.; Durango, 599 mm, 8° C.; Monticello, 587 mm, 8° C.; and Salt Lake City, 654 mm, 11° C.; respectively.

RESULTS

During the period of sampling for this program, a total of 892 samples were collected, 209 of which were onpile samples and 683 were offpile samples. The numbers of onpile and offpile samples by study area are: 85 and 320 in Grand Junction; 30 and 82 in Durango; 31 and 150 in Salt Lake City; and 63 and 131 in Monticello. The average concentration of radon 222 found at each station in the four study sites is given in table 1. (Each sample result is in appendix II.)

The data shown in table 1 covers the following dates at each of the four study areas:

Grand Junction	June 6, 1967 to August 20, 1968
Salt Lake City	October 27, 1967 to October 9, 1968
Monticello	August 8, 1967 to July 29, 1968
Durango	August 3, 1967 to July 30, 1968

As stated earlier, each of the 57 sampling stations was resampled at 3-week intervals throughout the study.

Table 2 presents an overall summary of the onpile and offpile radon concentrations for the four study sites. Four of the offpile stations in Grand Junction, and one of the offpile stations in Durango, have been shown separately from the other offpile stations. The reasons for this are explained below. The averages are also shown in figures 1 to 4 with the corresponding sampling location at each of the four study areas. For the sake of clarity, only the principal city and residential areas have been shown. In figure 1, the average of the onpile stations is shown for clarity instead of the individual averages.

DISCUSSION

The conclusions and trends are presented below for each of the four study areas:

GRAND JUNCTION

It is apparent when examining these data that there are three distinct groups: (1) onpile stations; (2) near-pile stations in the prevailing wind patterns; and (3) all other stations.

Table 1. *Average concentrations of radon 222 found at the four study areas*

Station and location	Number of samples	Concentration of radon 222 (pCi/liter)		
		Average	Standard deviation	Range
Grand Junction, Colo.				
11[a]	17	11	6.7	3.3 - 28
12[a]	17	4.7	1.7	2.2 - 7.1
13[a]	17	9.0	3.6	4.6 - 21
14[a]	17	5.7	2.4	1.1 - 9.7
15[a]	17	8.7	3.9	3.5 - 16
16	17	1.1	.53	.50 - 2.6
21	16	.77	.35	.37 - 1.8
22	17	1.3	.67	.53 - 2.3
23	17	3.4	3.0	.60 - 13
24	17	.78	.45	.31 - 2.2
25	17	.84	.45	.28 - 1.9
26	17	.82	.50	.30 - 2.2
31	16	1.1	.88	.42 - 3.3
32	16	.75	.41	.19 - 1.8
33	17	1.8	1.1	.50 - 4.5
34	15	.84	.39	.46 - 2.2
35	17	.88	.51	.32 - 2.1
36	17	.88	.41	.33 - 1.9
41	16	.69	.30	.13 - 1.2
42	16	.70	.27	.27 - 1.1
43	15	.78	.48	.17 - 1.9
44	16	1.1	.93	.48 - 4.4
45	16	.82	.33	.40 - 1.6
46	15	.74	.43	.35 - 2.1
Control 47 (5 miles)	10	.79	.48	.29 - 1.9

[a] Onpile stations.

$WL = 100\ pCi\ ^{222}Rn \cdot l^{-1}$

Table 1. Average concentrations of radon 222 found at the four study areas (continued)

Station and location	Number of samples	Concentration of radon 222 (pCi/liter)		
		Average	Standard deviation	Range
Salt Lake City, Utah				
81[a]	16	10	6.4	1.6 - 22
82[b]	15	4.2	1.4	2.3 - 6.6
83	16	.43	.31	.09 - 1.3
84	15	.39	.24	.21 - 1.1
85	13	.68	.30	.23 - 1.4
86	13	.28	.14	.11 - .54
91	15	.44	.30	.15 - .99
92	14	.42	.24	.17 - .85
93	14	.24	.12	.06 - .55
94	17	.44	.26	.07 - .94
95	17	.29	.16	.13 - .60
96	16	.22	.12	.06 - .45
Monticello, Utah				
61[a]	17	4.1	2.0	.68 - 8.1
62[a]	15	2.4	1.2	.55 - 4.4
63[a]	15	4.5	3.1	.12 - 12
64[a]	16	3.1	1.8	.89 - 6.1
65	17	.52	.29	.18 - 1.3
66	16	.41	.17	.12 - .64
71	15	.34	.18	.10 - .72
72	17	.24	.13	.03 - .53
73	16	.29	.17	.06 - .59
74	17	.24	.13	.06 - .59
75	16	.31	.18	.14 - .87
76	17	.40	.20	.11 - .94
Durango, Colo.				
51[a]	16	19	7.2	3.8 - 34
52[a]	14	12	9.1	.48 - 32
53	15	.49	.17	.25 - .75
54	10	1,4	.67	.44 - 2.3
55	17	.52	.27	.11 - 1.3
56	14	.47	.17	.22 - .78
57	13	.59	.35	.17 - 1.2
58	13	.47	.34	.09 - 1.3

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[a] Onpile stations.

[b] This station is not actually onpile, but adjacent to the pile at the sewage plant.

Table 2. Summary of onpile and offpile stations at the four study areas

Location	Number of stations	Number of samples	Concentration of radon 222 (pCi/liter)	
			Average	Range
Grand Junction, Colo.				
Onpile	5	85	7.8$\times 10^{-9} \frac{\mu Ci}{ml}$	1.1 - 28.0
Near-pile[a]	4	68	1.9	.50 - 4.5
Other	16	252	.83	.13 - 4.4
Durango, Colo.				
Onpile	2	30	16.0	.48 - 34.0
Station 54	1	10	1.4	.44 - 2.3
Other	5	72	.51	.09 - 1.3
Monticello, Utah				
Onpile	4	63	3.5	.12 - 12
Offpile	8	131	.34	.03 - 1.3
Salt Lake City, Utah				
Onpile	1	16	10	1.6 - 22
Station 82	1	15	4.2	2.3 - 6.6
Offpile	10	150	.38	.06 - 1.4

[a] Near-pile stations were stations 16, 22, 23, and 33.

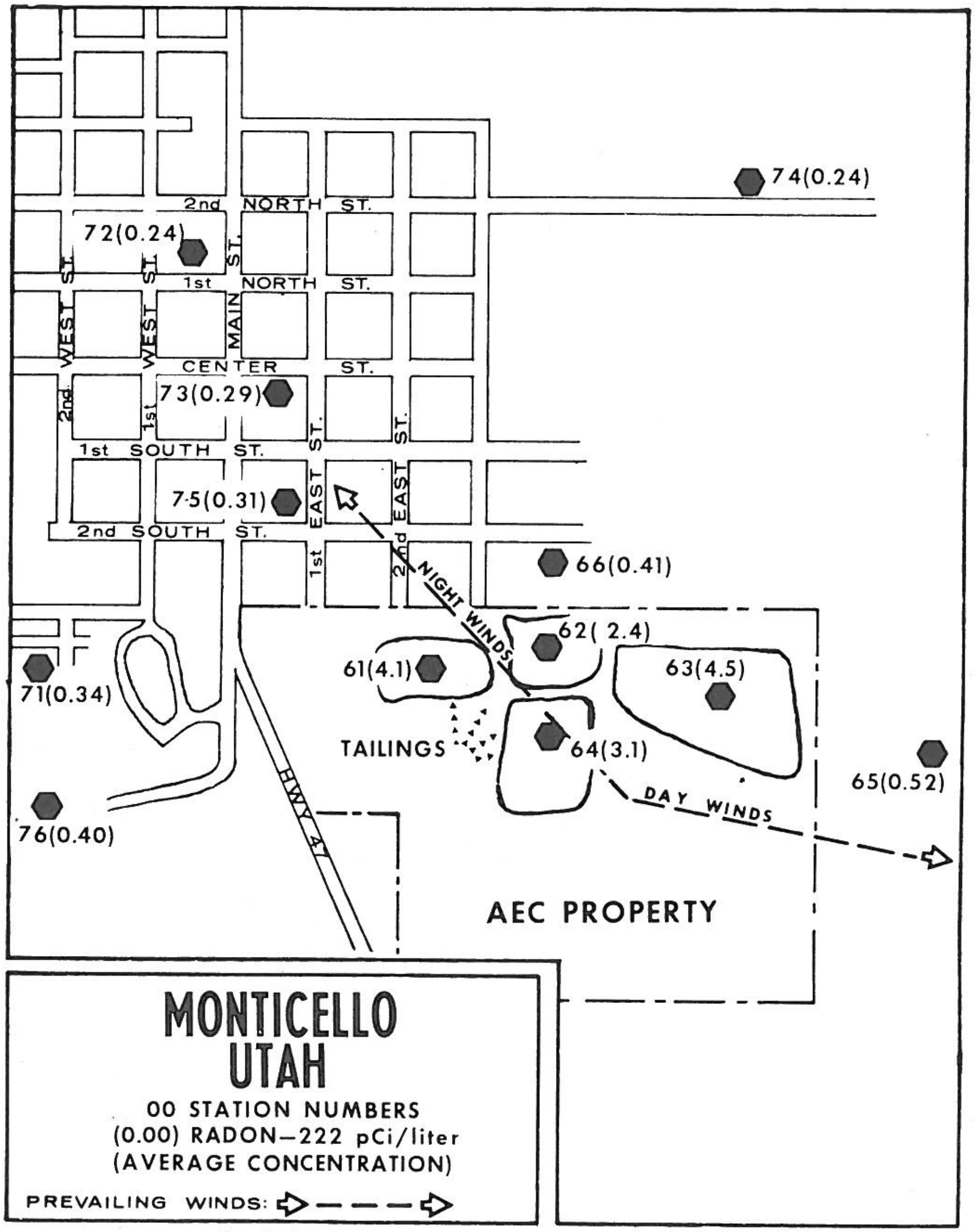
The wind patterns (shown as dotted lines on figure 1) represent conditions that occur about 80 percent of the time. The early daytime winds are from the southeast while the afternoon and evening winds are from the northwest. The shift is about equally divided in the two directions; about 53 percent of the time from the northwest and 47 percent of the time from the southeast.

It is interesting to note that station 11, which has the highest average radon 222 concentration, is positioned at the northwest corner of the main tailings pile at the foot of a 25-foot bluff in the prevailing wind envelope for the nocturnal inversion conditions. This station can be expected to intercept the drainage of radon from the pile down the slope during periods of highest concentration. In contrast, the lowest value of the onpile stations is obtained at station 12, which is almost in the geometric center of the pile. The pile is slightly conical with station 12 near the apex. Apparently, except under conditions of strong vertical mixing, the radon drains down the slope and away from the sampler, minimizing the concentration available at a height of 3 feet where the inlet is located.

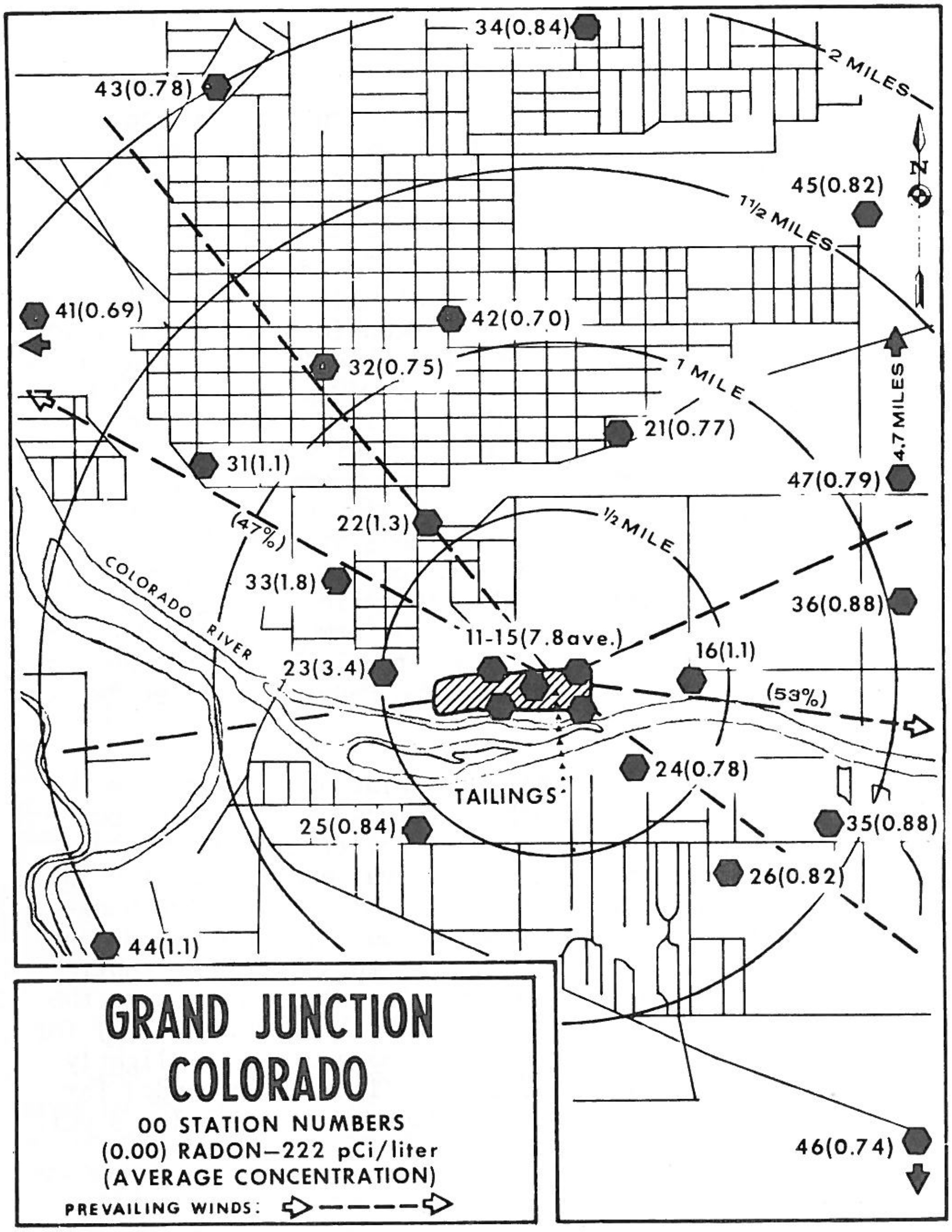
As previously stated, it was considered valid to consider stations 16, 22, 23, and 33 as a separate group from the other offpile stations. There are several reasons for this: (1) they are all about one-half mile from the pile; (2) they are in the predominant wind envelopes; (3) the area is characteristically industrial; and (4) they are all on the mill side of the river. In addition, standard t-test and analysis of variance comparisons of station averages clearly showed that stations 23 and 33 were significantly different from the other offpile station averages. Stations 16 and 22, while exhibiting higher averages than offpile stations, were not determined to be significantly higher, but were considered to fall into the same "population group" as stations 23 and 33.

Station 24 was not included in this group because, while it is less than one-half mile from the pile and is in the predominant wind envelope, it is situated across the river close to the edge of a mesa about 80 feet higher than stations 16, 22, 23, and 33. Station 23 (fig. 1) is the closest offpile station and has the highest average.

The remaining 16 offpile stations were considered as a third group of stations. For these stations, the individual station averages were compared utilizing standard t-test and analysis of variance comparisons of the averages. The results of these statistical techniques showed that none of the individual station averages could be considered significantly different (at the 95 percent confidence level) from each other and, therefore, would represent data from the same "population group."



Sample location and prevailing winds for Monticello, Utah
Figure 3



Sample location and prevailing winds for Grand Junction, Colorado
Figure 1

The above conclusion is quite significant when comparing station 47 with the others. Previous to 1966 a quantity of tailings material was distributed widely throughout the Grand Junction community. These tailings were used as fill material, subgrade material under buildings, and other uses. It was felt that the tailings pile at the mill might not represent a single point source of radon release to the general environment, and that the distributed tailings might influence the radon concentrations at outlying stations. To investigate this possible variable, a station was set up at a considerable distance from the main tailings pile in an area where it was known that no tailings had been distributed; station 47 was located at a distance approximately 5 miles north of the main tailings pile. This station was placed in operation in early February 1968. As can be seen from table 1, the average radon concentration at station 47 for the study period was 0.79 pCi/liter. This average is not significantly different from the overall average of 0.83 pCi/liter for the offpile stations. It is thus concluded that the radon concentrations at station 47 are indicative of background levels in the Grand Junction area. In comparing this station's average with the other offpile stations (exclusive of stations 16, 22, 23, and 33) it is reasonable to conclude that the main tailings pile is not appreciably increasing the general atmospheric radon concentration in Grand Junction. The true influence of the distributed tailings on the general atmospheric radon levels is not known.

No definitive quantitative correlation of radon concentrations with distance from the tailings pile could be obtained. Because of this lack of correlation, and because a known background station indicates a value of at least 0.79 pCi/liter, it appears reasonable to consider that the background concentration of atmospheric radon 222 for Grand Junction as a whole is 0.8 pCi/liter. If this figure is subtracted from the other values, no offpile stations are above the value of 3 pCi/liter permitted by Federal regulations (3) for uncontrolled areas. Stations 23 and 33 are at, or slightly above, the screening level of 1.0 pCi/liter recommended for this study. All other station averages are well below 3 pCi/liter.

DURANGO

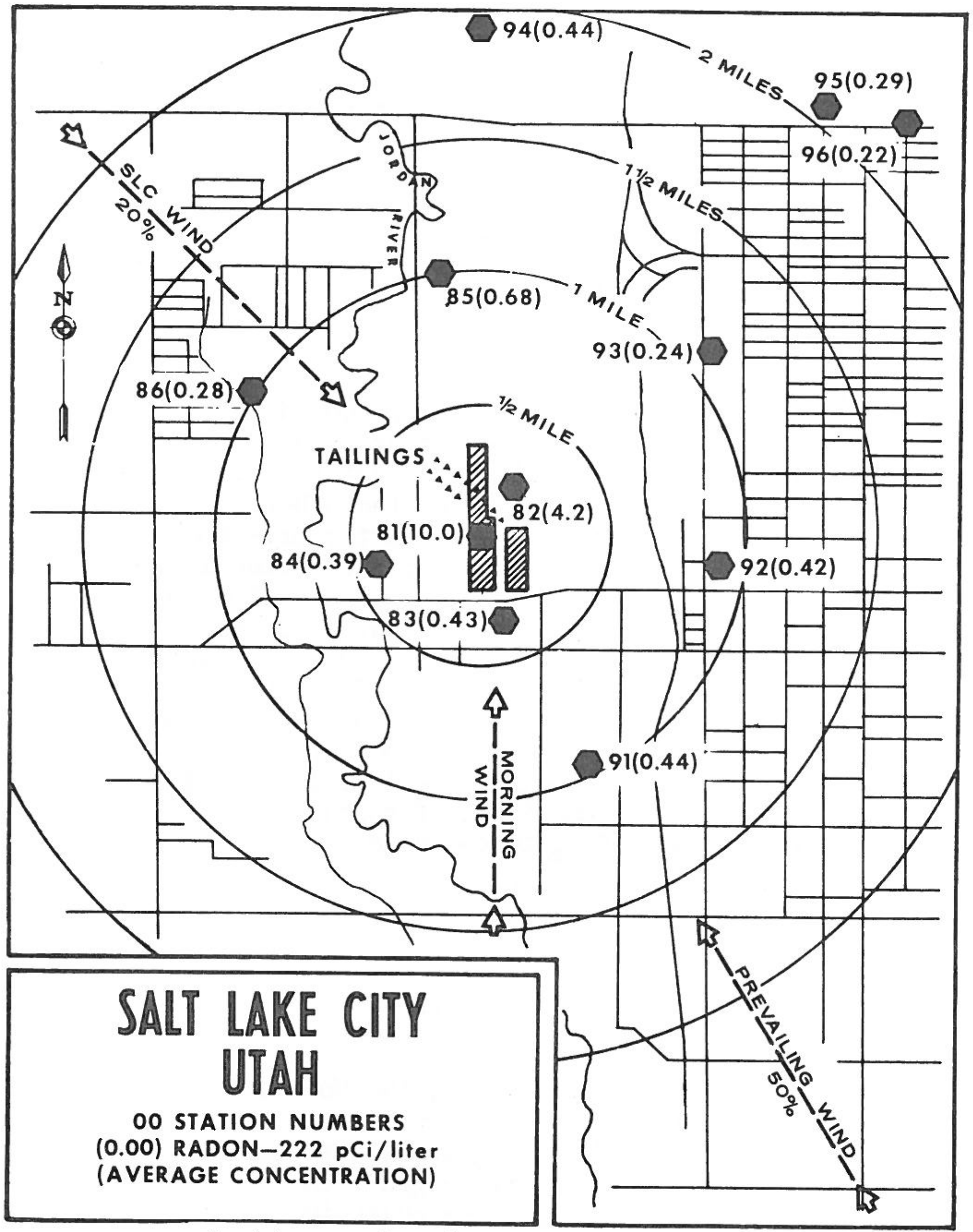
The onpile station averages at Durango are considerably higher than the other study locations. The most likely reason for this is the physical location of the sampling sites. Because of the very steep side slopes of the tailings pile, as well as its location against the side of a mountain, it was not convenient to locate the sampling sites directly on top of the pile; instead, the samplers were located on tailings material at the base of the tailings dike. It is probable that the radon diffusing out of the entire side slope of the pile will be carried by air movement directly down to the sampler at the base of the pile under almost all meteorological conditions, thereby ensuring a high concentration of radon at all times.

The wind patterns at Durango are shown as dotted envelopes in figure 2. The daytime winds are from the southeast and split toward the northeast and west at about the mill area. The nighttime winds are the reverse.

Standard t-test and analysis of variance comparisons of the averages of stations 53 through 58 showed that station 54 was significantly higher than the others, and that all other stations were not significantly different from each other. Station 54 is listed separately from the other offpile stations in table 2. Station 54, one-quarter mile southeast of the pile inside the wind envelope for the nocturnal inversion conditions, is across the river at the sewage-treatment plant. It is reasonable to conclude that the average of all offpile stations with the exception of station 54 represents the natural background levels for this area. This average (table 2) is 0.51 pCi/liter. If this figure is subtracted from the average at station 54, the resulting net average is 0.89 pCi/liter or less than the screening level of 1 pCi/liter. As at Grand Junction, no correlation of radon concentration with distance could be made from the Durango data.

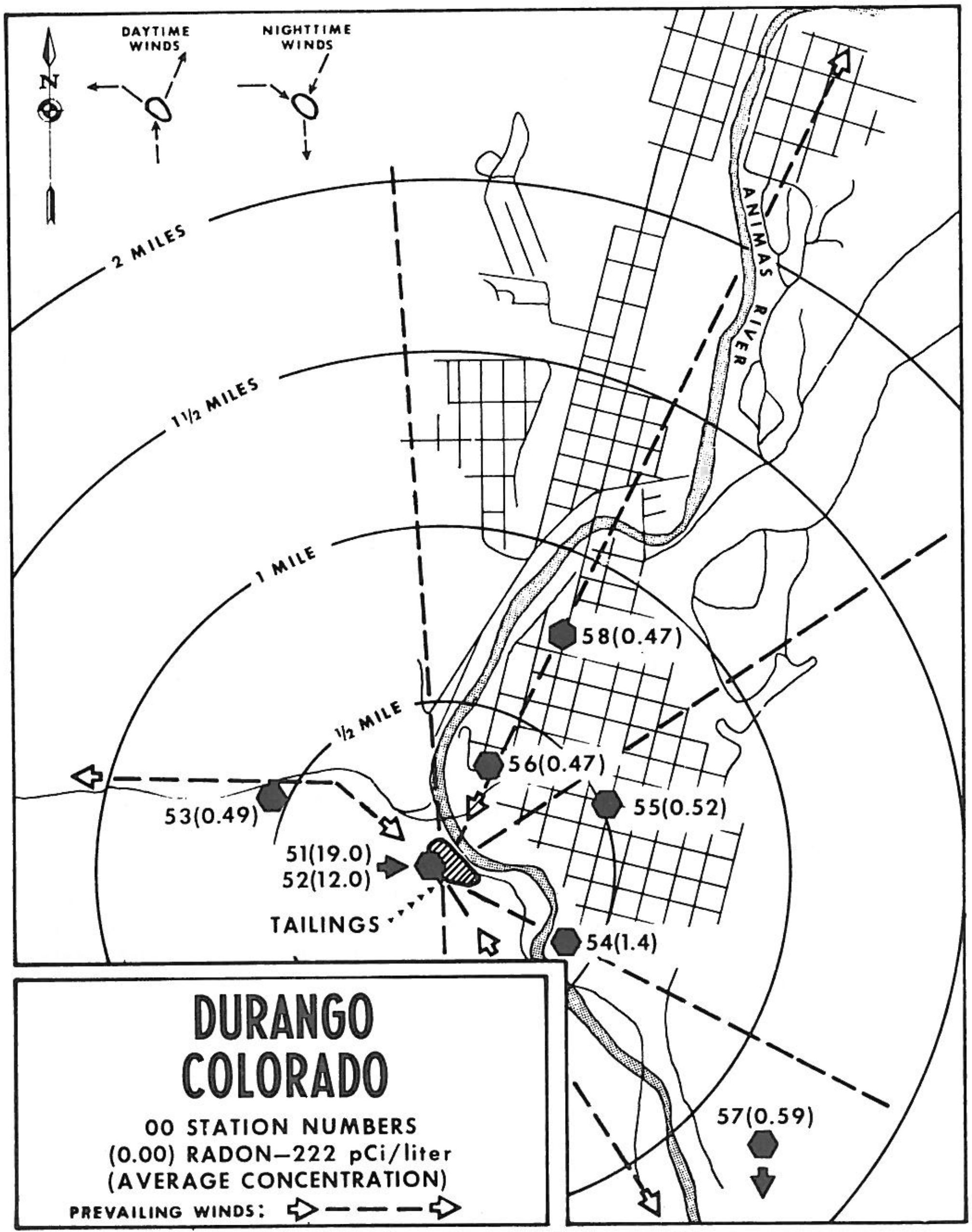
MONTICELLO

During its operational period, the Monticello mill was owned by the U.S. Atomic Energy Commission. Following termination of operation, the tailing areas were leveled and covered with earth and planted with a grass cover. This stabilization was completed in 1962. One objective of this study was to determine the effect of stabilization and covering on emanation of radon gas from piles. For this reason, Monticello was selected as one of the study locations. There are four distinct tailings areas at Monticello (fig. 3). It was deemed desirable to locate a sampling station on each of these areas. Other sampling locations were selected taking into consideration prevailing wind patterns.



Sample location and prevailing winds for Salt Lake City, Utah

Figure 4



Sample location and prevailing winds for Durango, Colorado
Figure 2

Standard t-test and analysis of variance comparisons of averages were made on all the offpile stations. The results showed that none of the offpile station averages was significantly different from the others. This indicates that the tailings do not significantly affect the environmental radon levels away from the tailings area. The average of all offpile stations (0.34 pCi/liter) can be considered to represent background for the Monticello area. If this value is subtracted from the other results, even the onpile net average concentration of 3.2 pCi/liter is only slightly above the permitted guideline (3) for continuous exposure in uncontrolled areas.

SALT LAKE CITY

Station 81 is located directly on tailings and station 82 is closely adjacent at the sewage-treatment plant (fig. 4). Individual occupancy is only 40 hours a week at the sewage-treatment plant. The averages for the offpile stations (exclusive of station 82) were compared using a standard t-test and an analysis of variance. There was no significant difference among stations.

As in Monticello, the offpile station average of 0.38 pCi/liter was considered to be the most reasonable estimate of the natural background concentration in Salt Lake City. Subtracting the background gives values for the onpile station and the sewage-treatment plant of about 3 times and 1-1/3 times, respectively, the regulatory guideline for continuous exposure in uncontrolled areas.

INTERCITY COMPARISONS

Because of the significant differences in the distances and orientation of samplers with respect to the piles, differences in meteorological variables, and the shape, size, and condition of the piles themselves, it is extremely difficult to make comparisons among cities from these data. There is no evidence of a significant contribution of radon to any of the cities beyond one-half mile from the piles. Even comparison of the piles is imprudent. Estimates of the radium 226 content of the tailings material show the concentrations to be almost identical for all four cities at about 900 pCi/gram;

consequently, concentrations of radon 222 above these tailings might also be expected to be quite similar. The data in table 2 show this to be true for the piles at Grand Junction and Salt Lake City. It is tempting to postulate that the concentration at Durango would also have been similar if it had been possible to locate the sampling station on top of the pile, and if the pile were essentially flat as were the other two.

EFFECT OF STABILIZATION

Any type of covering placed on tailings material will result in some decrease in the radon emanating from the tailings if for no other reason than the additional radiological decay resulting while the radon is diffusing through the covering. Based on the similar specific activity of the tailings at the four study locations, and the actual onpile radon concentrations obtained thus far, it is tempting to conclude that the type of stabilization carried out at Monticello has been effective in reducing the radon concentration over the tailings by approximately 50 percent; however, this is a tenuous conclusion. The quantity of tailings per unit area of land varies among the four sites in this study by a factor of four. Variations in vertical mixing, because of meteorological conditions, are undoubtedly more important in determining radon concentrations above the piles than small variations in specific activity or distribution of tailings.

Comparison of the offpile data among the four study areas indicates that the background radon concentrations in Durango, Monticello, and Salt Lake City are quite similar and are about one-half of the concentration in Grand Junction. It is apparent that the general Grand Junction area has a higher radon 222 background than the other locations studied.

RADIATION EXPOSURE INTERPRETATION

The guide for radon 222 assumes the parent in complete equilibrium with its short-lived daughters, which actually contribute about 95 percent of the total dose. These conditions would prevail directly over tailings only under completely stagnant weather conditions or at considerable distances from the pile. With a 10-mph wind, the composition of air at the 0.5-mile arc would correspond to the so-called

"3-min air;" that is, air aged sufficiently to build up 50 percent of the equilibrium activity of 3.05-min polonium 218 and little else. The actual dose received, therefore, will generally be far less than that inferred from the concentration of radon 222 alone. At distances more remote than one-half mile, the daughters might more nearly approach equilibrium conditions, but the total concentrations will have been so diluted as to be essentially negligible.

THERMOLUMINESCENT DOSIMETER RESULTS

During the latter part of this study it was considered desirable to obtain information on external radiation exposure at a number of the radon sampling stations. Thermoluminescent dosimeters (TLD's) were placed at each of the four study sites.

The TLD's used were of the $CaF_2:Mn$ type. They were shipped from the laboratory and placed at a number of stations. At each station three TLD's were placed at the same height above the ground as the air intakes of the radon samplers. They were exposed for 30 days and returned for readout. The dates of exposure were June 17 to July 17, 1968.

Those stations situated directly over tailings (with the exception of Monticello) range from 0.2 to 1.1 mR/hr. This range is in good agreement with values found during previous environmental surveys at the Tuba City, Ariz. and Mexican Hat, Utah tailings areas. The Monticello site (covered pile) shows exposure rates of 0.03 and 0.06 mR/hr on the pile. These values agree with those presented by Paas (4). All other stations show normal background levels of exposure. The difference between Grand Junction offpile stations (0.02 mR/hr) and the offpile stations at the other locations (0.01 mR/hr) is insignificant.

Table 3. Thermoluminescent dosimeter results

Location	Station	Net average exposure rate (mR/hour)
Grand Junction, Colo.	11[a]	0.2
	12[a]	.4
	16	.02
	33	.02
	42	.02
	47	.02
Durango, Colo.	51[a]	.4
	55	.02
	58	.01
Monticello, Utah	63[a]	.03
	64[a]	.06
	72	.01
	74	.01
Salt Lake City, Utah	81[a]	1.1
	85	.01
	86	.01
	91	.01
	96	.01

[a] Onpile stations.

SUMMARY AND CONCLUSIONS

The results of a joint PHS — AEC yearlong study to evaluate the public health aspects of atmospheric radon 222 concentrations in the vicinity of uranium mill tailings piles are presented. Samples were collected from 13 onpile and 44 offpile stations in the four study cities of Grand Junction and Durango, Colo., and Monticello and Salt Lake City, Utah. The tailings pile at Monticello has been covered and stabilized; the other three are uncovered and unstabilized. The side slopes of the pile at Grand Junction are partially stabilized with a grass cover.

On the basis of the data gathered at the four study sites, it is possible to reach the following conclusions:

1. The background radon 222 concentration at Grand Junction averages 0.8 pCi/liter and is approximately double the background concentrations at the other three study sites.
2. The tailings at the four study sites are not significantly affecting the atmospheric radon concentrations beyond a distance of one-half mile in the prevailing wind directions.
3. Of the 44 offpile stations, exclusive of station 82 at Salt Lake City, only two exhibited an average radon concentration (above background) equal to or higher than the 1 pCi/liter screening value adopted for this study.
4. The measured concentrations of radon over the stabilized tailings at Monticello are less than those over the other tailings in this study. Determination of the precise effect of stabilization would require sampling before and after stabilization at a specific site.

The conclusions are:

1. A technique for taking integrated air samples for radon near uranium tailings piles has been developed, tested, and proven through use in the field.
2. Atmospheric concentrations of radon in areas near uranium tailings piles have been evaluated as an index to radiation exposure of the population. The results indicate no significant radiation exposure to the public from this source.
3. Stabilization and covering of uranium tailings piles in theory should reduce the emanation of radon from the piles; however, the evidence for this is not conclusive from data obtained during this study.
4. Development of point recommendations to control public exposure to radon from uranium tailings piles is not necessary, as no significant public exposure was indicated by the results of the study.

REFERENCES

(1) U.S. DEPARTMENT OF COMMERCE. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure, NBS Handbook No. 69 (August 1963), p. 6.

(2) INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. Recommendations of the International Commission on Radiological Protection, Report No. 2. Pergamon Press, New York, N.Y. (1959).

(3) FEDERAL REGISTER RULES AND REGULATIONS. Title 10, Code of Federal Regulations, Part 20, Standards for Protection against Radiation. Superintendent of Documents, Government Printing Office, Washington, D.C. 20402 (November 17, 1960).

(4) PAAS, H. J., JR. Radiological appraisal of the Monticello Project, San Juan County, Monticello, Utah, IDO-12049. U.S. Atomic Energy Commission (February 1966).

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Statement

APPENDIX I

AN INTEGRATING AIR SAMPLER FOR DETERMINATION OF RADON 222

During the processing of uranium ores for the recovery of uranium, the insoluble portion of the ore remaining after the uranium has been leached out is stored in huge piles adjacent to the mill. Since most of the ores processed are relatively low grade, averaging only about 0.25 percent U_3O_8, the quantity of tailings generated is 98 to 99 percent of the quantity of ore processed. By the end of 1970, the projected total tailings will amount to approximately 90-million tons contained in 35 separate piles. The radioactive daughters of uranium are not leached out of the ore significantly and remain almost completely in the tailings material. The most toxic of these waste products are 80,000-year thorium 230, 1,600-year radium 226, 22-year lead 210, and 138-day polonium 210, the first three of which are bone-seekers, and all are either alpha emitters or give rise to alpha emitters. Since the radioactivity of the tailings material averages about 700 pCi/gram for each radionuclide in the uranium chain, the total inventory amounts to about 58,000 curies of each radionuclide or the equivalent of over 125 pounds of radium 226.

Although the total inventory of radioactive nuclides in the tailings material is impressive, the hazard from particulate materials is not very great. The sands are quite coarse and settle back to the ground within a short distance, and most of the active piles are kept sprinkled to minimize blowing. The material has such a low specific activity that the small quantity that remains airborne for significant distances is thought by many experts to represent more of a hazard from pneumoconiosis or a civic nuisance than any real threat from the standpoint of internal dose; in fact, air dust surveys show concentrations of less than a few percent of the maximum permissible concentration (MPC) for continuous exposure to the entire population at distances in excess of perhaps one-half mile from the pile.

Recently, attention has been directed toward the possibility of a larger dose to the population in the vicinity of the tailings piles from radon and its daughters than from the particulates. Unlike any of the other uranium daughters, radon, the immediate decay produce of radium 226, is a gas that diffuses out of the solid tailings into the air where it decays further to produce other radioactive products; 3.05-minute polonium 218, 26.8-minute lead 214, 19.7-minute bismuth 214, and 164-μsecond polonium 214. These short-lived radon daughters are particulate and are filtered out in the lungs during normal respiration. When in equilibrium with their parent, the daughters are responsible for approximately 95 percent of the total dose resulting from the presence of radon. Because of the large mass of tailings materials, its associated radium 226 content, and the ability of radon to diffuse out of the solid pile, the radiological dose to the lungs from the gaseous radon and its particulate daughters might actually exceed that from the longer-lived nuclides in the tailings material itself. Recent calculations (1) suggest that the dose is maximal to the segmental bronchi, with an annual dose of 13.8 rads resulting from a concentration of 10.1 pCi/liter. A program was initiated to evaluate the radiological hazard to those in the vicinity of the mill tailing piles resulting from radon and its short-lived daughters.

In an exploratory survey to determine how great the hazard might be, 36 samples from four different cities were analyzed for radon 222 by a modification of a conventional method (2) involving absorption of the radon on activated carbon, elution at 500° C., and counting in a scintillation chamber (3). These preliminary samples were obtained by allowing an evacuated 16-liter stainless steel tank to fill to atmospheric pressure spontaneously. Samples were taken directly both under convective conditions in the afternoon and under the inversion conditions occurring in the early morning hours.

The highest value of 38.3 pCi/liter was obtained directly over tailings under nocturnal inversion conditions; the value dropped to 5.6 pCi/liter for the afternoon sample at the same location. The second highest value of 24.7 pCi/liter was taken near one edge of the tailings pile, but definitely off the property in an unrestricted area. Five other samples taken within about one-half mile from the respective piles were between 1/3 and 1 times the MPC of 3 pCi/liter permitted by regulation for continuous exposure to the general public in uncontrolled areas (4). The remaining samples from residential areas were not significantly different from background samples taken at approximately the same time several miles distant from tailings areas.

These preliminary results suggest that radon concentrations above the regulatory values for unrestricted areas can be obtained at almost any time directly over tailings and occasionally in uncontrolled areas, particularly at short distances downwind from the pile during nocturnal inversions. Although there appeared no need for alarm, the data clearly demonstrate the need for more sophisticated measurements to determine the average yearly concentrations of radon issuing from the piles and in unrestricted areas. The actual radiological hazard from radon emitted from tailings piles is difficult to assess. Exhalation of radon from the ground varies markedly with time and is particularly dependent on the condition of the surface and the prevailing meteorological conditions (5-11). Hosler (5) refers to recent measurements that have shown that ". . . variations of radon exhalation rates from a given type of bed rock or soil surface are small relative to the variations in air concentrations that can be attributed to vertical mixing." Normally, the radon content in the air near the ground increases during the nocturnal inversion period and decreases during the daytime convective period when atmospheric dilution is at a maximum and can be expected to change significantly by the hour.

Federal regulations permit the radiation dose received from licensed facilities by the population in uncontrolled areas to be averaged over a period of 1 year (4). A reasonable sampling program should logically cover at least a 1-year period to sample radon under all meteorological conditions prevailing during the same time period over which the radiation dose is averaged. If separate samples were taken by conventional techniques employing evacuated flasks that literally sample for only a few seconds at a time, such a program would become almost prohibitively expensive in terms of numbers of samples and analyses required if many sampling stations were involved. In contrast, if the sample itself could be averaged by being collected continuously at a constant flow rate for several hours at a time, a single analysis would give an average value for the entire period sampled. Such integrated samples would obviously permit air to be sampled for a greater fraction of the total time available for a given cost, and permit a more realistic evaluation of the radiation dose to be made.

A sampling period of 48 hours was selected as being about the longest time that could be used without introducing a large uncertainty due to radioactive decay of the 3.823-day radon 222 during the sample collection period. If the activity were calculated to the midpoint of the collection period, the error from this cause could not exceed about 15 percent, if all the radon were collected during the first or last 2 hours (a most unlikely occurrence). With the variations in radon concentrations normally encountered, the error is not expected to exceed about 5 percent. Sampling for 2 diurnal cycles should smooth out the marked diurnal fluctuations and give a good average value for the entire period. This single integrated sample should be far superior to that obtained from many spot samples taken over the same time period. Sampling will be repeated at each location every 3 weeks to cover 10 percent of the total time available for exposure and to sample every calendar month, every season, and every usual meteorological condition occurring within 1 calendar year with only 17 samples per station.

To minimize transportation problems, the sample collected should be no larger than that necessary for analysis. Only 6 liters of air is required to detect activities higher than about 0.01 pCi/liter in a 1-hour count. Allowing for duplication of analyses and radiological decay during shipment from field location to the laboratory, approximately 30 liters of air should be adequate even for cross-checking between laboratories. If the sampling period is to cover 48 hours, the flow rate must not exceed 10 ml/min. The present investigation was initiated to develop equipment for collecting air at a reasonably constant low flow rate, in outdoor locations under all kinds of weather conditions and at locations frequently remote from a source of electric power.

Available equipment capable of doing the job was too expensive to permit large numbers of stations to be sampled simultaneously and meet the desired schedules. Initial attempts to assemble adequate equipment from commercially available parts were unsuccessful. A conventional piston-type compressor was used to pump filtered air through a flowmeter into an evacuated 2-liter stainless steel tank in the hope that the pump would be sufficiently powerful to fill the tank to several atmospheres pressure without decreasing the flow rate. When the pump was choked down from its rated capacity of 1.5 cfm to the required rate of only 10 ml/min, nearly 10 times as much air slipped past the piston as came in through the inlet. It is absolutely necessary to the success of this procedure that all air entering the sample container be filtered free of any dust containing radium 226 that will contribute additional radon during the long times involved from sample collection to final analysis and interfere seriously with proper decay corrections. A similar pump, having a rubber diaphragm to prevent leakage, could not maintain a constant flow as the rigid-walled container filled with gas. From these preliminary attempts, it seemed evident that (1) a pump would have to be used whose nominal capacity did not exceed greatly the sampling rate desired, and (2) a collapsible bag would have to be employed as a sample container to eliminate decreasing flow rate as sampling proceeded.

SAMPLING EQUIPMENT

PUMP

The pump finally used was a small 4-watt, 117-volt aquarium aerator called the Silent Giant (Model 120, Aquarium Pump Supply Inc., Prescott, Ariz.) that employs a cup and plunger compression chamber sealed by a flexible web and operated by an electromagnet. The pump also employs an efficient method of back-pressure compensation so that the flow rate is not affected significantly by conditions of air use or depth of water in the aquarium that is helpful in the present application. Under conditions of free flow, the pump delivers about 3 liters/min of air. With a needle valve restricting the flow from 0 to 125 ml/min, the pump builds up a pressure of about 6 psi.

As supplied commercially, the air inlet to the pump consists of several small holes in the interior can in which the pump mechanism is contained. To provide a single specific air inlet so that the incoming air can be filtered free of radium 226 and also to permit a tube to be run directly into the air stream to be sampled while the pump itself is protected inside a weather shelter, the interior can was reencased in a plastic housing made conveniently from 3.5-inch o.d. tubing, 4 inches long and 1/8 inch thick. Both ends were sealed with flat plates one-half inch thick, one end of which had been previously drilled and tapped to provide the necessary air inlet and outlet and electrical connections. When sampling at locations remote from a source of electric power, the pump can be operated from a 12-volt storage battery through a small power inverter (Model 50-103, Newark Electronics Corp., Chicago, Ill.) built for use in operating an electric shaver from an automobile storage battery.

FLOW REGULATOR

The first samplers used a small variable-area type flowmeter and a fairly coarse needle valve to control and indicate the air flow obtained. Even with fairly expensive models, the flowmeter itself appeared to contribute considerably to the instability of the air flow because of sticking floats, and so forth; consequently, the flowmeter and needle valve assembly were replaced by a precision extra-low-flow needle valve with a direct reading digital handle (Model 8502, Brooks Instrument Division, Hatfield, Pa.). Under the pressure of 6 psi supplied by the aquarium pump, a flow rate of about 125 ml/min is obtained with the valve wide open. The valve requires 15 turns from fully open to fully closed and can be read to about one-twentieth of a turn. The flow rate can be quickly and easily calibrated by water displacement after which the same volume can be reproduced to within ± 1 percent by resetting the digital indicator.

SAMPLE CONTAINER

A collapsible container is necessary for use with the present low-volume pump to prevent significant changes in flow rate because of changing back pressure as the sample is collected. It is well-known that rubber, polyethylene, and many other kinds of plastics are extremely permeable to radon gas; in addition, natural rubber generally contains sufficient radium 222 to interfere seriously with the determination of radon. Bags made of Mylar have been used for years as meteorological balloons in weather science and are known to be capable of flying long distances without losing significant amounts of various gases such as oxygen, nitrogen, helium, and so forth. The present investigation shows that the same material is perhaps the best presently available for retention of radon.

The bags used were fabricated from a double layer of 3/4-mil Mylar laminated together to eliminate pin holes (GT-21, G. T. Schjeldahl Company, Northfield, Minn.). To make the bags, a strip of the laminated material of the size desired is folded over, and the side and both ends are sealed by inserting a strip of sealing tape (GT-400) between the two faces and ironing the tape area with a hand sealing iron at approximately 350° F. until the milky appearance disappears from the tape, indicating that a good bond has been achieved. A dill valve available from bicycle or hardware stores, is placed in the face of the bag prior to sealing. The bags used in the present study have inside dimensions of 17-3/4 inches by 31-3/4 inches with the bag lying flat, and hold approximately 40 liters when filled completely. The bags are made somewhat larger than the volume to be contained to provide room for expansion at temperatures and pressures other than those at which the sample is collected (mountain passes, aircraft, and so forth).

The complete sampling equipment (figure 1) is connected to the small electric shaver inverter and storage battery for use in locations that are remote from a source of electric power. For sampling in remote or difficult-to-reach locations where weight and bulk must be kept to a minimum, such as in a uranium mine, the small 10-ampere-hour motorcycle battery provides sufficient capacity for an 8-hour integration over a shift. For sampling in remote areas above ground, a regular automobile storage battery of about 70-ampere-

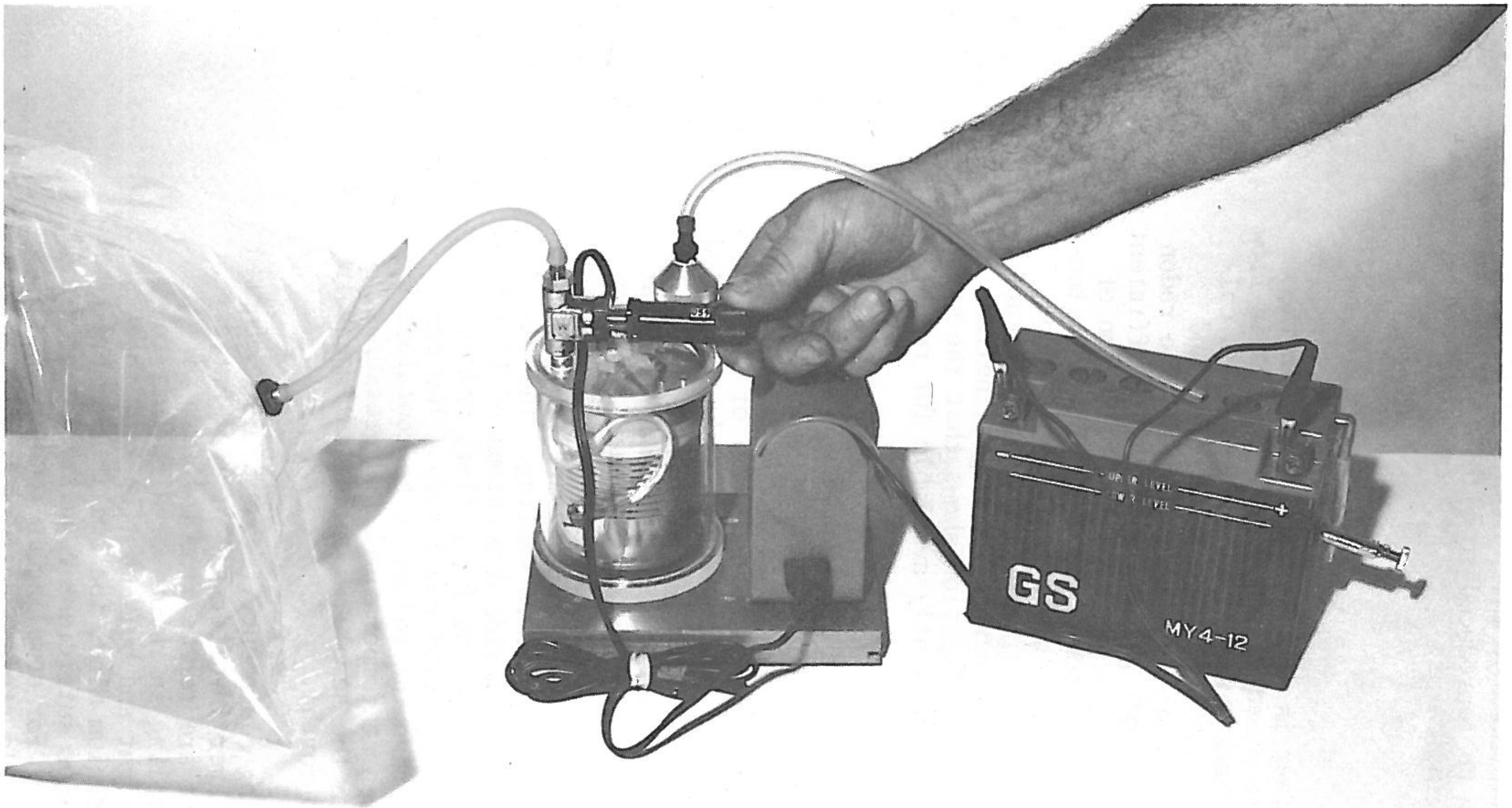

FIG. 1. EQUIPMENT USED FOR TAKING INTEGRATED AIR SAMPLES FOR DETERMINATION OF RADON 222

hour capacity is necessary for a 48-hour sample integration. When 115-volt power is available, the electric plug is simply removed from the inverter shown and plugged into the source of a.c. power.

In operation, the entire equipment shown in figure 1 is placed in a weather shelter, and the piece of gum rubber tubing shown on the right is allowed to extend out of one end into the airstream to be sampled. A small funnel is inserted in the end of the tubing to prevent rain from being drawn in and saturating the filter, which would cause a marked decrease or complete stoppage of the airflow. The air is then drawn through a double 1-inch filter (in the conical holder) consisting of a glass-fiber roughing filter, followed by a membrane filter (GS-6 Gelman Instrument Company, Ann Arbor, Mich.) into the plastic case. The pump then draws the air through holes in the bottom of the can and expels it through the coiled tube, the needle valve, and into the Mylar bag. In actual use, the Mylar bag is contained in a cardboard box, 10.5 inches by 12 inches by 30 inches, inside the weather shelter to protect the bag from abrasion, air motion, and so forth, and to serve as a container in which to ship the gas sample back to the laboratory. Current cost of the equipment shown is about $55 for the a.c.-operated system, about $80 for the battery-operated system, and about $6 each for the Mylar bags.

PERFORMANCE

The operating characteristics of the pump and needle valve were determined by measuring the volume of water displaced from an inverted 10-ml graduated cylinder in 60 seconds under various conditions. A flow rate of 9.6 ml/min could be reproduced to within 0.1 ml/min or about 1 percent by setting the indication handle back to the same number from either fully open or fully closed provided the final adjustment was always made from the same direction.

EFFECT OF VOLTAGE

At a flow rate of 9.6 ml/min, changing the voltage from 135 to 105 volts changed the flow rate by less than about 1 percent. The flow rate drops to about 50 percent of its initial value at 90 volts and decreases rapidly at lower values. In fact, this same pump makes an excellent low-cost transfer pump for laboratory use, using a variable transformer to change the flow rate continuously and smoothly by changing the voltage in the lower voltage ranges. Care should be taken so the voltage at the end of long runs of wiring required to reach remote locations is not permitted to drop so low that the flow rate becomes susceptible to normal voltage fluctuations. For the year-long program for which this equipment was developed, several thousand feet of No. 14 electric wire were used to reach most of the sampling stations on and around the mill tailings piles with a resultant voltage drop of less than 1 volt. Because of the very small power consumption of the pumps, longer runs of even smaller wire can be used to reach even more remote locations before the voltage drop becomes significant.

When battery operated, the pump and inverter together draw about 0.7 ampere which will use about one-half of the total capacity of a 10-ampere-hour motorcycle battery in 8 hours or of a 70-ampere-hour automobile battery in 48 hours. During an 8-hour period, the voltage of a new motorcycle battery dropped from 12.5 to 11.6 volts with less than about 2 percent change in flow rate. The automobile battery will undoubtedly act similarly, but either battery should be recharged before taking another sample.

EFFECT OF TEMPERATURE

The effect of temperature is more difficult to assess and interpret. Initially, the outlet from the pump was connected to the Mylar bag through a flowmeter. The entire assembly of pump, needle valve, and flowmeter were placed in a steel ammunition box only slightly larger than the assembly itself, the lid was closed tightly, and the flowmeter was read periodically through a single small opening in the box over a period of 2 days. The box was placed outdoors near the west wall of the laboratory building, so it would become cold during the night, warm up slowly during the forenoon hours when the box was in the shadow of the building, and finally become extremely hot during the afternoon when the hot summer sun shined directly on the box for several hours. Since the change in flow rate observed was less than 10 to 15 percent at most, no attempt was made to define temperatures quantitatively except to state that the steel box was so hot all afternoon that it could not be touched comfortably for longer than a few seconds at a time. At night, the air temperature was approximately 35° F. These temperature extremes are thought to be greater than those that need be tolerated if the pump assembly is placed in a ventilated weather shelter to protect it from the direct rays of the sun.

In another attempt to evaluate the effect of temperature, the flow rate was determined by water displacement while the needle valve and pump were alternately heated and cooled. After an initial adjustment of the flow rate to 9.6 ml/min at 24° C., the flow rate decreased to 7.1 ml/min, or about 26 percent when the needle valve was heated with an infrared lamp hotter than could be touched comfortably for any significant period of time. When the needle valve was cooled with an aerosol spray used to cool electric circuits, the flow rate increased to 10.6 ml/min, or about 10 percent. Since the flow rate was measured by water displacement from a large tray of water at room temperature, the changes observed obviously reflect variations in mass transfer rather than volume. Both changes would undoubtedly have been smaller had the exit air remained more nearly at the temperature of the air being sampled. Since respiratory processes are more dependent on volume transfer than on mass transfer, it appears that the effect of temperature on the pump is not very different from its effect on the volumes breathed by humans. Again, no attempt was made to make a precise determination of a characteristic which is fundamentally imprecise in usage. It is unlikely that any reasonable temperature variation will introduce more than a 10 to 15 percent uncertainty between the volume sampled by the pump and that breathed by people.

DIFFUSION OF RADON 222 THROUGH MYLAR

The use of Mylar bags as containers for air samples for the determination of radon 222 depends on their ability to retain radon for the several days required for sampling, transportation to the laboratory, and analysis. To determine possible losses from diffusion, pin holes, faulty seams, or whatever cause under actual conditions of use, a bag was filled with approximately 30 liters of air containing sufficient radon 222 to give an initial counting rate of about 4×10^5 gamma counts per minute of daughter activity at equilibrium under the counting conditions employed. The bag of air was placed horizontally on a stretcher in a 9-foot cubical steel room used for whole-body counting and an 8-inch by 4-inch NaI(Tl) detector was placed over the center of the bag at a distance of about 12 inches. The bag was allowed to stand overnight to ensure ingrowth of the radon daughters to complete equilibrium. After rechecking the experimental set-up the following morning, the door to the vault was closed and sealed to prevent any traffic or air motion inside the vault that might change the orientation of the bag and thereby change the counting efficiency. A 1-minute count was made immediately and was repeated at approximately the same time on each successive day for the next 6 days during that time the door to the vault was never opened. An additional measurement was obtained on the 15th day that had not been

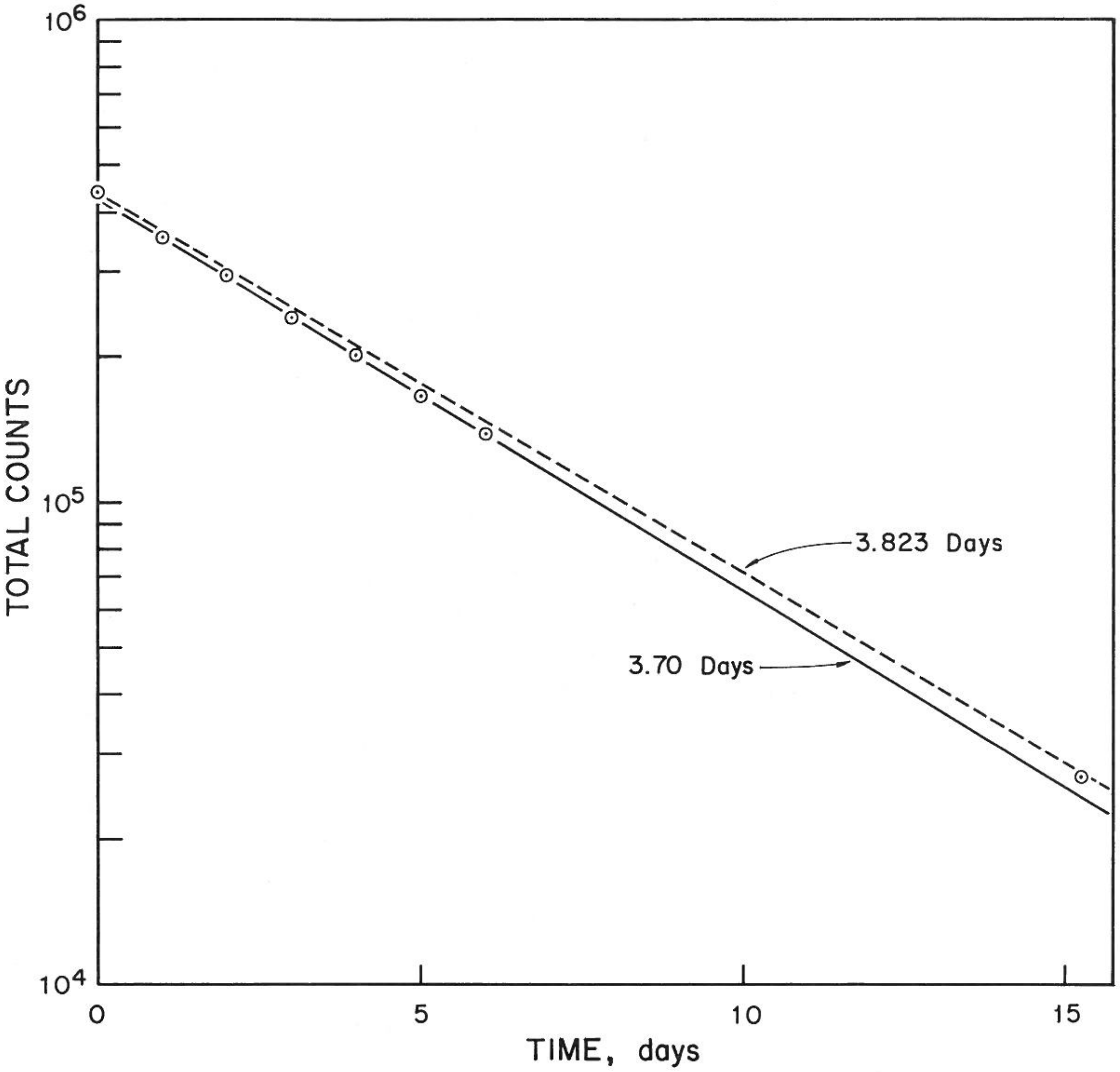

FIG. 2. DECAY OF RADON 222 CONTAINED IN A MYLAR BAG

Aged air was then pumped from a Mylar bag into an empty one at 10 ml/min for 48 hours to determine the quantity of radon that would diffuse back into a subsequent low-level sample during the lengthy collection period used in the field. The radon found in the purge and subsequent eluate was about 2.5 and 0.5 percent, respectively, of that taken in the original 30 liters of gas of which 1 percent is attributed to the free-volume space of about 300 ml. This contamination would increase the concentration of a subsequent 30-liter sample by a maximum of 1.2 pCi/liter, which can be reduced to 0.2 pCi/liter by a short purge with the valve wide open. In practice, the contamination will be even less because of decay between uses. Pumps used over tailings or in other areas of high radon concentrations should be purged before being used for sampling in low-level areas unless sufficient time is allowed for adequate radiological decay.

PRACTICAL APPLICATION

In cooperation with the U.S. Public Health Service and the health departments of the States of Colorado and Utah, a 1-year program involving 57 stations in four cities was instituted, based on the philosophy and equipment described above. The philosophy of employing 48-hour integrated samples to increase the reliability and decrease the cost of long-term measurements worked extremely well. Excellent coverage of the four study areas was obtained at minimum cost and results are clear, consistent, and singularly free of any significant anomalies. The sampling equipment performed almost as well in the field as it had in the laboratory, with a few exceptions. Of 18 complete samplers in use, five of the $15 pumps burned out and had to be replaced. This was probably due to the low flow rate that caused a much higher back pressure than that recommended by the manufacturer. A more frequent problem encountered was the occasional sticking of the needle valves that would not retract when the handle was turned to the open position. On prolonged use, a very small amount of corrosion occurs that tends to fix the needle in its existing position so that the spring-loaded return is insufficient to break it loose and open the valve. This problem is easily remedied by removing the needle and wiping it gently with a dry cloth before each 48-hour run.

The Mylar bags have held up very well on repeated use, with each bag being used an average of eight times without showing signs of significant deterioration. The infrequent breaks that develop where the Mylar has been creased sharply, and even an occasional tear, are easily and rapidly repaired using sealing tape and a hand iron. The one really frustrating problem encountered in the entire program was the occasional obstinate refusal of some of the bags to fill up in the proper time even though it could be shown that air was entering the bag at the proper rate. The only reasonable explanation is the presence of pin holes in the bags or rubber tubing, minute leaks in the seams or valves, or a faulty connection to the valve. Obviously, it would not take much of an opening to permit the gas to bleed off as fast as it is collected, considering the very low rate involved. Some of the leaks are extremely difficult to find. If a bag is partially filled with air and then tested in the conventional manner by immersion in a large container of water, some of the leaks, particularly in the seams, will close off when pressure is applied and then open up again when the pressure is relaxed to the conditions under which the samples are collected. Leaks from very small pin holes, observed if covered with a very thin layer of water or soap solution, will stop if immersed under a greater depth of water; however, most leaks are readily detected by immersion in a vessel of water, and this method is used routinely to leak test all bags in the laboratory after the analysis has been completed and before they are returned to the field.

The same philosophy and sampling equipment will undoubtedly find many other applications in air pollution control.

ACKNOWLEDGMENTS

The author acknowledges the many timely suggestions and assistance that he has received from his associates in the laboratory. Particular thanks are due *M. Wilhelmsen*, *D. Parker*, and *P. R. Boren* for assistance in procurement of the instrumental components; to *D. G. Olson* and *D. R. Percival* for much of the data; and to *P. R. McKnight* and *W. E. Bush* for solving many of the initial problems of field implementation.

REFERENCES

(1) HAQUE, A. K. M. and A. J. L. COLLINSON. Radiation dose to the respiratory system due to radon and its daughter products. Health Physics 13:5:431-443. Pergamon Press, New York, N. Y. (1969).

(2) STEHNEY, A. F., W. P. NORRIS, H. F. LUCAS, and W. H. JOHNSTON. Radium therapy and nuclear medicine. Amer J Roentgen 73:774 (1955).

(3) LUCAS, H. F. Improved low-level alpha-scintillation counter for radon. Rev Sci Instrum 28:680 (1957).

(4) FEDERAL REGISTER RULES AND REGULATIONS. Title 10, Code of Federal Regulations, Part 20, Standards for Protection against Radiation. Superintendent of Documents, Government Printing Office, Washington, D.C. 20402 (November 17, 1960).

(5) HOSLER, C. R. Natural radioactivity (^{222}Rn) and air pollution measurements in Washington, D.C. J Appl Meteorol 5:653-662 (October 1966).

(6) HOSLER, C. R. Meteorological effects of atmospheric concentrations of radon (^{222}Rn), RaB (^{214}Pb), and RaC (^{214}Bi) near the ground. Monthly Weather Rev 94:89-99 (February 1966).

(7) HOSLER, C. R. and L. B. LOCKHART, JR. Simultaneous measurements of ^{222}Rn, ^{214}Pb, and ^{214}Bi in air near the ground. J Geophys Res 70:4537-4546 (September 15, 1965).

(8) MOSES, H., J. F. LUCAS, JR., and G. A. ZERBE. The effect of meteorological variables upon radon concentration three feet above the ground. J Air Pollut Contr Assn 13:12-19 (January 1963).

(9) MOSES, H., A. F. STEHNEY, and H. F. LUCAS. The effect of meteorological variables upon the vertical and temporal distributions of atmospheric radon. J Geophys Res 65:1223-1238 (April 1960).

(10) STALEY, D. O. Diurnal oscillations of radon and thoron and their decay products. J Geophys Res 71:3357-3367 July 15, 1966).

(11) LOCKHART, L. B., JR. (Edited by J. A. S. Adams and W. M. Lowder). Radioactivity of the Radon-222 and Radon-220 Series in the Air at Ground Level. In The Natural Radiation Environment, Chapter 18. University of Chicago Press, Chicago, Ill. (1964).

APPENDIX II

RADON SAMPLING RESULTS

All sample results for the program are shown in the following tables in chronological order for each sampling station. All values have been corrected for decay to the midpoint of the 48-hour collection period and corrected to the mean annual temperature and pressure for the site as follows: Grand Junction, 638 mm, 11° C.; Durango, 599 mm, 8° C.; Monticello, 587 mm, 8° C.; Salt Lake City, 654 mm, 11° C.

Results are shown under the appropriate contributing laboratory: "USAEC" denotes the Health Services Laboratory, Idaho Operations Office, U.S. Atomic Energy Commission, Idaho Falls, Idaho; "SWRHL" denotes the Southwestern Radiological Health Laboratory, Bureau of Radiological Health, U.S. Public Health Service, Las Vegas, Nev.

Whenever more than one determination was made on the same sample, the arithmetical average of the determinations was used in further calculations. The ± values give the standard deviation because of the counting statistics only.

Table 1. Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo.

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
11	1200	6-6-67	4.23 ± 0.21	4.72 ± 0.24	5.62	4.45
	1128	7-27-67	13.5 ± 0.2	12.9 ± 0.1		
	1215	9-6-67	20.9 ± 0.2	21.0 ± 0.2		
	1300	9-28-67	14.2 ± 0.1			
	1430	10-19-67	19.4 ± 0.2	19.1 ± 0.2		
	1010	11-14-67	27.5 ± 0.2			
	1450	12-9-67	4.30 ± 0.07		5.36	
	0935	12-27-67	7.3 ± 0.1			
	1010	1-23-68	10.2 ± 0.1			
	1000	2-13-68	6.42 ± 0.08			
	1000	3-5-68	7.7 ± 0.1			
	0945	3-26-68	6.67 ± 0.08			
	1000	4-16-68	3.34 ± 0.06			
	1015	5-7-68	12.3 ± 0.1			
	1015	5-28-68	12.0 ± 0.1			
	1320	6-27-68	12.9 ± 0.1			
	1000	8-20-68	8.40 ± 0.08			
12	0900	6-8-67	2.17 ± 0.11	2.21 ± 0.11	2.28	2.41
	1102	7-6-67	1.39 ± 0.05	1.28 ± 0.08	9.48	
	1115	9-26-67	5.71 ± 0.09			
	1027	10-17-67	5.19 ± 0.07	5.13 ± 0.07	5.15	
	1000	11-7-67	4.7 ± 0.1			
	1420	11-30-67	6.0 ± 0.3			
	1330	12-21-67	2.40 ± 0.07			
	1355	1-18-68	3.4 ± 0.1			
	1330	2-8-68	7.0 ± 0.1			
	1330	2-29-68	4.51 ± 0.07			
	1330	3-21-68	4.62 ± 0.07		4.78	
	1325	4-11-68	7.35 ± 0.09			
	1345	5-2-68	4.76 ± 0.08	5.15 ± 0.09		
	1315	5-23-68	5.71 ± 0.08	5.61 ± 0.08		
	1320	6-13-68	7.7 ± 0.1			
	1305	7-25-68	5.76 ± 0.09		4.53	3.33
	1320	8-15-68	2.83 ± 0.06	2.55 ± 0.06		

Table 1. Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo. (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
13	0900	6-8-67	7.05 ± 0.35		1.51	
	0935	6-28-67	9.1 ± 0.2	9.7 ± 0.2	6.18	5.91
	1200	7-27-67	20.4 ± 0.2	21.2 ± 0.2		
	1230	9-26-67	10.1 ± 0.1			
	1012	10-17-67	10.8 ± 0.1			
	0930	11-7-67	8.8 ± 0.1	9.8 ± 0.1		
	1400	11-30-67	8.8 ± 0.2			
	1315	12-21-67	7.6 ± 0.1	7.2 ± 0.1		
	1335	1-18-68	9.3 ± 0.1			
	1315	2-8-68	7.8 ± 0.1			
	1315	2-29-68	12.6 ± 0.1	12.1 ± 0.1		
	1310	3-21-68	8.3 ± 0.1			
	1305	4-11-68	8.3 ± 0.1			
	1330	5-2-68	7.9 ± 0.1			
	1300	5-23-68	7.4 ± 0.1	7.21 ± 0.09		
	1305	6-13-68	4.63 ± 0.08			
	1305	8-15-68	4.66 ± 0.08			
14	1200	6-6-67	1.17 ± 0.06	1.32 ± 0.07	1.09	0.99
	1215	9-26-67	9.9 ± 0.1		9.44	
	0945	10-17-67	6.50 ± 0.07		6.07	
	1030	11-7-67	8.3 ± 0.1			
	1500	11-30-67	5.9 ± 0.2			
	0915	12-27-67	7.1 ± 0.1			
	1320	1-18-68	5.3 ± 0.1			
	1405	2-8-68	6.6 ± 0.1			
	1405	2-29-68	4.55 ± 0.08			
	1515	3-23-68	5.61 ± 0.07	5.57 ± 0.06		
	1400	4-11-68	6.97 ± 0.09	6.80 ± 0.09		
	1400	5-2-68	4.17 ± 0.08		2.06	2.58
	1330	5-23-68	7.7 ± 0.1	7.9 ± 0.1		
	1340	6-13-68	3.2 ± 0.1			
	1400	6-27-68	7.09 ± 0.09			
	1350	7-25-68	5.90 ± 0.09	5.55 ± 0.09		
	1335	8-15-68	1.78 ± 0.04		3.03	2.97

Table 1. *Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo.* (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
15	1200	6-6-67	3.15 ± 0.16	3.46 ± 0.17	4.03	3.41
	1145	9-26-67	8.8 ± 0.1	9.2 ± 0.1		
	0927	10-17-67	8.8 ± 0.1			
	1045	11-7-67	11.5 ± 0.1			
	1440	11-30-67	9.5 ± 0.3			
	1400	12-21-67	9.1 ± 0.1			
	1300	1-18-68	4.9 ± 0.1			
	1350	2-8-68	6.41 ± 0.09	6.01 ± 0.09		
	1350	2-29-68	8.2 ± 0.1			
	1400	3-21-68	5.78 ± 0.08		5.27	
	1345	4-11-68	9.3 ± 0.1			
	1415	5-2-68	7.8 ± 0.1		7.49	6.36
	1345	5-23-68	8.6 ± 0.1	8.4 ± 0.1		
	1405	6-13-68	22.0 ± 0.2			
	1340	6-27-68	16.2 ± 0.2	15.0 ± 0.1		
	1330	7-25-68	13.5 ± 0.1		10.61	9.50
	1350	8-15-68	3.53 ± 0.05		4.32	4.01
16	1420	6-15-67	0.62 ± 0.03	0.61 ± 0.10	0.66	
	1100	9-12-67	1.14 ± 0.05	1.00 ± 0.03		
	0920	10-3-67	0.87 ± 0.05			
	0915	10-24-67	0.87 ± 0.04			
	1310	11-16-67	1.57 ± 0.05			
	1330	12-7-67	0.97 ± 0.04			
	0915	1-4-68	1.75 ± 0.05			
	1305	1-25-68	2.62 ± 0.06			
	1310	2-15-68	1.07 ± 0.04			
	1305	3-7-68	0.84 ± 0.04		1.02	
	1305	3-28-68	0.82 ± 0.03			
	1305	4-18-68	0.53 ± 0.03	0.50 ± 0.03		
	1310	5-9-68	0.66 ± 0.03			
	1310	5-30-68	0.58 ± 0.03			
	0945	6-18-68	0.50 ± 0.02			
	1015	7-18-68	1.53 ± 0.05		1.28	0.74
	1300	8-1-68	1.17 ± 0.04			
21	1345	6-15-67	0.72 ± 0.04	0.55 ± 0.06	0.80	
	0945	9-12-67	0.85 ± 0.04			
	1000	10-3-67	0.62 ± 0.03			
	1000	10-24-67	0.50 ± 0.03			
	1400	11-16-67	1.13 ± 0.03			
	1415	12-7-67	0.98 ± 0.03			

Table 1. *Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo.* (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
21	1000	1-4-68	1.11 ± 0.04			
	1350	1-25-68	1.77 ± 0.05			
	1345	2-15-68	0.60 ± 0.03			
	1345	3-7-68	0.66 ± 0.03			
	1345	3-28-68	0.69 ± 0.03	0.76 ± 0.03		
	1340	4-18-68	0.37 ± 0.02			
	1345	5-9-68	0.53 ± 0.03	0.56 ± 0.02		
	1345	5-30-68	0.43 ± 0.02			
	1015	6-18-68	0.54 ± 0.02	0.51 ± 0.02		
	1330	8-1-68	0.76 ± 0.03			
22	1405	6-15-67	0.58 ± 0.03	0.56 ± 0.03	0.67	
	1245	9-6-67	1.89 ± 0.06	1.91 ± 0.05		
	1330	9-28-67	1.36 ± 0.05			
	1415	10-19-67	1.50 ± 0.05			
	1030	11-14-67	2.27 ± 0.05	2.41 ± 0.05		
	1115	12-5-67	1.90 ± 0.03			
	1000	12-27-67	1.43 ± 0.05			
	1025	1-23-68	1.68 ± 0.04			
	1015	2-13-68	0.62 ± 0.02			
	1015	3-5-68	0.86 ± 0.06			
	1000	3-26-68	0.77 ± 0.02			
	1015	4-16-68	0.53 ± 0.02			
	1030	5-7-68	0.88 ± 0.03			
	1030	5-28-68	0.73 ± 0.03			
	0950	7-18-68	0.69 ± 0.03			
	1020	7-30-68	1.58 ± 0.04	1.54 ± 0.03		
	1020	8-20-68	2.65 ± 0.05	2.79 ± 0.05		
23	2200	6-22-67	0.88 ± 0.04	0.78 ± 0.05	0.81	0.75
	1200	9-6-67	4.11 ± 0.10	4.04 ± 0.06		
	1400	9-28-67	6.28 ± 0.09	6.45 ± 0.09		
	1345	10-19-67	7.2 ± 0.1			
	0945	11-14-67	12.7 ± 0.1			
	1045	12-5-67	4.99 ± 0.06			
	1315	12-29-67	2.02 ± 0.05			
	0950	1-23-68	2.60 ± 0.07			
	0940	2-13-68	1.16 ± 0.03			
	0935	3-5-68	1.60 ± 0.04	1.91 ± 0.06		
	0930	3-26-68	1.83 ± 0.04			
	0945	4-16-68	0.60 ± 0.02			

Table 1. Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo. (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
23	0955	5-7-68	2.24 ± 0.06			
	0945	5-28-68	2.75 ± 0.07			
	1305	6-27-68	2.19 ± 0.05			
	1005	7-30-68	2.04 ± 0.04	1.88 ± 0.04		
	0940	8-20-68	3.23 ± 0.05			
24	1324	6-15-67	0.66 ± 0.04	0.59 ± 0.03	0.83	
	1405	9-14-67	0.64 ± 0.02			
	1400	10-5-67	0.47 ± 0.03			
	1340	10-26-67	0.69 ± 0.03			
	1015	11-21-67	0.95 ± 0.04			
	0940	12-12-67	0.78 ± 0.03			
	0945	1-9-68	2.24 ± 0.06			
	0955	1-30-68	0.56 ± 0.03			
	0950	2-20-68	1.03 ± 0.04			
	0945	3-12-68	0.81 ± 0.02			
	0950	4-2-68	0.53 ± 0.02			
	0945	4-23-68	0.61 ± 0.02			
	0950	5-14-68	0.56 ± 0.02			
	0945	6-4-68	0.32 ± 0.02	0.30 ± 0.02		
	1320	6-20-68	0.66 ± 0.03			
	0930	7-23-68	1.34 ± 0.02	1.35 ± 0.03		
	0930	8-6-68	0.39 ± 0.04			
25	1320	6-21-67	1.28 ± 0.06	1.48 ± 0.05	1.83	1.54
	1430	9-14-67	0.64 ± 0.02			
	1430	10-5-67	0.29 ± 0.02	0.36 ± 0.02		
	1315	10-26-67	0.83 ± 0.04			
	0945	11-21-67	0.83 ± 0.04			
	1300	12-14-67	0.48 ± 0.02			
	0930	1-9-68	1.89 ± 0.05	2.00 ± 0.05		
	0935	1-30-68	0.52 ± 0.02			
	0930	2-20-68	0.83 ± 0.03			
	0925	3-12-68	0.93 ± 0.03			
	0935	4-2-68	0.74 ± 0.02			
	0930	4-23-68	0.63 ± 0.02			
	0930	5-14-68	0.83 ± 0.03			
	0925	6-4-68	0.28 ± 0.02			
	1300	6-20-68	0.47 ± 0.03			
	1025	7-23-68	1.09 ± 0.03			
	1030	8-6-68	1.41 ± 0.03			

Table 1. Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo. (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
26	1310	6-21-67	1.18 ± 0.05	1.72 ± 0.06	1.65	1.83
	1340	9-14-67	1.14 ± 0.04			
	1330	10-5-67	0.39 ± 0.03			
	1400	10-26-67	0.81 ± 0.03	0.84 ± 0.03		
	1030	11-21-67	0.79 ± 0.05			
	1000	12-12-67	0.73 ± 0.03	0.69 ± 0.03	0.60	0.66
	1015	1-9-68	2.21 ± 0.06			
	1010	1-30-68	0.52 ± 0.02			
	1010	2-20-68	1.07 ± 0.04			
	1000	3-12-68	0.75 ± 0.02			
	1005	4-2-68	0.41 ± 0.03			
	1005	4-23-68	0.58 ± 0.02	0.48 ± 0.02		
	1010	5-14-68	0.60 ± 0.02			
	1005	6-4-68	0.30 ± 0.02			
	1345	6-20-68	0.45 ± 0.02	0.50 ± 0.03		
	0950	7-23-68	0.48 ± 0.02			
	0950	8-6-68	1.21 ± 0.03			
31	0900	6-28-67	0.36 ± 0.03	0.53 ± 0.04	0.41	0.39
	0915	9-12-67	0.90 ± 0.04			
	1030	10-3-67	0.73 ± 0.04	0.61 ± 0.03		
	1020	10-24-67	1.57 ± 0.05			
	1425	11-16-67	1.61 ± 0.05			
	1430	12-9-67	0.58 ± 0.03			
	1020	1-4-68	1.11 ± 0.04	1.18 ± 0.04		
	1420	1-25-68	1.65 ± 0.05			
	1410	2-15-68	0.77 ± 0.03	0.79 ± 0.03		
	1400	3-7-68	0.65 ± 0.03		0.74	
	1410	3-28-68	0.82 ± 0.03			
	1400	4-18-68	0.57 ± 0.03			
	1415	5-9-68	0.75 ± 0.03			
	1405	5-30-68	0.77 ± 0.03			
	1030	6-18-68	0.73 ± 0.02			
	1245	8-13-68	3.37 ± 0.05	3.28 ± 0.05		
32	1345	7-6-67	0.38 ± 0.03	0.43 ± 0.02	0.78	0.34
	0915	9-19-67	1.74 ± 0.05	1.82 ± 0.04		
	0900	10-10-67	0.78 ± 0.03	0.71 ± 0.03		
	1030	10-21-67	0.86 ± 0.03			
	1305	11-23-67	0.54 ± 0.03			
	1330	12-14-67	1.26 ± 0.04			
	1300	1-11-68	1.23 ± 0.05			

Table 1. Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo. (continued)

Sta-tion no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
32	1305	2-1-68	0.54 ± 0.03	0.55 ± 0.03		
	1300	2-22-68	0.55 ± 0.03			
	1310	3-14-68	0.59 ± 0.02			
	1300	4-4-68	0.43 ± 0.02			
	1305	4-25-68	0.67 ± 0.03	0.73 ± 0.03		
	1305	5-16-68	0.43 ± 0.02	0.46 ± 0.02		
	1305	6-6-68	0.19 ± 0.02			
	0930	6-25-68	1.10 ± 0.03			
	1400	8-8-68	0.50 ± 0.02			
33	1010	6-28-67	0.58 ± 0.05	0.63 ± 0.03	1.46	1.27
	1130	9-6-67	1.83 ± 0.06	1.66 ± 0.04		
	1345	9-28-67	2.91 ± 0.07			
	1330	10-19-67	2.59 ± 0.06			
	0930	11-14-67	4.5 ± 0.1			
	1030	12-5-67	1.96 ± 0.04			
	1020	12-27-67	1.59 ± 0.05			
	0930	1-23-68	1.63 ± 0.04			
	0925	2-13-68	0.89 ± 0.03			
	0915	3-5-68	1.04 ± 0.03			
	0910	3-26-68	1.32 ± 0.03			
	0925	4-16-68	0.50 ± 0.02			
	0940	5-7-68	1.06 ± 0.03	0.99 ± 0.03		
	0930	5-28-68	1.04 ± 0.04	1.05 ± 0.05		
	0930	7-18-68	4.01 ± 0.07			
	0945	7-30-68	1.56 ± 0.04			
	0920	8-20-68	0.95 ± 0.03			
34	0925	7-11-67	0.68 ± 0.06	0.62 ± 0.04		
	1445	9-21-67	0.83 ± 0.03			
	1420	10-12-67	0.83 ± 0.03			
	1445	11-2-67	0.66 ± 0.03			
	1045	11-28-67	0.97 ± 0.04			
	1430	12-16-67	0.86 ± 0.03			
	1034	1-16-68	2.09 ± 0.05	2.20 ± 0.08		
	1025	2-6-68	1.02 ± 0.03			
	1415	2-24-68	0.76 ± 0.03			
	1035	3-19-68	0.70 ± 0.02			
	1040	4-9-68	0.46 ± 0.02			
	1045	4-30-68	0.87 ± 0.02	0.75 ± 0.02		

Table 1. *Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo.* (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
34	1040	5-21-68	0.71 ± 0.03			
	1035	6-11-68	0.43 ± 0.03	0.50 ± 0.03		
	1430	8-8-68	0.72 ± 0.03	0.77 ± 0.03		
35	1145	7-6-67	0.52 ± 0.03	0.66 ± 0.05	2.54	1.14
	1315	9-14-67	0.62 ± 0.02	0.63 ± 0.03		
	1315	10-5-67	0.70 ± 0.03			
	1415	10-26-67	0.80 ± 0.03			
	1045	11-21-67	0.67 ± 0.04			
	1020	12-12-67	0.81 ± 0.02			
	1030	1-9-68	2.00 ± 0.06			
	1030	1-30-68	0.52 ± 0.02			
	1025	2-20-68	0.88 ± 0.04			
	1015	3-12-68	0.76 ± 0.02			
	1025	4-2-68	0.52 ± 0.02			
	1020	4-23-68	0.52 ± 0.02			
	1030	5-14-68	0.61 ± 0.02			
	1020	6-4-68	0.32 ± 0.01			
	1400	6-20-68	0.46 ± 0.02	0.48 ± 0.02		
	1005	7-23-68	1.43 ± 0.03			
	1010	8-6-68	2.07 ± 0.04			
36	1127	7-6-67	0.38 ± 0.02	0.46 ± 0.04		
	1015	9-12-67	0.95 ± 0.04			
	0940	10-3-67	0.88 ± 0.04			
	0940	10-24-67	0.82 ± 0.04	0.73 ± 0.04		
	1330	11-16-67	1.28 ± 0.04		0.65	0.54
	1345	12-7-67	0.98 ± 0.03			
	0935	1-4-68	0.99 ± 0.03			
	1330	1-25-68	1.91 ± 0.06	1.89 ± 0.05		
	1325	2-15-68	0.75 ± 0.03			
	1320	3-7-68	0.49 ± 0.03			
	1325	3-28-68	0.72 ± 0.03			
	1320	4-18-68	0.36 ± 0.02			
	1330	5-9-68	0.49 ± 0.03	0.57 ± 0.03		
	1325	5-30-68	0.33 ± 0.03			
	1000	6-18-68	0.51 ± 0.02			
	1030	7-18-68	1.14 ± 0.04	1.13 ± 0.04		
	1315	8-1-68	0.78 ± 0.03			

Table 1. Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo. (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)		
	hour	day	USAEC		SWRHL
41	0940	7-11-67	0.47 ± 0.05	0.54 ± 0.04	1.95
	1030	9-19-67	0.96 ± 0.03	1.13 ± 0.06	
	1045	10-10-67	0.76 ± 0.03		
	1130	10-31-67	1.14 ± 0.04		
	1425	11-23-67	0.44 ± 0.03		
	1030	12-19-67	0.52 ± 0.03		
	1405	1-11-68	1.24 ± 0.04		
	1430	2-1-68	0.51 ± 0.03		
	1400	2-22-68	0.78 ± 0.03	0.76 ± 0.04	
	1415	3-14-68	0.58 ± 0.02		
	1405	4-4-68	0.49 ± 0.02		
	1405	4-25-68	0.51 ± 0.03		
	1405	5-16-68	0.53 ± 0.03		
	1405	6-6-68	0.13 ± 0.01		
	1030	6-25-68	0.91 ± 0.03	1.10 ± 0.03	
	1330	8-8-68	0.83 ± 0.03	0.79 ± 0.03	
42	0942	7-25-67	0.65 ± 0.03	0.65 ± 0.02	
	0930	9-19-67	1.07 ± 0.04		
	0920	10-10-67	0.73 ± 0.03		
	1145	10-31-67	0.77 ± 0.03	0.76 ± 0.03	
	1330	11-23-67	0.53 ± 0.03		
	1345	12-14-67	0.58 ± 0.03		
	1315	1-11-68	1.10 ± 0.04		
	1320	2-1-68	1.13 ± 0.04		
	1315	2-22-68	0.59 ± 0.03		
	1325	3-14-68	0.61 ± 0.02	0.62 ± 0.02	
	1320	4-4-68	0.57 ± 0.03	0.52 ± 0.03	
	1325	4-25-68	0.27 ± 0.02		
	1325	5-16-68	0.69 ± 0.03		
	1325	6-6-68	0.34 ± 0.03		
	0950	6-25-68	1.05 ± 0.03		
	1020	8-15-68	0.49 ± 0.04		
43	0932	7-25-67	0.74 ± 0.04		
	1400	9-21-67	0.90 ± 0.03		
	1400	10-12-67	0.76 ± 0.03	0.73 ± 0.02	
	1420	11-2-67	0.60 ± 0.02	0.61 ± 0.03	
	1030	11-28-67	0.81 ± 0.03		
	1140	12-19-67	0.62 ± 0.03		
	1015	1-16-68	1.68 ± 0.04		2.01

Table 1. Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo. (continued)

Sta-tion no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
43	1015	2-6-68	0.92 ± 0.03			
	1020	2-27-68	0.60 ± 0.02			
	1020	3-19-68	0.38 ± 0.02			
	1030	4-9-68	0.54 ± 0.02			
	1030	4-30-68	0.17 ± 0.01			
	1015	5-21-68	0.50 ± 0.02			
	1015	6-11-68	0.48 ± 0.03			
	1020	8-13-68	1.86 ± 0.04			
44	1530	7-20-67	0.47 ± 0.03	0.49 ± 0.03		
	1530	7-20-67	0.73 ± 0.04	0.69 ± 0.04		
	1005	9-24-67	0.69 ± 0.02	0.68 ± 0.03		
	1300	10-12-67	0.88 ± 0.03			
	1330	11-2-67	0.73 ± 0.03			
	9030	11-28-67	1.20 ± 0.03		0.89	
	0910	12-19-67	1.26 ± 0.05			
	0920	1-16-68	1.94 ± 0.04		2.10	
	0910	2-6-68	1.12 ± 0.03			
	0925	2-27-68	0.89 ± 0.03			
	0930	3-19-68	0.77 ± 0.02			
	0940	4-9-68	0.62 ± 0.02			
	0940	4-30-68	0.99 ± 0.03			
	0930	5-21-68	0.92 ± 0.03			
	0925	6-11-68	0.66 ± 0.04			
	0930	8-13-68	4.37 ± 0.06			
45	0900	7-11-67	0.82 ± 0.06	0.79 ± 0.05	1.08	1.18
	1000	9-19-67	1.60 ± 0.07			
	1030	10-10-67	0.79 ± 0.03			
	1110	10-31-67	1.12 ± 0.04			
	1350	11-23-67	0.52 ± 0.03			
	1415	12-14-67	0.80 ± 0.03			
	1335	1-11-68	1.33 ± 0.05	1.34 ± 0.05		
	1345	2-1-68	0.43 ± 0.03			
	1335	2-22-68	0.75 ± 0.03			
	1345	3-14-68	0.50 ± 0.02			
	1340	4-4-68	0.60 ± 0.03	0.59 ± 0.02		
	1345	4-25-68	0.61 ± 0.03	0.57 ± 0.03		
	1345	5-16-68	0.87 ± 0.03			
	1345	6-6-68	0.40 ± 0.02	0.47 ± 0.02		
	1015	6-25-68	0.77 ± 0.02			
	1300	8-8-68	0.98 ± 0.03			

Table 1. Concentrations of radon 222 found in 48-hour integrated air samples from Grand Junction, Colo. (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)	
	hour	day	USAEC	SWRHL
46	1800	7-20-67	0.51 ± 0.04	0.43 ± 0.04
	1330	9-21-67	0.48 ± 0.02	
	1320	10-12-67	0.66 ± 0.03	
	1400	11-2-67	0.78 ± 0.03	
	0947	11-28-67	0.79 ± 0.03	0.84 ± 0.03
	0930	12-19-67	0.80 ± 0.05	
	0945	1-16-68	2.08 ± 0.06	
	0945	2-6-68	0.99 ± 0.03	
	0950	2-27-68	0.84 ± 0.03	
	1000	3-19-68	0.49 ± 0.02	
	1000	4-9-68	0.47 ± 0.02	
	1000	4-30-68	1.04 ± 0.03	
	0950	5-21-68	0.39 ± 0.02	
	0950	6-11-68	0.44 ± 0.03	0.42 ± 0.03
	0950	8-13-68	0.35 ± 0.02	
47	1035	2-13-68	1.15 ± 0.03	
	1100	2-27-68	0.54 ± 0.02	
	1045	3-5-68	0.62 ± 0.02	
	1030	3-26-68	1.05 ± 0.02	
	1045	4-16-68	0.39 ± 0.02	
	1045	5-7-68	0.65 ± 0.02	0.62 ± 0.02
	1050	5-28-68	0.53 ± 0.03	
	1045	6-18-68	0.29 ± 0.02	
	1415	7-25-68	0.73 ± 0.03	
	1045	8-20-68	1.93 ± 0.04	

Location of radon sampling stations in Grand Junction, Colo.:

11 — 15	On and around Climax tailings pile
16	Grand Valley Rendering Company, 347 — 27½ Road.
21	Union Carbide Office, 1600 Ute Avenue.
22	Colorado State Patrol Garage, 606 South 9th.
23	LDS Bishop's Storehouse, 8th and Struthers Avenue.
24	John Cordray, 318 — 27-3/8 Road.
25	Bert Wales, 1761 Palisade.
26	Duward Pifer, 287 Mountain View (Orchard Mesa).
31	Space Age Builders, 309 Pitkin Avenue.
32	Post Office, 4th and White Avenue.
33	Smith Chemical Company, 645 East 4th Avenue.
34	W. E. Bush, 2005 North 17th Street.
35	Ray Erickson, 2785 Laguna Drive.
36	Gerald Myers, 2795 D Road.
41	National Guard Shop, 325 West Avenue.
42	Richard Shay, 961 Chipeta.
43	John Barnes, 469 Sherwood Drive.
44	AEC Compound.
45	National Guard Armory, 428 — 28 Road.
46	Paul McKnight, 172 Shamrock (Orchard Mesa).

Table 2. Concentrations of radon 222 found in 48-hour integrated air samples from Durango, Colo.

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)		
	hour	day	USAEC	SWRHL	
51	1100	8-3-67		10.7	10.3
	2300	8-21-67		19.2	
	0630	9-19-67		13.3	
	0915	10-13-67		11.38	11.40
	0815	10-31-67		29.36	39.31
	0745	11-28-67		21.51	21.13
	1030	12-27-67		26.83	
	0800	1-16-68		28.97	
	0805	2-13-68		3.80	
	1000	3-8-68		14.13	
	0740	4-2-68		22.35	
	0750	4-26-68		23.67	
	1635	5-14-68		13.96	
	0820	5-30-68		21.37	
	0715	6-19-68		19.55	
	0440	7-17-68		12.90	10.13
52	1100	8-3-67		7.4	7.5
	0800	8-22-67		7.4	
	0630	9-19-67		32.0	
	0915	10-13-67		21.72	
	0825	10-31-67		9.20	
	1000	12-27-67		21.63	
	0755	1-16-68		23.10	
	0800	2-13-68		9.45	
	1005	3-8-68		12.82	
	0920	4-5-68		5.38	
	0740	4-26-68		0.48	
	0745	5-23-68		9.12	
	0745	5-28-68		7.96	
	0720	6-19-68		1.00	
53	0730	8-8-67	0.41 ± 0.03	0.70	
	0715	8-29-67		0.47	
	0720	9-26-67		0.42	
	0735	11-7-67		0.30	0.26
	0810	12-5-67		0.75	
	1500	1-1-68		0.44	
	0800	1-23-68		0.39	
	0800	2-6-68		0.34	
	1000	3-10-68		0.57	
	0840	4-16-68		0.30	

Table 2. Concentrations of radon 222 found in 48-hour integrated air samples from Durango, Colo. (continued)

Sta- tion no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
53	1130	5-12-68			0.73	
	0755	5-17-68			0.25	
	0830	5-30-68			0.54	
	0745	6-21-68			0.44	0.51
	0455	7-19-68			0.75	
54	0800	10-3-67			2.31	
	0825	10-27-67			1.84	
	0755	11-14-67			0.65	0.74
	0950	12-13-67			0.60	
	0800	1-30-68			1.94	
	1100	3-27-68			1.40	
	1425	4-18-68			0.44	
	1200	5-7-68			0.71	
	0800	6-9-68			1.62	
	0820	7-14-68			1.91	
55	0730	8-15-67			0.35	0.33
	0740	9-5-67	0.68 ± 0.03		0.44	0.43
	0730	9-12-67			1.28	
	0730	9-28-67			0.48	0.54
	0735	10-17-67			0.51	
	0735	11-21-67			0.68	
	0740	12-19-67			0.86	
	0805	1-30-68			0.60	
	0800	1-4-68			0.75	
	1015	2-16-68			0.41	
	0755	3-12-68			0.41	
	1050	4-11-68			0.39	
	0750	5-1-68			0.34	
	0740	5-23-68			0.11	
	0745	6-6-68			0.43	
	0750	7-2-68			0.51	
	1650	7-30-68	0.44 ± 0.05		0.24	0.10
56	0700	8-8-67	0.31 ± 0.03	0.31 ± 0.03	0.41	0.36
	0715	8-29-67	0.29 ± 0.03	0.29 ± 0.02	0.61	
	0715	9-26-67			0.47	
	0740	11-5-67			0.35	
	0800	12-7-67			0.62	
	0805	1-19-68			sample lost	
	0750	1-4-68			0.38	
	1025	2-16-68			0.45	

Table 2. Concentrations of radon 222 found in 48-hour integrated air samples from Durango, Colo. (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)		
	hour	day	USAEC	SWRHL	
56	0835	4-9-68		0.68	
	0730	4-23-68		0.37	
	0750	5-10-68		0.37	
	1200	5-26-68		0.22	
	0740	6-2-68		0.78	
	0750	6-21-68		0.44	
	0515	7-19-68	0.79 ± 0.06	0.66	0.64
57	0730	9-12-67		0.88	
	0740	9-28-67		0.44	
	0745	10-17-67		0.45	
	0750	11-21-67		1.15	
	0800	12-19-67		1.08	0.85
	0800	1-9-68		1.18	
	0745	1-30-68		0.51	
	0755	2-20-68		0.48	
	1035	3-25-68		0.56	
	1320	4-18-68		0.17	
	1155	5-12-68		0.26	
	0740	6-16-68		0.38	
	0810	7-14-68		0.19	
58	0745	10-3-67		0.90	
	0740	10-24-67		0.47	
	0740	11-14-67		0.28	
	1005	12-13-67		0.21	
	1515	1-1-68		1.28	
	0840	1-26-68		0.57	
	0830	2-6-68		0.69	
	1105	3-29-68		0.31	
	0720	4-23-68		0.09	
	0735	5-10-68		0.41	
	0735	6-6-68		0.21	
	0745	7-2-68		0.47	
	1705	7-30-68		0.19	0.13

Location of radon sampling stations in Durango, Colo.:

51	South side of tailings pile.
52	North side of tailings pile.
53	Richards Motel, Route 160 West.
54	Sewage Plant, 4th Avenue
55	Used car lot, 6th and 84th Streets.
56	State Patrol Garage, 6th Street.
57	Lumber Mill, Route 160 South.
58	Ballager Tire Service, 12th and Main.

Table 3. Concentrations of radon 222 found in 48-hour integrated air samples from Monticello, Utah

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
61	1245	8-8-67	5.13 ± 0.12		4.91	3.99
	1300	8-30-67	5.05 ± 0.1	5.20 ± 0.1	4.37	
	1000	9-28-67	4.8 ± 0.1	4.4 ± 0.1	4.36	3.22
	1000	10-19-67	4.2 ± 0.1		5.52	
	1000	11-9-67	5.9 ± 0.1		5.19	
	1000	12-1-67			2.27	
	1345	1-10-68			6.52	
	1100	2-3-68			3.75	
	1120	2-24-68			4.03	
	0820	3-13-68			1.64	
	1030	4-24-68			0.68	
	0930	4-5-68			2.77	
	1130	5-16-68			1.12	
	0930	6-4-68			8.11	
	0930	6-26-68			6.16	
	0930	7-15-68			3.47	
	0945	7-29-68			5.45	
62	1320	8-8-67	1.66 ± 0.08		2.33	1.70
	1015	9-28-67	2.32 ± 0.08		2.31	
	1015	10-19-67	3.4 ± 0.1		3.34	3.26
	0945	11-9-67			2.48	
	0900	12-1-67	3.2 ± 0.1		2.60	
	1330	1-10-68			4.41	
	1030	2-3-68			1.86	
	1145	2-24-68			3.38	
	0800	3-13-68			0.91	
	1015	4-24-68			1.83	
	1000	4-5-68			1.66	
	1115	5-16-68			0.55	
	0915	6-4-68			3.94	
	0915	6-26-68			1.07	
	0915	7-15-68			3.92	
63	1310	8-8-67	5.23 ± 0.10		4.23	4.92
	1030	9-28-67	5.2 ± 0.1		4.64	
	1030	10-19-67			4.61	
	0930	11-9-67	6.2 ± 0.1		5.21	
	0930	12-1-67	3.62 ± 0.07		2.75	
	1300	1-10-68	3.62 ± 0.07		4.12	
	1245	2-3-68			2.63	
	1200	2-24-68			11.99	

Table 3. Concentrations of radon 222 found in 48-hour integrated air samples from Monticello, Utah (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
63	0745	3-13-68			1.12	
	1030	4-5-68			1.76	
	1000	4-24-68			0.12	
	1100	5-16-68			1.06	
	0900	6-4-68			7.47	
	0900	6-26-68			5.34	
	0900	7-15-68			7.63	
	0900	7-29-68			5.78	
64	1345	8-8-67	3.79 ± 0.07		2.41	2.49
	1115	9-28-67	2.92 ± 0.08		2.75	2.81
	1045	10-19-67	3.4 ± 0.1		3.68	3.56
	1015	11-9-67			2.00	
	1030	12-1-67			2.17	
	1400	1-10-68			1.83	
	1300	2-3-68			4.08	
	1100	2-24-68			5.65	
	0730	3-13-68			0.89	
	0900	4-5-68			1.19	
	1045	4-24-68			1.23	
	1145	5-16-68			1.19	
	1000	6-4-68			4.47	
	1000	6-26-68			4.95	
	1000	7-15-68			5.25	
	1000	7-29-68			6.07	
65	1245	8-22-67			0.78	
	1000	9-7-67	0.60 ± 0.02		0.60	0.62
	1100	9-20-67	0.77 ± 0.04	0.81 ± 0.03	0.78	
	0945	10-12-67			0.77	
	0900	11-2-67			0.19	
	0800	11-23-67			0.46	
	0930	12-14-67			0.51	
	1000	12-28-67			0.62	
	1000	1-18-68			0.35	
	1000	2-13-68			0.31	
	0900	3-6-68			0.26	
	1030	3-28-68			0.32	
	0930	4-16-68			0.18	
	0715	5-8-68			0.24	
	0900	5-31-68			0.22	
	0900	6-18-68			0.54	
	0930	7-8-68			1.28	

Table 3. Concentrations of radon 222 found in 48-hour integrated air samples from Monticello, Utah (continued)

Sta- tion no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
66	1245	8-15-67	0.65 ± 0.05	0.63 ± 0.04	0.37	0.52
	1030	9-7-67	0.42 ± 0.02		0.48	
	1130	9-20-67	0.54 ± 0.03		0.49	
	1000	10-12-67			0.48	
	0915	11-2-67			0.17	
	1000	11-25-67			0.12	
	1000	12-14-67			0.28	
	1200	1-25-68			0.59	
	1015	2-13-68			0.64	
	0930	3-6-68			0.59	
	1100	3-28-68			0.30	
	1000	4-16-68			0.25	
	0915	5-31-68			0.18	
	0915	6-18-68			0.31	
	1000	7-8-68			0.25	
71	1315	8-15-67	1.06 ± 0.05	0.47 ± 0.04	0.83	0.52
	1230	9-14-67	0.17 ± 0.02	0.21 ± 0.02	0.17	
	0945	10-5-67			0.19	
	1045	10-26-67			0.23	
	1130	11-14-67			0.11	
	1230	1-4-68			0.57	
	1115	1-25-68			0.43	
	1100	2-8-68			0.38	
	1030	2-28-68			0.28	
	1300	3-21-68			0.16	
	1100	4-9-68			0.10	
	1100	5-1-68			0.20	
	0915	6-11-68			0.37	
	0900	7-5-68			0.16	
	0930	7-23-68			0.28	
72	1345	8-15-67	0.50 ± 0.03	0.30 ± 0.04	0.52	0.52
	1200	9-14-67	0.16 ± 0.02		0.16	
	0930	10-5-67			0.15	0.17
	1030	10-26-67			0.25	
	1115	11-14-67			0.25	0.17
	1130	12-7-67			0.18	
	1200	12-28-67			0.53	
	1030	1-19-68			0.23	
	1130	2-8-68			0.34	
	1100	2-28-68			0.28	

Table 3. Concentrations of radon 222 found in 48-hour integrated air samples from Monticello, Utah (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
72	1350	3-21-68			0.12	
	1115	4-9-68			0.11	
	1115	5-1-68			0.07	
	1030	5-24-68			0.15	
	0930	6-11-68			0.03	0.03
	0915	7-5-68			0.15	
	0915	7-23-68			0.26	
73	1400	8-15-67	0.48 ± 0.04	0.47 ± 0.04	0.37	0.44
	1130	9-14-67	0.13 ± 0.01		0.15	
	0915	10-5-67			0.33	
	1015	10-26-67			0.23	
	1145	11-14-67			0.06	
	1245	12-7-67			0.31	
	1015	12-28-67			0.57	
	1100	1-25-68			0.45	
	1015	2-8-68			0.46	
	1130	2-28-68	0.10 ± 0.01		0.19	0.21
	1045	4-9-68			0.10	
	1045	5-1-68			0.29	
	1015	5-24-68			0.16	
	1030	6-11-68			0.11	
	0930	7-5-68			0.59	
	1000	7-23-68			0.20	
74	1345	8-22-67			0.26	
	1100	9-14-67	0.17 ± 0.02		0.17	0.13
	0945	10-5-67			0.35	
	1000	10-26-67			0.28	
	1200	11-14-67			0.14	
	1230	12-7-67			0.18	
	1030	12-28-67			0.33	
	1030	1-25-68			0.59	
	1000	2-8-68			0.12	
	1200	2-28-68			0.33	
	1400	3-20-68			0.18	
	1030	4-9-68			0.06	
	1030	5-1-68			0.14	
	1100	5-24-68			0.21	
	0900	6-11-68			0.25	
	1000	7-7-68			0.38	
	0900	7-23-68			0.29	

Table 3. Concentrations of radon 222 found in 48-hour integrated air samples from Monticello, Utah (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
75	1315	8-22-67			0.87	
	1145	9-7-67	0.39 ± 0.02	0.34 ± 0.02	0.32	
	1200	9-20-67	0.43 ± 0.03		0.32	
	1015	10-12-67			0.35	
	0930	11-2-67			0.17	
	0830	11-23-67			0.29	
	1100	12-14-67			0.16	
	1245	1-4-68			0.55	
	1130	1-18-68			0.21	
	1030	2-13-68			0.28	
	1000	3-6-68			0.27	
	1130	3-28-68			0.18	
	0900	4-16-68			0.14	
	0930	5-31-68			0.14	
	0930	6-18-68			0.16	
	0900	7-8-68			0.37	
76	1330	8-22-67			0.49	
	1100	9-7-67	0.44 ± 0.03		0.49	
	1230	9-20-67	0.50 ± 0.03		0.43	0.45
	1030	10-12-67			0.23	
	1000	11-2-67			0.11	
	0845	11-23-67			0.38	
	1030	12-14-67			0.50	
	1200	1-4-68			0.94	
	1100	1-18-68			0.67	
	1100	2-13-68			0.35	
	1030	3-6-68			0.16	
	1200	3-28-68			0.23	
	0915	4-16-68			0.33	
	0745	5-8-68			0.22	
	1000	5-31-68			0.20	
	1000	6-18-68			0.47	
	0915	7-8-68			0.49	

Location of radon sampling stations in Monticello, Utah:

61 – 64	On tailings area.
65	Bailey Farm.
66	Southwest Gas Corporation tanks – 2d South.
71	Christenson's – 136 Uranium Drive.
72	Fire Station – 1st North.
73	Agriculture Building – 60 Center Street.
74	State Highway Check Station – Route 160 East.
75	Garage – 1st East and 2d South.
76	Sewage Plant.

Table 4. Concentrations of radon 222 found in 48-hour integrated air samples from Salt Lake City, Utah

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
81	1458	10-31-67	18.3 ± 0.1			
	1035	11-7-67	17.6 ± 0.2			
	1115	11-28-67			16.66	
	1600	1-4-68			5.70	
	1100	1-16-68	4.24 ± 0.05			
	1330	2-14-68			9.69	
	1135	3-6-68			6.92	
	1030	3-20-68			1.62	
	1115	4-17-68	2.55 ± 0.05			
	1100	5-1-68	11.5 ± 0.1			
	1145	5-28-68	7.8 ± 0.1			
	1505	7-11-68	16.2 ± 0.1	17.5 ± 0.1		
	1052	7-31-68	7.44 ± 0.08			
	1050	8-21-68	5.67 ± 0.08			
	1240	9-11-68			5.11	
	1005	10-3-68	22.1 ± 0.2	21.8 ± 0.1		
82	1245	10-27-67	5.9 ± 0.1		6.49	7.09
	1115	11-16-67	5.1 ± 0.1		7.42	7.34
	1025	12-27-67	4.4 ± 0.1			
	1120	12-5-67			2.26	
	1400	1-23-68			4.55	
	0740	2-7-68			3.49	4.39
	1110	2-28-68			2.49	
	1035	3-20-68			4.38	
	1050	5-7-68	4.17 ± 0.06			
	1115	4-9-68			2.97	
	1130	5-28-68	3.13 ± 0.08			
	1220	6-19-68			3.70	
	1100	7-24-68	6.39 ± 0.09			
	1205	8-7-68			5.20	
	1105	9-5-68			3.07	
83	0830	11-1-67			1.30	
	1035	11-21-67	0.39 ± 0.03			
	1115	12-12-67			0.50	
	1415	1-11-68	0.50 ± 0.02		0.26	
	1250	1-30-68			0.12	
	1340	2-20-68			0.39	
	1120	3-13-68	0.30 ± 0.02			
	1105	4-3-68	0.31 ± 0.02			
	1010	4-24-68	0.21 ± 0.01			
	1145	5-14-68	0.17 ± 0.01			

Table 4. Concentrations of radon 222 found in 48-hour integrated air samples from Salt Lake City, Utah (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
83	1140	6-5-68			0.63	
	1125	6-25-68			0.48	
	1000	7-18-68			0.60	
	1110	8-14-68			0.42	
	1100	8-28-68	0.71 ± 0.03			
	1530	9-18-68			0.09	
84	1200	10-29-67			0.76	
	1040	11-28-67	0.44 ± 0.02		0.38	
	1100	11-7-67			0.23	
	0945	12-20-67	0.42 ± 0.03			
	1040	1-16-68			0.85	
	1125	3-6-68	0.21 ± 0.02			
	1045	3-20-68	0.25 ± 0.02			
	1140	4-17-68			0.27	
	1110	5-1-68			0.31	
	1125	5-21-68			0.43	
	1130	6-11-68	0.21 ± 0.01			
	1040	7-31-68			0.28	
	1110	8-21-68			0.24	
	1255	9-11-68			0.39	
	1235	9-25-68	0.68 ± 0.02	0.53 ± 0.02	0.60	
	1020	10-9-68			1.23	1.05
85	1122	10-29-67	0.60 ± 0.02			
	1050	11-16-67			0.63	0.58
	1130	12-5-67			0.36	0.33
	1155	1-23-68	0.98 ± 0.04			
	0755	2-7-68	0.83 ± 0.04	1.00 ± 0.04		
	1135	3-6-68	0.23 ± 0.02			
	1015	3-27-68	0.58 ± 0.02			
	1100	4-9-68	0.81 ± 0.02			
	1030	5-7-68	0.82 ± 0.03			
	1120	5-28-68	0.47 ± 0.03			
	1055	6-19-68	0.51 ± 0.02			
	1150	7-24-68			0.62	
	1020	10-3-68	1.30 ± 0.03	1.44 ± 0.05	1.4	
86	1315	10-29-67			0.50	
	1045	11-21-67	0.44 ± 0.02			
	1125	12-12-67			0.15	
	1547	1-3-68	0.54 ± 0.03			

Table 4. Concentrations of radon 222 found in 48-hour integrated air samples from Salt Lake City, Utah (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
86	1305	1-30-68			0.11	
	1310	2-20-68	0.23 ± 0.01			
	1045	3-13-68			0.31	
	1120	4-3-68			0.28	
	1050	4-24-68			0.17	
	1100	5-21-68	0.30 ± 0.02			
	1130	6-5-68	0.15 ± 0.02	0.17 ± 0.01		
	1110	6-25-68	0.29 ± 0.02			
	1030	7-18-68	0.51 ± 0.04		0.32	
	1305	8-14-68			0.17	
	1100	8-28-68	0.20 ± 0.01	0.19 ± 0.02		
91	1117	10-27-67	0.38 ± 0.02			
	1025	11-7-67			0.17	
	1105	11-28-67			0.99	
	1005	12-20-67			0.48	0.46
	1110	1-16-68	0.69 ± 0.04	0.73 ± 0.05		
	1255	2-14-68			0.61	
	1155	3-6-68			0.27	
	1100	3-20-68			0.80	
	1045	4-17-68	0.18 ± 0.02	0.17 ± 0.01		
	1040	5-1-68			0.24	
	1150	5-21-68			0.26	
	1125	6-11-68			0.24	
	1105	7-8-68	0.99 ± 0.04			
	1045	8-21-68			0.15	
	1220	9-11-68	0.22 ± 0.01	0.20 ± 0.02		
92	1550	10-31-67			0.42	
	1025	11-14-67			0.82	
	1105	12-5-67	0.21 ± 0.01	0.26 ± 0.01		
	1055	12-27-67			0.84	
	1415	1-23-68			0.85	
	1110	2-28-68			0.42	
	1100	3-27-68	0.26 ± 0.01			
	1020	4-9-68	0.23 ± 0.01			
	1120	5-7-68			0.29	
	1230	5-28-68			0.22	
	1215	6-19-68	0.40 ± 0.02			
	1130	8-7-68	0.30 ± 0.01	0.22 ± 0.02		
	1150	9-5-68	0.40 ± 0.02	0.45 ± 0.03		
	1530	9-18-68			0.17	
	0945	10-3-68			0.26	

Table 4. *Concentrations of radon 222 found in 48-hour integrated air samples from Salt Lake City, Utah* (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)		
	hour	day	USAEC		SWRHL
93	1450	10-31-67	0.55 ± 0.02		
	1045	12-12-67	0.25 ± 0.02		
	1335	1-11-68	0.25 ± 0.02		
	1335	1-30-68	0.19 ± 0.02		
	1335	2-20-68	0.16 ± 0.01		
	1115	3-13-68			0.22
	1005	4-24-68			0.06
	1100	4-3-68			0.25
	1145	5-14-68			0.07
	1120	6-5-68			0.20
	1045	6-25-68	0.30 ± 0.02		
	1000	7-18-68	0.38 ± 0.02	0.42 ± 0.02	
	1115	7-31-68	0.20 ± 0.01		
	1045	8-28-68			0.26
	0900	10-5-68			0.54
94	1427	10-27-67	0.58 ± 0.03	0.60 ± 0.02	
	1000	11-7-67	0.83 ± 0.03	0.95 ± 0.04	
	1122	11-28-67	0.57 ± 0.03		
	1010	1-16-68			0.94
	1225	2-14-68	0.60 ± 0.03		
	1045	3-13-68	0.17 ± 0.02		
	1135	3-20-68			0.46
	0945	4-17-68			0.13
	1125	5-1-68	0.29 ± 0.02		
	1035	5-21-68	0.07 ± 0.01		
	1040	6-11-68	0.24 ± 0.01		
	1050	7-2-68			0.50
	1025	7-31-68			0.37
	1000	8-21-68	0.14 ± 0.01	0.12 ± 0.02	
	1235	9-11-68	0.24 ± 0.01	0.29 ± 0.02	
	1200	9-25-68	0.69 ± 0.02	0.71 ± 0.03	
	1000	10-9-68	0.55 ± 0.03	0.57 ± 0.03	
95	1000	11-14-67	0.52 ± 0.02		
	1047	12-5-67	0.20 ± 0.01		
	1055	1-23-68	0.58 ± 0.03		
	0825	2-7-68	0.58 ± 0.03		
	1130	2-28-68	0.32 ± 0.02		
	1015	3-20-68			0.17
	1050	4-9-68			0.22
	1040	5-7-68			0.19

Table 4. Concentrations of radon 222 found in 48-hour integrated air samples from Salt Lake City, Utah (continued)

Station no.	Midpoint of sampling time		Concentration of radon 222 (pCi/liter)			
	hour	day	USAEC		SWRHL	
95	1120	5-28-68			0.21	
	1045	6-19-68			0.21	
	1350	7-11-68			0.20	
	1100	7-24-68			0.28	
	1205	8-7-68	0.20 ± 0.02	0.19 ± 0.01		
	1300	8-14-68	0.10 ± 0.01	0.16 ± 0.04		
	1030	8-28-68			0.21	
	1435	9-18-68	0.14 ± 0.01	0.16 ± 0.02		
96	1417	10-29-67	0.16 ± 0.01			
	1045	11-21-67			0.15	
	1155	12-12-67	0.17 ± 0.02			
	1200	1-7-68			0.45	
	1400	1-30-68	0.12 ± 0.01			
	1320	2-20-68			0.21	
	1225	3-13-68	0.12 ± 0.01	0.12 ± 0.01		
	1205	4-3-68	0.17 ± 0.01			
	1155	5-14-68	0.06 ± 0.01			
	1235	6-5-68	0.09 ± 0.01			
	1145	6-25-68			0.24	
	0915	7-18-68	0.22 ± 0.02	0.42 ± 0.03	0.38	0.31
	1200	8-14-68	0.25 ± 0.02			
	1525	9-25-68			0.44	
	2230	10-8-68	0.28 ± 0.02	0.27 ± 0.02		

Location of radon sampling stations in Salt Lake City, Utah:

81	Center of tailings (700 West 3300 South).
82	Sewage Plant, 650 West 3300 South.
83	American Smelting & Refining Company, Hygiene & Research Department, 3422 South 7th West.
84	D. B. Harmon, 1080 West 3300 South.
85	Bonneville News Company, 965 Beardsley Place.
86	J. A. Skogg, 1501 West Claybourne Avenue.
91	D. Bolton, 570 West 3740 South.
92	Chris Body and Paint Shop Inc., 3152 South 2d West.
93	Tuloma Gas Products Co., 201 West 27th South.
94	Aluminum Manufacturing & Supply Co., 1809 South 8th West.
95	A. H. Higham, 105 Westwood Avenue.
96	Salt Lake City Health Department, 610 South 2d East.

The following samples were taken on the covered tailings at the old mill site east of Rifle, Colo.:

	Midpoint		pCi/liter
Northwest corner	1220	8-27-68	32.8
Southwest edge[a]	1215	8-27-68	23.8

[a] Downwind for night time inversion conditions.

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Appendix 22

Radon Flux from Evaporation Ponds

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and

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Homestake Mining Company of California
Grants, NM

Current Issue: Regulatory Agencies Expressing Interest in Radon Emissions from Ponds

- Approach to evaluate issue included
  - Modeled radon emissions from pond
  - Studied water vapor adsorption on activated charcoal flux canisters
  - Studied effect of water vapor adsorption on flux measurements
  - Performed Radon Flux Measurements on a pond

Model

- Stagnant-Film model for the transport of a gas across an air-water interface[1]
  - Results of:

Radon Flux = 0.01 pCi m^{-2} s^{-1} per pCi L^{-1} of dissolved radon

[1] **Summarized in** Schwarzenbach, Rene P., Philip M. Gschwend, and Dieter M. Imboden. *Environmental Organic Chemistry*. 2nd Edition. 2002

Predicted Flux at Homestake Evaporation Pond (EP-1)

- Measured Ra-226 concentration = 165 pCi L^{-1}
- Measured Temperature = 20.6 ºC
- Assume Rn-222 in secular equilibrium with Ra-226

Model Predicted Flux at EP-1 = 1.65 pCi $m^{-2}s^{-1}$

ERG Radon Flux Canister Design

Figure 1. ERG Radon Flux Canister

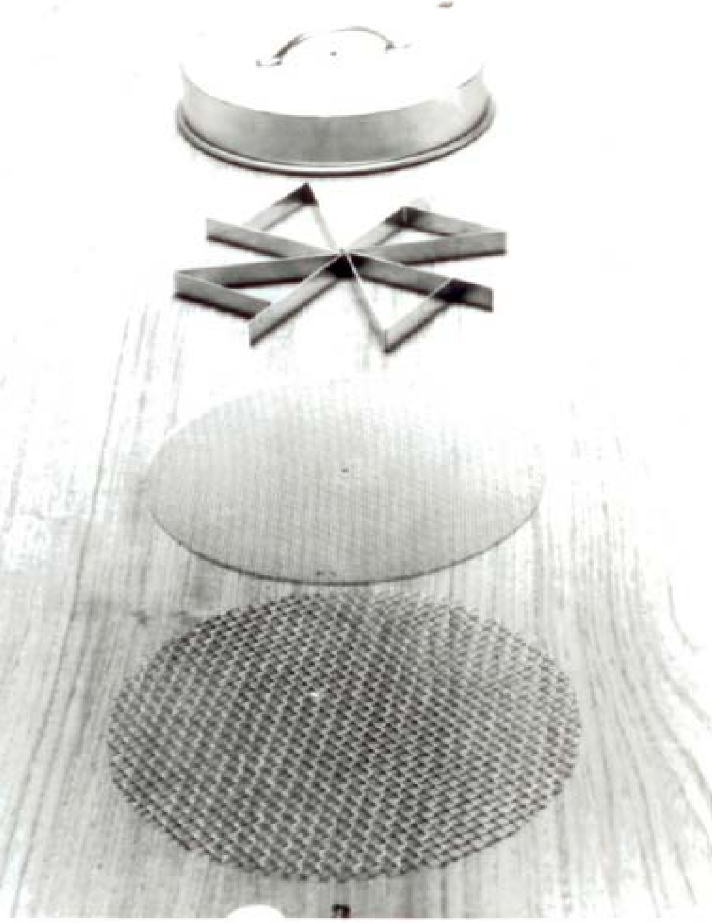

Figure 2. ERG Canister Internal Components

- Charcoal weight is approximately 385 grams
- EPA design calls for 170 grams of charcoal

Flux Canister Floatation Platform

- 10-in. ID plastic pipe
- 4-in. low density foam
- Tape band

Previous Water Vapor Adsorption Studies

- Affects observed in previous studies
  - **radon adsorption efficiency is reduced as temperatures and humidity increases**
  - **water vapor competes with radon adsorption**
  - **water vapor reduces radon adsorption when water mass gain of charcoal exceeds 11 %**

Radon Flux Baseline Studies

Configuration: Analyzed 9 Unexposed Canisters

Result: Mean Flux = 0.12 ± 0.11 pCi $m^{-2}s^{-1}$

Radon Flux Baseline Studies

- Configuration: Analyzed 10 canisters exposed for 24 hours to only water

Result: Mean Flux = 0.13 ± 0.10 pCi $m^{-2}s^{-1}$

Radon Flux Baseline Studies

- Deployed 23 flux canisters on newly constructed radon barrier in NM (August 2009) following EPA Method 115 procedures :
  - Increase in mass of 5.9 ± 1.0 percent, based on dry weight of charcoal
  - Three canisters placed at background location with results of 1.08, 1.15, and 1.42 pCi $m^{-2}s^{-1}$

Water Vapor Adsorption Studies with Desiccant

- Inserted 2-cm thick desiccant between canister
- Desiccant became saturated within 6 hours
- Abandoned possible desiccant use

Water Vapor Adsorption Studies

- Configuration: Floating Platform on pool of aged-city water
  - Five canisters deployed for 24 hours
  - Uniform temperature of 20-23 °C

Result: Increase in mass ranging from 4.5 to 5.2 percent, based on dry weight of charcoal, with an average of 4.8 percent

Assessment of Radon Adsorption During Study
(24-hour exposure)

Canisters	Number	Moisture Content (%)	Mean Flux (pCi $m^{-2}s^{-1}$)	Standard Deviation (pCi/$m^{-2}s^{-1}$)
After Baking Out	5	0	0.10	0.10
After Placement On Water	5	0 - 5.2 4.8 avg	0.11	0.08
After Placement On Flux Pad	5	4.8 avg	1.76	0.06

Shows that canisters do not adsorb radon from air while on floating platform

Influence of Canister Moisture on Flux Measurements

Canisters	Number	Moisture Content (%)	Mean Flux (pCi $m^{-2}s^{-1}$)	Standard Deviation (pCi $m^{-2}s^{-1}$)
Exposed to Flux Pad Only	7	≈ 0	1.84	0.34
Exposed to Water before Flux Pad	8	7.1 -8.8 Avg 7.9	2.10	0.16

Flux Measurements on EP-1 Homestake Uranium Mill Site

Canister Number	Flux (pCi $m^{-2}s^{-1}$)	Flux Standard Deviation (pCi $m^{-2}s^{-1}$)	Percent Moisture Increase
43	1.77	0.06	11.06
12	1.12	0.05	10.57
82	.99	0.05	13.38
44	1.02	0.05	10.68
13	0.77	0.05	9.38
Mean	1.13		11.0

Summary

- Canisters adsorb little radon from air while on water
- Measured radon flux was not affected by charcoal moisture content under measurement conditions
- Model predicted 1.65 pCi/m^{2}s which compares well with the mean measured flux of 1.13 pCi/m^{2}s

Questions?

Appendix 23

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J. Radiol. Prot. **28** (2008) 303–325 doi:10.1088/0952-4746/28/3/002

A cohort study of uranium millers and miners of Grants, New Mexico, 1979–2005

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Received 23 April 2008, in final form 4 June 2008, accepted for publication 9 June 2008
Published 20 August 2008
Online at stacks.iop.org/JRP/28/303

Abstract

A cohort mortality study of workers engaged in uranium milling and mining activities near Grants, New Mexico, during the period from 1955 to 1990 was conducted. Vital status was determined through 2005 and standardised mortality ratio (SMR) analyses were conducted for 2745 men and women alive after 1978 who were employed for at least six months. Overall, mortality from all causes (SMR 1.15; 95% CI 1.07–1.23; $n = 818$) and all cancers (SMR 1.22; 95% CI 1.07–1.38; $n = 246$) was greater than expected on the basis of US mortality rates. Increased mortality, however, was seen only among the 1735 underground uranium miners and was due to malignant (SMR 2.17; 95% CI 1.75–2.65; $n = 95$) and non-malignant (SMR 1.64; 95% CI 1.23–2.13; $n = 55$) respiratory diseases, cirrhosis of the liver (SMR 1.79; $n = 18$) and external causes (SMR 1.65; $n = 58$). The lung cancer excess likely is attributable to the historically high levels of radon in uranium mines of the Colorado Plateau, combined with the heavy use of tobacco products. No statistically significant elevation in any cause of death was seen among the 904 non-miners employed at the Grants uranium mill. Among 718 mill workers with the greatest potential for exposure to uranium ore, no statistically significant increase in any cause of death of *a priori* interest was seen, i.e., cancers of the lung, kidney, liver, or bone, lymphoma, non-malignant respiratory disease, renal disease or liver disease. Although the population studied was relatively small, the follow-up was long (up to 50 yrs) and complete. In contrast to miners exposed to radon and radon decay products, for uranium mill workers exposed to uranium dusts and mill products there was no clear evidence of uranium-related disease.

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0952-4746/08/030303+23$30.00

Abbreviations

CI	Confidence interval
ICD-9	Ninth revision of the international classification of diseases
NDI	National death index
NIOSH	National Institute of Occupational Health and Safety
SMR	Standardised mortality ratio
SSA	Social security administration

1. Introduction

Underground uranium miners exposed to high levels of radon and radon decay products are at increased risk of lung cancer but apparently no other cancer (Wagoner *et al* 1965, Lundin *et al* 1971, Whittemore and McMillan 1983, Hornung and Meinhardt 1987, Samet *et al* 1991, Lubin *et al* 1995, Darby *et al* 1996, NRC 1999). Several non-cancer causes of death (i.e., tuberculosis, non-malignant respiratory disease and accidents), however, were increased among early miners in the United States (Archer *et al* 1976, Roscoe 1997).

Uranium mill workers, however, have not been consistently found to be at increased risk for cancer. The National Institute for Occupational Health and Safety (NIOSH) conducted a study of 1484 men who worked at one of seven uranium mills on or after January 1, 1940 and reported a statistically significant increase in non-malignant respiratory disease mortality (SMR 1.43; $n = 100$) and non-statistically significant increases in mortality from lung cancer, lymphoma, and kidney disease (Pinkerton *et al* 2004). The authors were cautious in interpreting their findings, however, because increased length of employment (and assumed increased exposure to uranium compounds) was not associated with increased mortality from any of these conditions. A recent study of 450 uranium mill workers at Uravan, Colorado followed through 2004 revealed no statistically significant excess deaths from any cause, including non-malignant respiratory disease (SMR 0.99; $n = 24$) and lung cancer (SMR 1.26; $n = 24$) (Boice *et al* 2007b). Some of the uranium millers in the Uravan study were also included in the NIOSH study.

Although there have been many studies of underground uranium miners, few studies have been conducted of uranium millers. Exposures among these two groups differ appreciably, with underground miners being exposed primarily to radon and radon decay products, and millers being exposed primarily to uranium ore dust and mill products but not radon. Other than the recent study of Uravan uranium workers, there have been few studies of a workforce that includes both miners and millers. We report here such a study of workers employed by a large milling and mining company in Grants, New Mexico.

1.1. Exposure potential

The Grants, New Mexico uranium belt is an area of 100 by 25 miles in Cibola, McKinley and Sandoval Counties. In the 1950s and 1960s, 60 mines and five mills were in operation and New Mexico led the nation in uranium production (Samet *et al* 1983). The chief mining districts were Laguna, Ambrosia Lake and Church Rock.

The heyday of New Mexico mining and milling activities began in the mid to late 1950s and after the hazards of underground mining had been recognised in studies by the US Public Health Service (Lundin *et al* 1971). As such, state and federal regulations limited radon progeny exposures and New Mexico miners experienced generally lower cumulative exposures than for other miners of the Colorado plateau (Morgan and Samet 1986). Nonetheless, a statistically significant risk of lung cancer (SMR 4.0; $n = 68$) was reported among 3469 male miners from New Mexico with a mean cumulative exposure concentration of 111 WLM (Samet *et al* 1991). An increase in external causes of death (SMR 1.5; $n = 173$) was also statistically significant. The mortality data also supported an association between pneumoconiosis and exposure to silica and other dusts (Samet *et al* 1984b, 1991). Increased mortality due to lung cancer, tuberculosis and non-malignant respiratory disease has also been reported among Navajo miners from New Mexico (Wagoner *et al* 1975, Samet *et al* 1984a, Roscoe *et al* 1995)

The Grants uranium mill was located in Cibola County, New Mexico, about 5.5 miles northwest of the Village of Milan and about seven miles northeast of the Town of Grants. Uranium milling began in 1958 and continued through 1990. Radon and radon decay product exposures are relatively insignificant among mill workers due to the aboveground nature of their work. However, there is the potential for exposure to other radioactive substances such as uranium-238, uranium-234 and thorium-230, as well as exposure from uranium ore dust, vanadium pentoxide, yellowcake, ammonium diuranate, silica and slight traces of radium-226 (Waxweiler *et al* 1983).

Uranium milling involves ore crushing and grinding; ore leaching, i.e., removing and dissolving uranium; uranium recovery from leach solutions; and drying and packaging of yellowcake (uranium oxide, U_3O_8)—the final product of the milling process. Crushing and grinding of ore and yellowcake drying and packaging are dusty operations where inhalation potential is highest. The solid and liquid wastes remaining after uranium is extracted from ore are called tailings, and contain the same radionuclides found in the ore, i.e., uranium, thorium, radium and other decay products. Potential sources of environmental exposures around uranium milling operations include these tailings piles, in addition to runoff collection ponds, ore transport and airborne and liquid effluents (NCRP 1993). There are two tailings piles covering about 200 acres near the Grants uranium mill (EPA 2007).

Radium, a component of mill tailings, occurs naturally in uranium ore but generally is not extracted during the milling process. Ingestion of large amounts of radium by dial painters during the early part of the last century resulted in excesses of bone cancer and a rare carcinoma of the paranasal sinuses, but no other cancer was significantly increased (Fry 1998, IARC 2001). Radium decays into radon gas, a known cause of lung cancer, and also emits gamma radiation, which at sufficiently high levels can cause leukaemia, breast cancer and other malignancies (UNSCEAR 2000, NRC 2006). Leukaemia, however, has not been found to be significantly increased in studies of uranium processors, millers or miners (Harley *et al* 1999, IOM 2001, Pinkerton *et al* 2004, Darby *et al* 1996, NRC 1999, Boice *et al* 2007b, Canu *et al* 2008). Descriptive studies of communities living near uranium milling or processing facilities in Texas (Boice *et al* 2003a), Pennsylvania (Boice *et al* 2003b, 2003c) and Colorado (Boice *et al* 2007a) also provide little evidence for elevated rates of leukaemia or other cancers associated with penetrating external radiation.

The route of intake and the biological solubility of a given uranium compound influences the potential for chemical or radiological toxicity (ATSDR 1999, IOM 2001). Natural uranium, i.e., uranium ore, is largely soluble and passes through the body rather quickly whether inhaled or ingested (Harley *et al* 1999, Priest 2001). Yellowcake and other mill products are largely insoluble uranium oxides that, if inhaled, would accumulate in the lung and tracheobronchial lymph nodes (ATSDR 1999, Pinkerton *et al* 2004); the tracheobronchial lymph nodes, however, do not appear radiosensitive and are not considered a target for uranium toxicity (Eidson 1994). Different uranium ore processing schemes involve different uranium compounds with different dissolution rates so that workers could be exposed to mixtures of both soluble and insoluble forms of uranium (Eidson and Mewhinney 1980, Eidson 1994). Chemical toxicity, primarily renal dysfunction, may be a consequence of high intakes of soluble uranium. Lung injury may occur after high intakes of insoluble uranium. In general, ingested uranium is poorly absorbed from the intestinal tract and retention in the body would be low (ATSDR 1999, IOM 2001).

Based on associations reported in previous studies of uranium millers and miners and knowledge of the likely distribution of uranium within body tissues after inhalation or ingestion (Leggett 1989, ATSDR 1999, IARC 2001), we focused our attention on cancers of the lung, kidney, liver and bone, lymphoma and non-malignant respiratory, non-malignant renal and non-malignant liver diseases.

2. Material and methods

A retrospective cohort mortality study was conducted of uranium miners and millers of Grants, New Mexico. Institutional Review Board approval of the research protocol was received from Independent Review Consulting, Inc. (www.irb-irc.com).

2.1. Population identification

All uranium miners and millers who worked for a large uranium mining and milling company in Grants, New Mexico were eligible for study. The study population was identified from computerised listings of 3390 company personnel (1955–1991) and from overlapping job history records for 5606 workers (1955–2001). Duplicates were removed and persons without identifying information excluded (figure 1). We also excluded persons who worked less than 6 months.

2.1.1. Demographic information. Available demographic information included name, date of birth, social security number, sex, marital status and current address.

2.1.2. Work histories. Available work history information included year of hire, year of termination, pay type (hourly, salaried) and job history (job location, department, job title). Employment at uranium mines and mills was readily determined on the basis of job location (mine or mill) and job title (e.g., miner, underground labourer, driller, shaftman, tailings pile operator, yellowcake filter and dryer operator, crusher operator). Everyone who worked underground was classified as a ‘miner’ regardless of job classification. A sample of 19 millers was submitted to NIOSH to learn of any additional uranium work that was not known from the existing company records. Similarly, linkages of worker rosters were made with a Colorado milling and mining study (Boice *et al* 2007b). NIOSH had conducted health studies of uranium millers (Pinkerton *et al* 2004) and Colorado plateau uranium miners (Roscoe 1997). The NIOSH records often included detailed occupational histories, questionnaires with smoking information, and pathology evaluations for many of the workers. The Grants uranium mill was not one of the seven mills included in the NIOSH study (Pinkerton *et al* 2004), but some of the Grants underground miners were likely included in previous studies of miners in New Mexico (Samet *et al* 1991).

2.1.3. Exposure to ore or uranium processing. Workers who had not worked as an underground miner were classified as to the likelihood that they worked with uranium ore or with the processing of uranium ore at the mill. The assignment of exposure potential was based on job titles (e.g., accountants and clerks were assumed to be unlikely or infrequently exposed to ore or uranium processing activities, whereas crusher operators, yellowcake filter and dryer

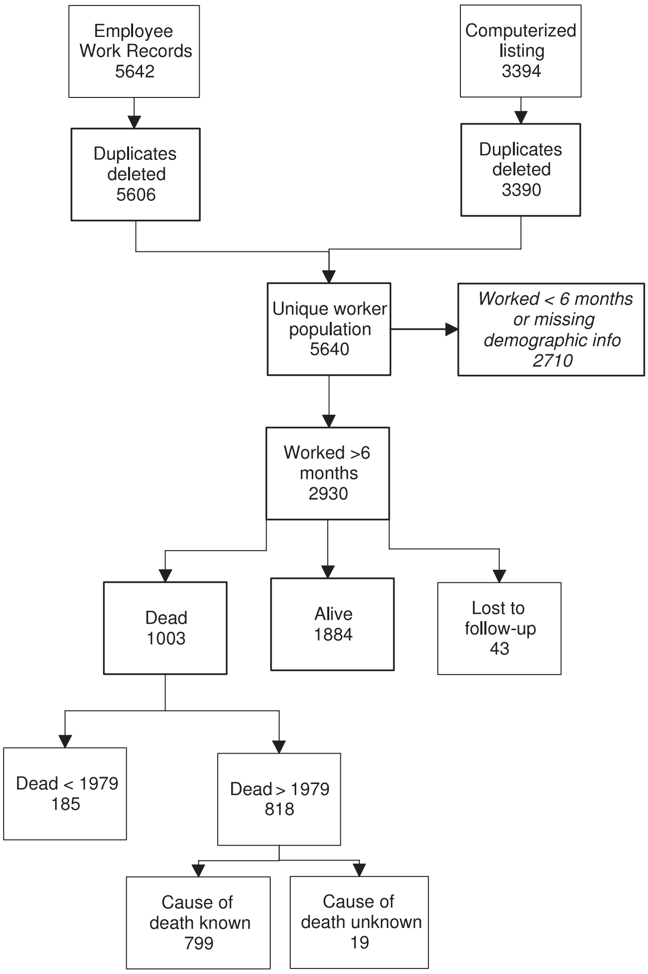

Figure 1. Identification of workers engaged in uranium milling and mining activities near Grants, New Mexico, and vital status as of December 31, 2005. Eligible subjects worked for 6 or more months with sufficient identifying information for tracing; duplicates were removed. Study subjects were assumed alive if NDI and Social Security Administration linkages failed to provide a death or vital status match ($n = 43$).

operators and tailings pond operators were assumed to have had the potential for exposure to ore and uranium dust). Interviews with employees were helpful in resolving uncertainties in specific job titles and work responsibilities. Some employees also lived in Milan and in areas close to the uranium mill.

2.1.4. Length of employment. Persons were categorised as to their length of employment as follows: <6 months (excluded); 6 months to 1.9 yrs; 2–4.9 yrs; $\geqslant$5 yrs. Based on the sample of records submitted to NIOSH, it was learnt that some workers had also been employed at different facilities in other parts of the country. Unfortunately our records of such employment were incomplete and we were unable to incorporate subsequent work histories into the analyses.

2.2. *Follow-up*

Mortality and vital status were determined from various linkages of the study roster with national databases including the National death index (NDI), the Social security administration (SSA) Death Master File and other SSA files, credit bureaus and Comserv, a computer services firm specialising in locating persons. SSA files confirmed that 1750 persons were alive in 2004. Searches with credit bureau records and LexisNexis, an online information service provider (www.lexisnexis.com), confirmed that 177 of the 220 persons without an SSA or NDI match were alive sometime after 1979. The remaining 43 persons (1.5%) without a SSA or NDI mortality match were assumed to be alive. Of the 818 deaths occurring after 1978, cause of death was not obtained for 19 (2.3%) including one person who died outside the United States. Deaths prior to 1979 ($n = 185$) were excluded from the SMR analyses (figure 1, table 1) because cause of death information from the National Death Index is not available before 1979 and attempts to obtain death certificates for these early deaths were in large part unsuccessful. Of the 185 deaths occurring before 1978, death certificates were sought but not obtained for 80 (43.2%) which precluded a meaningful cause of death analysis.

2.3. *Analysis*

Person-years of follow-up began on January 1, 1979 or the date of first employment (plus 6 months), whichever came later (except for those first employed July 1, 1978 to December 31, 1978 for whom follow-up began 6 months after hire date). Follow-up ended on the date of death, December 31, 2005 or age 95, whichever came earlier. There were 6 persons who were withdrawn from follow-up once they reached the age of 95. Standardised mortality ratios (SMR) were computed as the ratio of the observed numbers of deaths to the number of deaths that would have been expected using the mortality rates of the general population of the United States. Observed numbers of deaths from cancers and all other diseases were categorised by sex, age and calendar year for all workers and for subgroups defined by duration of employment and work experience at a uranium mine or uranium mill. Expected numbers of deaths were computed based on age-, calendar year and sex-specific rates in the general population of the United States. SMR analyses based on mortality rates of the general population of New Mexico were also conducted using race weightings of 90% white and 10% non-white. White rates included Hispanics and non-Hispanic whites, and non-white rates included primarily Navajo and other Native Americans. There were very few black workers. SMRs and 95% confidence intervals (95% CI) were calculated using OCMAP software for 41 causes of death categories (Marsh *et al* 1998).

3. Results

Computerised company records and imaged work history records were used to identify 2930 workers (2682 men and 248 women) who worked at least 6 months between 1955 and 2004 (table 1). The average length of time between the date of first employment and the date when follow-up was completed was 36.4 years. Over 28% of the workers had been employed for 5 or more years, and 38% of the workers were followed for more than 40 years after first employment. Just over one-third (34.2%) of the workers were found to have died, 64% were confirmed to be alive at the end of follow-up (December 31, 2005) and 1.5% were assumed to be alive.

After excluding 185 persons who died before 1979, 2745 workers remained for inclusion in the SMR analyses. Nearly 45% of the 818 deaths observed between 1979 and 2005 occurred

Table 1. Demographic and occupational characteristics of uranium millers and miners, Grants, New Mexico, 1955–2005.

	Miners $(N = 1867)$		Millers[a] $(N = 759)$		Other/Unk $(N = 304)$		Total $(N = 2930)$	
Characteristic	*N*	%	*N*	%	*N*	%	*N*	%
Gender								
Male	1813	97.1	692	91.2	177	58.2	2682	91.5
Female	54	2.9	67	8.8	127	41.8	248	8.5
Marital status								
Married	820	43.9	304	40.1	144	47.4	1268	43.3
Single	521	27.9	315	41.5	102	33.6	938	32.0
Unknown	306	16.4	133	17.5	51	16.8	490	16.7
Missing	220	11.8	7	0.9	7	2.3	234	8.0
Pay type								
Hourly	1168	62.6	366	48.2	82	27.0	1616	55.2
Salary	521	27.9	315	41.5	102	33.6	938	32.0
Unknown	178	9.5	78	10.3	120	39.5	376	12.8
Year of birth								
<1900	2	0.1	9	1.2	2	0.7	13	0.4
1900–1919	142	7.6	95	12.5	27	8.9	264	9.0
1920–1929	323	17.3	94	12.4	38	12.5	455	15.5
1930–1939	440	23.6	205	27.0	74	24.3	719	24.5
1940–1949	517	27.7	190	25.0	95	31.3	802	27.4
1950–1959	420	22.5	151	19.9	65	21.4	636	21.7
⩾1960	23	1.2	15	2.0	3	1.0	41	1.4
Calendar year of first employment								
1955–1964	603	32.3	339	44.7	99	32.6	1041	35.5
1965–1974	518	27.8	185	24.4	75	24.7	778	26.6
1975–1984	720	38.6	187	24.6	124	40.8	1031	35.2
1985–1989	26	1.4	48	6.3	6	2.0	80	2.7
Years since first employed								
<20	26	1.4	48	6.3	6	2.0	80	2.7
20–29	659	35.3	175	23.1	115	37.8	949	32.4
30–39	543	29.1	175	23.1	75	24.7	793	27.1
40–49	639	34.2	361	47.6	108	35.5	1108	37.8
Year of termination								
Prior to 1960	71	3.8	40	5.3	7	2.3	118	4.0
1960–1969	585	31.3	255	33.6	91	29.9	931	31.8
1970–1979	657	35.2	224	29.5	86	28.3	967	33.0
1980–1989	521	7.9	193	25.4	100	32.9	814	27.8
1990–2004	33	1.8	47	6.2	20	6.6	100	3.4
Duration of employment								
6 months–1.9 yrs	872	46.7	315	41.5	126	41.5	1313	44.8
2–4.9 yrs	489	26.2	216	28.5	73	24.0	778	26.6
5–9.9 yrs	287	15.4	111	14.6	53	17.4	451	15.4
⩾10 yrs	219	11.7	117	15.4	52	17.1	388	13.2
Work with ore or uranium processing[b]								
Likely	0	0.0	759	100	0	0.0	759	25.9
Unlikely	0	0.0	0	0.0	194	63.8	194	6.6
Missing/Not applicable[c]	1867	100.0	0	0.0	110	36.2	1977	67.5

Table 1. (Continued.)

	Miners (N = 1867)		Millers[a] (N = 759)		Other/Unk (N = 304)		Total (N = 2930)	
Characteristic	*N*	%	*N*	%	*N*	%	*N*	%
Vital status as of 12/31/2005								
Alive (confirmed)	1165	62.4	490	64.6	229	75.3	1884	64.3
Alive (assumed)	25	1.3	8	1.1	6	2.0	43	1.5
Dead after 1978	541	29.0	220	29.0	57	18.8	818	27.9
Dead before 1979	132	7.1	41	5.4	12	4.0	185	6.3

[a] Mill workers with job titles associated with uranium ore or processing activities (e.g., yellowcake dryer).
[b] Tabulations are only for the 953 workers at the Grants mill not known to have worked at a mine.
[c] Miners were not classified as to whether they worked at a uranium mill.

in New Mexico with over 55% occurring in 38 other states, indicating the appropriateness of using US mortality rates for the SMR analyses.

Most of the workers were male (92%) and paid hourly wages (55%), 50% were born before 1940 (average 1938), 62% were hired before 1975 (average 1969) and 69% terminated their employment before 1980 (average 1973) (table 1). There were 1867 (or 64%) workers known to have worked at a uranium mine at some time during their career. There were 1063 workers employed at the uranium mill or proximal facilities with no known mining experience; personnel job history records indicated that 759 of these workers held jobs that were likely to have involved working directly with uranium ore or with uranium processing activities (e.g., yellowcake drying).

Information requested from NIOSH to learn of subsequent employment at other uranium mines and mills was found for 8 (42%) of the 19 mill workers; 3 of the 11 workers without information had been hired after the NIOSH studies had been initiated in 1970. Of the 8 mill workers, one had worked at another uranium mill in Arizona, two as surface workers at uranium mines and two as underground miners. Three had also worked at a mine but details were not available. Linkages of worker rosters had also revealed that 9 of the 904 mill workers had been employed at the Uravan mill in Colorado (Boice *et al* 2007b).

Table 2 presents the observed and expected number of deaths and SMRs for the 2745 workers at uranium mines or mills who were alive in 1979 and followed through 2005 by sex. There were 63 395 person-years of observation (average 23.1 yrs). Overall, 818 workers were found to have died compared with 713.7 expected (SMR 1.15; 95% CI 1.07–1.23). Statistically significant increased numbers of deaths were found for lung cancer (SMR 1.65; 95% CI 1.36–1.97; $n = 117$), diseases of the nervous system (SMR 1.60; 95% CI 1.01–2.39; $n = 23$), non-malignant respiratory disease (SMR 1.42; 95% CI 1.14–1.76; $n = 84$), accidents (SMR 1.44; 95% CI 1.05–1.92; $n = 46$) and suicides (SMR 1.61; 95% CI 1.04–2.37; $n = 25$). The only cause with statistically significant decreased numbers of deaths was AIDS (SMR 0.0; expected number 7.2). Lung cancer was increased only among males. There were no statistically significant findings among the small number of 245 female workers.

The observed numbers of deaths were not statistically different from the expected numbers in the general population for cancers of the kidney (SMR 1.11; 95% CI 0.41–2.42; $n = 6$) and liver (SMR 1.70; 95% CI 0.78–3.23; $n = 9$) or for non-Hodgkin lymphoma (SMR 0.75; 95% CI 0.28–1.64; $n = 6$), leukaemia other than CLL (SMR 1.36; 95% CI 0.59–2.68; $n = 8$), heart disease (SMR 0.93; 95% CI 0.81–1.06; $n = 218$), liver cirrhosis (SMR 1.47; 95% CI 0.93–2.21; $n = 23$) or non-malignant kidney disease (SMR 0.86; 95% CI 0.32–1.87; $n = 6$).

Table 2. Observed and expected numbers of deaths and standardised mortality ratios (SMRs) among employees at uranium mills or mines near Grants, New Mexico, followed 1979–2005, by sex.

Sex	Males				Females				Total			
No. of persons	2500				245				2745			
Person-years	57 284				6110				63 395			
Cause of death (ICD9)	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI
All causes of death (001–999)	789	689.3	1.15[b]	1.07–1.23	29	24.4	1.19	0.80–1.70	818	713.7	1.15[b]	1.07–1.23
All malignant neoplasms (140–208)	235	192.2	1.22[b]	1.07–1.39	11	9.3	1.18	0.59–2.11	246	201.5	1.22[b]	1.07–1.38
Buccal cavity and pharynx (140–149)	1	4.1	0.25	0.01–1.37	1	0.1	10.9	0.27–60.8	2	4.2	0.48	0.06–1.73
Oesophagus (150)	4	6.0	0.67	0.18–1.71	0	0.1	0.00	—	4	6.1	0.66	0.18–1.69
Stomach (151)	5	5.1	0.99	0.32–2.30	0	0.1	0.00	—	5	5.2	0.96	0.31–2.24
Colon (153)	11	15.9	0.69	0.35–1.24	0	0.6	0.00	—	11	16.5	0.67	0.33–1.19
Rectum (154)	1	3.1	0.33	0.01–1.82	0	0.1	0.00	—	1	3.2	0.32	0.01–1.76
Biliary passages and liver (155, 156)	9	5.1	1.76	0.80–3.34	0	0.2	0.00	—	9	5.3	1.70	0.78–3.23
Pancreas (157)	7	9.6	0.73	0.29–1.50	2	0.4	5.01	0.61–18.1	9	10.0	0.90	0.41–1.71
Bronchus, trachea, and lung (162)	114	68.8	1.66[b]	1.37–1.99	3	2.4	1.27	0.26–3.72	117	71.1	1.65[b]	1.36–1.97
Breast (174, 175)	0	0.2	0.00	0.00–15.9	2	2.0	1.00	0.12–3.62	2	2.2	0.90	0.11–3.25
All uterine (179–182)	—	—	—	—	0	0.4	0.00	0.00–8.35	0	0.4	0.00	0.00–8.35
Other female genital organs (183–184)	—	—	—	—	2	0.6	3.17	0.38–11.5	2	0.6	3.17	0.38–11.5
Prostate (185)	13	14.6	0.89	0.47–1.52	—	—	—	—	13	14.6	0.89	0.47–1.52
Kidney (189.0–189.2)	6	5.3	1.14	0.42–2.49	0	0.2	0.00	0.00–24.3	6	5.4	1.11	0.41–2.42
Bladder and other urinary (188, 189.3–189.9)	3	4.9	0.61	0.13–1.80	1	0.1	13.1	0.33–72.7	4	5.0	0.81	0.22–2.07
Melanoma of skin (172)	6	3.7	1.63	0.60–3.54	0	0.1	0.00	—	6	3.8	1.57	0.57–3.41
Brain and CNS (191–192)	5	5.4	0.93	0.30–2.16	0	0.3	0.00	—	5	5.7	0.88	0.29–2.06
Thyroid and other endocrine glands (193–194)	1	0.6	1.82	0.05–10.1	0	0.0	0.00	—	1	0.6	1.71	0.04–9.52
Bone (170)	0	0.4	0.00	0.00–10.3	0	0.0	0.00	—	0	0.4	0.00	0.00–9.87
All lymphatic, haematopoietic tissue (200–208)	23	18.8	1.22	0.78–1.84	0	0.8	0.00	0.00–4.87	23	19.6	1.18	0.75–1.77
Non-Hodgkin lymphoma (200, 202)	6	7.6	0.79	0.29–1.71	0	0.3	0.00	—	6	8.0	0.75	0.28–1.64
Hodgkin lymphoma (201)	1	0.7	1.52	0.04–8.48	0	0.0	0.00	—	1	0.7	1.45	0.04–8.08
Leukaemia and aleukaemia (204–208)	12	7.1	1.69	0.87–2.95	0	0.3	0.00	—	12	7.4	1.62	0.84–2.83

Table 2. (Continued.)

Sex	Males				Females				Total			
No. of persons	2500				245				2745			
Person-years	57 284				6110				63 395			
Cause of death (ICD9)	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI
Chronic lymphocytic leukaemia (204.1)	4	1.5	2.71	0.74–6.93	0	0.0	0.00	—	4	1.5	2.65	0.72–6.79
Leukaemia other than CLL	8	5.6	1.42	0.61–2.80	0	0.2	0.00	—	8	5.9	1.36	0.59–2.68
Multiple myeloma (203)	4	3.2	1.24	0.34–3.16	0	0.1	0.00	—	4	3.4	1.19	0.32–3.04
Pleura and peritoneum (158.8, 158.9, 163) and mesothelioma (ICD10 C45)[a]	2	0.7	2.71	0.33–9.80	0	0.0	0.00	—	2	0.8	2.66	0.32–9.61
AIDS (042–044, 795.8)	0	7.1	0.00^{b}	0.00–0.52	0	0.1	0.00	—	0	7.2	0.00^{b}	0.00–0.51
Diabetes (250)	19	15.9	1.20	0.72–1.87	1	0.8	1.31	0.03–7.29	20	16.6	1.20	0.74–1.86
Mental and behavioural disorders (290–319)	9	8.0	1.13	0.52–2.14	0	0.2	0.00	—	9	8.2	1.10	0.50–2.08
Diseases of the nervous system (320–389)	21	13.8	1.52	0.94–2.32	2	0.6	3.29	0.40–11.9	23	14.4	1.60^{b}	1.01–2.39
Cerebrovascular disease (430–438)	30	31.4	0.95	0.64–1.36	2	1.2	1.61	0.20–5.81	32	32.7	0.98	0.67–1.38
All heart disease (390–398, 404, 410–429)	212	228.9	0.93	0.81–1.06	6	5.2	1.16	0.43–2.53	218	234.0	0.93	0.81–1.06
Non-malignant respiratory disease (460–519)	83	57.1	1.45^{b}	1.16–1.80	1	1.9	0.52	0.01–2.91	84	59.1	1.42^{b}	1.14–1.76
Bronchitis, emphysema, asthma (490–493)	35	18.8	1.86^{b}	1.30–2.59	0	0.9	0.00	0.00–4.28	35	19.7	1.78^{b}	1.24–2.48
Cirrhosis of liver (571)	22	15.1	1.46	0.91–2.20	1	0.5	2.02	0.05–11.3	23	15.6	1.47	0.93–2.21
Nephritis and nephrosis (580–589)	6	6.7	0.89	0.33–1.94	0	0.2	0.00	0.00–15.1	6	7.0	0.86	0.32–1.87
All external causes of death (800–999)	77	52.1	1.48^{b}	1.17–1.85	1	1.8	0.56	0.01–3.10	78	53.9	1.45^{b}	1.14–1.81
Accidents (850-949)	46	30.9	1.49^{b}	1.09–1.99	0	1.1	0.00	0.00–3.40	46	32.0	1.44^{b}	1.05–1.92
Suicides (950-959)	24	15.1	1.59^{b}	1.02–2.37	1	0.5	2.20	0.06–12.3	25	15.5	1.61^{b}	1.04–2.37
Unknown causes of death	18				1				19			

[a] Mesothelioma was not a codeable cause of death until 1999: ICD10 (C45). Before 1999, cancers of the pleura and peritoneum (ICD9 158.8, 158.9, 163) have been used to approximate mesothelioma mortality.

[b] $p < 0.05$.

No deaths were observed for bone cancer (0.4 expected) and only one death occurred from cancer of the thyroid (0.6 expected).

Table 3 presents the observed and expected number of deaths and SMRs by employment at a uranium mine. Among the 1735 miners, the total number of deaths, 541, was statistically higher than expected, 426.4 (SMR 1.27; 95% CI 1.16–1.38). The excess number of deaths among workers with mining experience arose primarily from five causes: lung cancer (SMR 2.17; 95% CI 1.75–2.65; $n = 95$); non-malignant respiratory diseases (i.e., bronchitis, emphysema and asthma combined, influenza and pneumonia) (SMR 1.64; 95% CI 1.23–2.13; $n = 55$), cirrhosis of the liver (SMR 1.79; 95% CI 1.06–2.83; $n = 18$), accidents (SMR 1.50; 95% CI 1.02–2.13; $n = 31$) and suicides (SMR 2.06; 95% CI 1.28–3.15; $n = 21$). Among men with mining experience, heart disease occurred as expected (SMR 0.96; 95% CI 0.80–1.14; $n = 133$).

The overall SMR for the 106 workers whose mining experience was unknown was 0.95 (95% CI 0.61–1.42; $n = 24$) and their total-cancer SMR was 0.58 (95% CI 0.16–1.47; $n = 4$).

There were no statistically significant high or low SMRs among the 904 workers not known to have worked at a uranium mine. Their overall SMR for all causes of death was 0.97 (95% CI 0.85–1.09) and their total-cancer SMR was 0.89 (95% CI 0.69–1.14). Lung cancer was not increased (SMR 0.85; 95% CI 0.52–1.29; $n = 21$), nor was non-malignant respiratory disease (SMR 1.07; 95% CI 0.69–1.58; $n = 25$). Deaths from heart disease occurred below expectation (SMR 0.84; 95% CI 0.66–1.05; $n = 73$).

Table 4 presents the observed and expected numbers of deaths and SMRs for the 904 workers at the uranium mill who were not known to have worked at a mine. Among the 718 millers with the highest potential for exposure to uranium ore, there were no statistically significant increased causes of death. The all-cause SMR was 1.00 (95% CI 0.87–1.14; $n = 220$), the total-cancer SMR was 0.94 (95% CI 0.71–1.22; $n = 56$), the lung cancer SMR was 0.88 (95% CI 0.52–1.38; $n = 18$), the SMR for non-malignant respiratory disease was 1.22 (95% CI 0.78–1.81; $n = 24$), the SMR for non-malignant kidney disease was 1.30 (95% CI 0.27–3.79; $n = 3$) and the SMR for heart disease was 0.84 (95% CI 0.65–1.08; $n = 63$).

SMR analyses were conducted for uranium millers not known to have worked at an underground mine by duration of employment (data not shown). There were no statistically significant increased SMRs for any cause of death for those employed for the longest time. The all-cause SMR for the 209 persons who worked for more than 5 yrs (SMR 0.87; 95% CI 0.70–1.07; $n = 88$) was slightly lower than for all 718 mill workers combined (SMR 1.00), as were the SMRs for total cancer (0.72; $n = 19$), lung cancer (0.56; $n = 5$) and non-malignant respiratory disease (0.68; $n = 7$), although the numbers were small. A decreased risk of heart disease (SMR 0.77; 95% 0.51–1.11; $n = 28$) was consistent with the low SMR (0.84) seen for all millers.

SMR analyses were conducted using general population rates for the state of New Mexico and the mortality patterns were generally similar to those using rates for the United States. The all-cause SMR among all workers was 1.19 (95% CI 1.11–1.28) and similar to the SMR of 1.15 (95% CI 1.07–1.23) based on US rates. The total-cancer SMR was somewhat higher based on New Mexico rates (SMR 1.49; 95% CI 1.30–1.68) compared with US rates (SMR 1.22; 95% CI 1.07–1.38)—mainly due to the somewhat higher lung cancer SMR based on New Mexico rates (SMR 2.56; 95% CI 2.12–3.07) compared with US rates (SMR 1.65; 95% CI 1.36–1.97). Non-malignant respiratory disease mortality was nearly identical based on New Mexico rates (SMR 1.38) compared with US rates (SMR 1.42). Deaths due to external causes were lower based on New Mexico rates (SMR 0.87; 95% CI 0.69–1.08) compared with US rates (SMR 1.45; 95% CI 1.14–1.92). Other than for external causes of death, there were no appreciable differences in the SMRs.

Table 3. Observed and expected numbers of deaths and standardised mortality ratios (SMRs) among employees at uranium mills or mines near Grants, New Mexico, followed 1979–2005, by mining experience.

Mining experience	Yes				No			
No. of persons	1735				904			
Person-years of observation	40 027				20 937			
Cause of death (ICD9)	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI
All causes of death (001–999)	541	426.4	1.27[b]	1.16–1.38	253	262.1	0.97	0.85–1.09
All malignant neoplasms (140–208)	177	121.6	1.46[b]	1.25–1.69	65	73.0	0.89	0.69–1.14
Buccal cavity and pharynx (140–149)	1	2.6	0.38	0.01–2.13	1	1.4	0.71	0.02–3.98
Oesophagus (150)	2	3.8	0.52	0.06–1.89	2	2.0	0.99	0.12–3.57
Stomach (151)	5	3.2	1.58	0.51–3.68	0	1.9	0.00	0.00–1.99
Colon (153)	9	9.9	0.91	0.42–1.73	2	6.1	0.33	0.04–1.19
Rectum (154)	1	1.9	0.52	0.01–2.90	0	1.1	0.00	0.00–3.26
Biliary passages and liver (155, 156)	6	3.2	1.85	0.68–4.02	3	1.9	1.62	0.33–4.72
Pancreas (157)	4	6.1	0.66	0.18–1.68	4	3.6	1.12	0.31–2.87
Bronchus, trachea, and lung (162)	95	43.8	2.17[b]	1.75–2.65	21	24.9	0.85	0.52–1.29
Breast (174, 175)	0	0.5	0.00	0.00–7.59	2	1.7	1.20	0.15–4.32
All uterine (179–182)	0	0.1	0.00	—	0	0.3	0.00	0.00–10.6
Other female genital organs (183–184)	0	0.1	0.00	—	2	0.5	3.94	0.48–14.2
Prostate (185)	9	8.3	1.08	0.49–2.05	4	5.8	0.69	0.19–1.76
Kidney (189.0–189.2)	3	3.4	0.89	0.18–2.61	3	1.9	1.61	0.33–4.71
Bladder and other urinary (188, 189.3–189.9)	0	2.9	0.00	0.00–1.26	4	1.9	2.15	0.59–5.50
Melanoma of skin (172)	6	2.4	2.49	0.91–5.41	0	1.3	0.00	0.00–2.87
Brain and CNS (191–192)	2	3.6	0.56	0.07–2.03	3	1.9	1.57	0.32–4.59
Thyroid and other endocrine glands (193–194)	1	0.4	2.80	0.07–15.6	0	0.2	0.00	0.00–17.8
Bone (170)	0	0.2	0.00	0.00–15.9	0	0.1	0.00	0.00–28.8
All lymphatic, haematopoietic tissue (200–208)	18	11.9	1.51	0.90–2.39	4	7.0	0.57	0.16–1.47
Non-Hodgkin lymphoma (200, 202)	4	4.9	0.82	0.22–2.11	1	2.8	0.36	0.01–1.98
Hodgkins lymphoma (201)	1	0.4	2.28	0.06–12.7	0	0.2	0.00	0.00–16.3
Leukaemia and aleukaemia (204–208)	9	4.5	2.01	0.92–3.82	3	2.7	1.12	0.23–3.28
Chronic lymphocytic leukaemia (204.1)	2	0.9	2.23	0.27–8.05	2	0.6	3.58	0.43–12.9
Leukaemia other than CLL	7	3.6	1.96	0.79–4.04	1	2.1	0.47	0.01–2.64
Multiple myeloma (203)	4	2.0	1.97	0.54–5.05	0	1.2	0.00	0.00–3.02
Pleura and peritoneum (158.8,158.9,163) and mesothelioma (ICD10 C45)[a]	1	0.5	2.14	0.05–11.9	1	0.3	3.85	0.10–21.5
AIDS (042-044, 795.8)	0	5.0	0.00[b]	0.00–0.74	0	2.0	0.00	0.00–1.86
Diabetes (250)	11	10.0	1.10	0.55–1.97	9	6.1	1.48	0.68–2.81
Mental and behavioural disorders (290–319)	8	4.9	1.65	0.71–3.25	1	3.1	0.33	0.01–1.81
Diseases of the nervous system (320–389)	14	8.3	1.69	0.92–2.83	9	5.6	1.60	0.73–3.03
Cerebrovascular disease (430–438)	16	18.3	0.88	0.50–1.42	14	13.3	1.06	0.58–1.77
All heart disease (390–398, 404, 410–429)	133	138.6	0.96	0.80–1.14	73	87.1	0.84	0.66–1.05
Non-malignant respiratory disease (460–519)	55	33.6	1.64[b]	1.23–2.13	25	23.4	1.07	0.69–1.58
Bronchitis, emphysema, asthma (490–493)	25	11.6	2.16[b]	1.40–3.19	8	7.4	1.08	0.47–2.12
Cirrhosis of liver (571)	18	10.1	1.79[b]	1.06–2.83	3	5.0	0.60	0.12–1.75
Nephritis and nephrosis (580–589)	3	4.0	0.76	0.16–2.21	3	2.8	1.08	0.22–3.17
All external causes of death (800–999)	58	35.1	1.65[b]	1.26–2.14	20	16.8	1.19	0.73–1.84
Accidents (850–949)	31	20.6	1.50[b]	1.02–2.13	15	10.1	1.48	0.83–2.45
Suicides (950–959)	21	10.2	2.06[b]	1.28–3.15	4	4.8	0.84	0.23–2.15
Unknown causes of death	12				7			

[a] There were 106 workers with 2431 person-years of follow-up whose mining experience was unknown. Their overall SMR was 0.95 (95% CI 0.61–1.42; $n = 24$) and their total-cancer SMR was 0.58 (95% CI 0.16–1.47; $n = 4$).

[b] $p < 0.05$.

Table 4. Observed and expected numbers of deaths and standardised mortality rates (SMRs) for employees at the uranium mill near Grants, New Mexico, who never worked at an underground mine and followed from 1979–2005, by whether they worked with ore or processed uranium.

Worked with ore or uranium processing activities	Likely[a]				Unlikely[b]			
No. of persons	718				186			
Person-years of observation	16 333				4604			
Cause of death (ICD9)	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI
All causes of death (001–999)	220	220.1	1.00	0.87–1.14	33	42.0	0.79	0.54–1.10
All malignant neoplasms (140–208)	56	59.6	0.94	0.71–1.22	9	13.5	0.67	0.31–1.27
Buccal cavity and pharynx (140–149)	1	1.2	0.84	0.02–4.69	0	0.2	0.00	0.00–17.4
Oesophagus (150)	2	1.7	1.15	0.14–4.16	0	0.3	0.00	0.00–12.8
Stomach (151)	0	1.6	0.00	0.00–2.35	0	0.3	0.00	0.00–13.0
Colon (153)	2	5.0	0.40	0.05–1.44	0	1.0	0.00	0.00–3.55
Rectum (154)	0	0.9	0.00	0.00–3.90	0	0.2	0.00	0.00–19.8
Biliary passages and liver (155, 156)	3	1.5	1.94	0.40–5.67	0	0.3	0.00	0.00–11.9
Pancreas (157)	4	2.9	1.37	0.37–3.49	0	0.6	0.00	0.00–5.80
Bronchus, trachea, and lung (162)	18	20.6	0.88	0.52–1.38	3	4.3	0.70	0.14–2.04
Breast (174, 175)	0	0.5	0.00	0.00–7.13	2	1.2	1.73	0.21–6.26
All uterine (179–182)	0	0.1	0.00	0.00–36.3	0	0.2	0.00	0.00–14.9
Other female genital organs (183–184)	0	0.1	0.00	0.00–27.0	2	0.4	5.39	0.65–19.5
Prostate (185)	3	5.1	0.59	0.12–1.71	1	0.7	1.47	0.04–8.18
Kidney (189.0–189.2)	3	1.6	1.92	0.40–5.62	0	0.3	0.00	0.00–12.3
Bladder and other urinary (188, 189.3–189.9)	4	1.6	2.50	0.68–6.40	0	0.3	0.00	0.00–14.1
Melanoma of skin (172)	0	1.1	0.00	0.00–3.46	0	0.2	0.00	0.00–16.9
Brain and CNS (191–192)	3	1.6	1.93	0.40–5.63	0	0.4	0.00	0.00–10.4
Thyroid and other endocrine glands (193–194)	0	0.2	0.00	0.00–22.3	0	0.0	0.00	—
Bone (170)	0	0.1	0.00	0.00–34.7	0	0.0	0.00	—
All lymphatic, haematopoietic tissue (200–208)	4	5.8	0.69	0.19–1.77	0	1.2	0.00	0.00–3.03
Non-Hodgkin lymphoma (200, 202)	1	2.3	0.43	0.01–2.40	0	0.5	0.00	0.00–7.40
Hodgkin lymphoma (201)	0	0.2	0.00	0.00–19.7	0	0.0	0.00	—
Leukaemia and aleukaemia (204–208)	3	2.2	1.35	0.28–3.96	0	0.5	0.00	0.00–8.13
Chronic lymphocytic Leukaemia (204.1)	2	0.5	4.21	0.51–15.2	0	0.1	0.00	0.00–44.2
Leukaemia other than CLL	1	1.7	0.57	0.01–3.20	0	0.4	0.00	0.00–9.95
Multiple myeloma (203)	0	1.0	0.00	0.00–3.68	0	0.2	0.00	0.00–17.0
Pleura and peritoneum (158.8,158.9,163) and mesothelioma (ICD10 C45)	1	0.2	4.60	0.12–25.6	0	0.0	0.00	—
AIDS (042-044, 795.8)	0	1.8	0.00	0.00–2.08	0	0.2	0.00	0.00–17.9
Diabetes (250)	8	5.0	1.62	0.70–3.18	1	1.1	0.89	0.02–4.98
Mental and behavioural disorders (290–319)	1	2.6	0.38	0.01–2.12	0	0.4	0.00	0.00–8.30
Diseases of the nervous system (320–389)	8	4.6	1.73	0.75–3.40	1	1.0	1.00	0.03–5.54
Cerebrovascular disease (430–438)	12	11.2	1.07	0.55–1.87	2	2.0	0.98	0.12–3.54
All heart disease (390–398, 404, 410–429)	63	74.8	0.84	0.65–1.08	10	12.4	0.81	0.39–1.49
Non-malignant respiratory disease (460–519)	24	19.7	1.22	0.78–1.81	1	3.7	0.27	0.01–1.51
Bronchitis, emphysema, asthma (490–493)	8	6.0	1.34	0.58–2.64	0	1.5	0.00	0.00–2.53
Cirrhosis of liver (571)	3	4.2	0.72	0.15–2.09	0	0.8	0.00	0.00–4.58
Nephritis and nephrosis (580–589)	3	2.3	1.30	0.27–3.79	0	0.5	0.00	0.00–8.15
All external causes of death (800–999)	17	14.3	1.19	0.69–1.90	3	2.4	1.23	0.25–3.59
Accidents (850–949)	13	8.6	1.51	0.80–2.58	2	1.5	1.36	0.16–4.90
Suicides (950–959)	3	4.1	0.73	0.15–2.14	1	0.7	1.47	0.04–8.19
Unknown causes of death	6				1			

[a] Mill worker with potential exposure to uranium ore and/or uranium processing activities, e.g., yellowcake drying.

[b] Workers employed at mill but with unlikely or minimal exposure to uranium ore or uranium processing activities, e.g., clerk or accountant.

4. Discussion

Underground uranium miners in the vicinity of Grants, New Mexico were found to be at statistically significant increased risk of dying from lung cancer, non-malignant respiratory disease, cirrhosis of the liver and external causes of death, similar to the findings of previous occupational studies of New Mexico and Colorado plateau miners (Samet *et al* 1984a, 1991, Roscoe *et al* 1995, Roscoe 1997). The increase in lung cancer is likely attributable to the high levels of radon and radon decay products in these early mines coupled with heavy smoking habits among miners (Lundin *et al* 1971, Whittemore and McMillan 1983, Hornung and Meinhardt 1987, Samet *et al* 1991). The increase in non-malignant respiratory disease, including pneumoconiosis, may be related in part to high levels of mining dusts, such as quartz (silica) present in the mines (Samet *et al* 1984b, 1991), as well as radon decay products, diesel exhaust and excessive tobacco use (Archer *et al* 1976). Increases in deaths from cirrhosis of the liver may be related to lifestyle factors of the early mining populations such as heavy alcohol consumption. Accidental deaths while on the job were not infrequent. An association with deaths from diseases of the nervous system for all workers combined was of borderline statistical significance and may be a chance finding. Interestingly, a healthy worker effect (Howe *et al* 1988) was not apparent in this miner population as indicated by the near normal rates of heart disease, cerebrovascular disease and most other conditions.

Although there are many studies of uranium miners (Lubin *et al* 1995, NRC 1999), there are few studies of uranium millers (Pinkerton *et al* 2004, Boice *et al* 2007b). Thus it is of interest that the 718 workers with the highest potential for exposure to uranium ore and processing activities were not found to be at increased risk of any of the diseases of *a priori* interest—based on possible associations seen in other studies and on knowledge of the likely distribution of uranium within the body once inhaled or ingested. No statistically significant increases were found for kidney disease, liver disease, non-malignant respiratory disease, lung cancer, bone cancer or non-Hodgkin lymphoma.

Table 5 compares the findings of the current study of uranium mill workers with the two other studies of mill workers at the Uravan mill in Colorado (Boice *et al* 2007b) and at the seven mills included in the NIOSH study of Colorado Plateau workers (Pinkerton *et al* 2004). The latter two studies are not independent since the Uravan mill was included in the NIOSH study. The general patterns of mortality are consistent across the three studies: there is no increase in all-cause mortality or all-cancer mortality, and cancer of the lung is increased in two studies but the increases were not statistically significant. An association between exposure to uranium and lung cancer has not been established in any study of uranium millers or uranium workers (IOM 2001).

No statistically significant associations were seen for cancers of the kidney, liver, bone or lymphoma (table 5). The risk of bladder cancer was increased in our study but was decreased in the other two series. Heart disease was below expectation in all three studies and the decreased risk was statistically significant in two of them. Non-malignant renal disease was not increased in any study at the level of statistical significance. The only statistically significant elevation was for non-malignant respiratory disease observed in the large NIOSH study (SMR 1.43; $n = 100$) but not in the Uravan study (SMR 0.99; $n = 24$) or in the current study (SMR 1.22; $n = 24$). Most (54%) of the uranium mill workers in the NIOSH study had begun work prior to 1955 when the potential for exposure to silica, uranium ore, vanadium and other mill contaminants was assumed higher than in later years. The Grants uranium mill began in 1955 but the Uravan mill began operations in 1936 and 42% were hired prior to 1955. The NIOSH investigators, however, were cautious in concluding that non-malignant respiratory disease was due to milling activities because of the inverse association seen with duration of

Table 5. Observed and expected numbers of deaths and standardised mortality ratios (SMRs) among mill workers near Grants, New Mexico (current study), Colorado (Boice *et al* 2007b), and the Colorado Plateau (Pinkerton *et al* 2004).

Worked with ore or uranium processing	Grants New Mexico Mill[a]				Uravan Colorado Mill[a]				7 Colorado Plateau Mills[b]			
No. of persons	718				450				1484			
Person-years of observation	16 333				9294				49 925			
Calendar years of mill operation	1958–1990				1936–1984				<1940–1970+			
Calendar years of follow-up	1979–2005				1979–2004				1940–1998			
Cause of death (ICD9)	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI
All causes of death (001–999)	220	220.1	1.00	0.87–1.14	186	233.6	0.80[e]	0.69–0.92	810	877.7	0.92[e]	0.86–0.99
All malignant neoplasms (140–208)	56	59.6	0.94	0.71–1.22	48	57.6	0.83	0.62–1.11	184	204.1	0.90	0.78-1.04
Buccal cavity and pharynx (140–149)	1	1.2	0.84	0.02–4.69	1	1.0	0.96	0.02–5.37	2	5.06	0.40	9.05–1.43
Oesophagus (150)	2	1.7	1.15	0.14–4.16	0	1.5	0.00	0.00–2.51	1	5.06	0.20	0.01–1.10
Colon (153)	2	5.0	0.40	0.05–1.44	0	5.3	0.00	0.00–0.70	12	19.0	0.63	0.33–1.11
Rectum (154)	0	0.9	0.00	0.00–3.90	1	0.9	1.06	0.03–5.91	2	4.77	0.42	0.05-1.51
Biliary passages and liver (155,156)	3	1.5	1.94	0.40–5.67	1	1.4	0.71	0.02–3.94	4	5.04	0.79	0.22–2.03
Pancreas (157)	4	2.9	1.37	0.37–3.49	3	2.7	1.10	0.23–3.20	6	10.3	0.58	0.21–1.27
Bronchus, trachea, and lung (162)	18	20.6	0.88	0.52–1.38	24	19.1	1.26	0.81–1.87	78	68.9	1.13	0.89–1.41
Prostate (185)	3	5.1	0.59	0.12–1.71	7	6.9	1.01	0.41–2.08	15[c]	19.7	0.76	0.43–1.26
Kidney (189.0–189.2)	3	1.6	1.92	0.40–5.62	1	1.4	0.74	0.02–4.10	4	4.96	0.81	0.22–2.06
Bladder and other urinary (188, 189.3–189.9)	4	1.6	2.50	0.68–6.40	1	1.9	0.54	0.01–2.99	5[d]	11.0	0.45	0.15–1.06
Bone (170)	0	0.1	0.00	0.00–34.7	0	0.1	0.00	0.00–39.3	Not given			
All lymphatic, haematopoietic tissue (200–208)	4	5.8	0.69	0.19–1.77	3	5.5	0.55	0.11–1.60	21	18.7	1.12	0.69–1.71
Non-Hodgkin lymphoma (200, 202)	1	2.3	0.43	0.01–2.40	1	2.1	0.47	0.01–2.63	4	2.29	1.74	0.48–4.46
Hodgkin lymphoma (201)	0	0.2	0.00	0.00–19.7	1	0.1	6.94	0.17–38.7	4	1.21	3.30	0.90-8.43
Leukaemia and aleukaemia (204–208)	3	2.2	1.35	0.28–3.96	1	2.2	0.46	0.01–2.54	5	7.62	0.66	0.21–1.53
Diabetes (250)	8	5.0	1.62	0.70–3.18	4	4.7	0.86	0.23–2.19	10	14.6	0.68	0.33–1.26

Table 5. (Continued.)

Worked with ore or uranium processing	Grants New Mexico Mill[a]				Uravan Colorado Mill[a]				7 Colorado Plateau Mills[b]			
No. of persons	718				450				1484			
Person-years of observation	16 333				9294				49 925			
Calendar years of mill operation	1958–1990				1936–1984				<1940–1970+			
Calendar years of follow-up	1979–2005				1979–2004				1940–1998			
Cause of death (ICD9)	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI	Obs	Exp	SMR	95% CI
All heart disease (390–398, 404, 410–429)	63	74.8	0.84	0.65–1.08	65	85.9	0.76[e]	0.58–0.97	293	349.0	0.84[e]	0.75–0.94
Non-malignant respiratory disease (460–519)	24	19.7	1.22	0.78–1.81	24	24.4	0.99	0.63–1.47	100	70.2	1.43[e]	0.65–1.05
Cirrhosis of liver (571)	3	4.2	0.72	0.15–2.09	0	2.9	0.00	0.00–1.27	Not given			
Nephritis and nephrosis (580–589)	3	2.3	1.30	0.27–3.79	3	2.7	1.09	0.23–3.19	9	7.07	1.28	0.59–2.44
All external causes of death (800–999)	17	14.3	1.19	0.69–1.90	7	10.1	0.69	0.28–1.43	47	37.2	1.26	0.93–1.68
Unknown causes of death	6				1				16			

[a] Mill workers with potential exposure to uranium ore and/or uranium processing activities based on job titles, e.g., yellowcake drying. Uravan mill values from table 6 of Boice *et al* (2007b).

[b] Cause of death categories are presented that are as similar as possible to those in the other two mill worker studies. Values from table 2 of Pinkerton *et al* (2004). The Uravan mill was included in the NIOSH study so the results are not independent. The Grants, New Mexico mill was not included in the NIOSH study.

[c] Male genital (ICD9 185–187).

[d] All urinary (ICD9 188–189).

[e] $p < 0.05$.

employment. Similar to lung cancer, non-malignant respiratory disease has not been established as a consequence of uranium exposure in any study (IOM 2001).

Ours is one of the few studies of uranium workers that include both underground miners exposed to radon, and uranium millers exposed to ore and milling products. These two types of uranium exposure showed very different risk patterns. Underground mining, with increased exposure to radon gas and its decay products, was clearly associated with increased risk of lung cancer, but no other cancer, consistent with previous studies of miners (Darby *et al* 1996, NRC 1999). In contrast, uranium milling and exposure to uranium ore was not associated with any cancer or non-malignant condition, also consistent with previous studies (Waxweiler *et al* 1983, Pinkerton *et al* 2004, Boice *et al* 2007b). Uranium is not considered carcinogenic in humans (IARC 2001, ATSDR 1999), in large part because it is not very radioactive given its long half-life of billions of years. The hazard associated with uranium exposure is due primarily to its chemical properties as a heavy metal, and kidney disease is the outcome of most concern following excessive exposure (Leggett 1989, ATSDR 1999). Apparently, such exposure was not sufficient to result in a detectable increase of renal disease among mill workers in our study or the two previous studies, consistent with practically all other studies that find no association between exposure to uranium and clinically important renal dysfunction (IOM 2001). Our findings of excess lung cancer among miners but not among millers are also consistent with a recent study of uranium millers and miners in Colorado (Boice *et al* 2007b).

4.1. Studies of environmental exposure to uranium

Although uranium can enter the body by ingestion of food and water or by inhalation of uranium-containing dust, environmental exposures have not been associated with detrimental health effects (Taylor and Taylor 1997). Epidemiologic studies of the ingestion of high levels of uranium, radium, radon and other radionuclides in drinking water in Finland have provided no evidence for increased rates of cancers of the bladder, kidney or stomach, or of leukaemia (Auvinen *et al* 2002, 2005, Kurttio *et al* 2006b). High intakes of natural uranium in drinking water have been linked to subtle effects on bone formation but only in males and not females and there was no evidence of overt bone disease (Kurttio *et al* 2005). Uranium millers and miners in the current study also were not found to be at increased risk for cancers of the bone, bladder, kidney and stomach or leukaemia.

Several descriptive correlation studies of populations living near uranium milling and mining facilities have been conducted in Texas (Boice *et al* 2003a) and in Colorado (Mason *et al* 1972, Boice *et al* 2007a). No association with any cancer was observed except for lung cancer in the Colorado study which was attributed, and then confirmed, to be most likely due to an occupational exposure to radon among underground miners residing in the area (Boice *et al* 2007b). The extensive uranium milling and mining activities in Texas were not associated with increased lung cancer mortality in all likelihood because only surface and *in situ* mining, and not underground mining, were performed and high exposures to radon were not possible (Boice *et al* 2003a). Similar studies of cancer incidence and mortality in populations residing within about one mile of nuclear fuel processing and uranium fabrication facilities in Pennsylvania have also failed to reveal increased cancer rates (Boice *et al* 2003b, 2003c).

4.2. Kidney disease

The possible chemical toxicity of uranium, a heavy metal, is considered more important for human health than the risk of cancer from its radioactive properties (Taylor and Taylor 1997, Leggett 1989). No statistically significant increase in renal disease, however, was found in the current study (3 observed versus 2.3 expected) nor in the NIOSH study of uranium millers of the Colorado plateau (9 observed versus 7.07 expected). The NIOSH study also reported that the risk of end-stage renal disease was not increased (Pinkerton *et al* 2004). Consistent with these results, renal disease was not increased among 450 millers in Uravan, Colorado (3 observed versus 2.7 expected) although many of these workers may have been included in the larger NIOSH investigation (Boice *et al* 2007b). Other studies of workers exposed to uranium have not found increases in kidney disease (Roscoe 1997, Russell *et al* 1996). One study of 39 uranium mill workers, however, reported changes in kidney function that suggested mild renal damage and, conversely, other changes that suggested improved glomerular function, but no apparent kidney disease (Thun *et al* 1985). Similarly, high levels of uranium in drinking water in Finland have produced subtle changes in some measures of kidney function but not kidney disease (Kurttio *et al* 2002, 2003, Kurttio *et al* 2006a). Studies of Gulf War veterans exposed to depleted uranium and of workers exposed to enriched uranium also find no evidence of clinically important renal dysfunction (IOM 2001, McDiarmid *et al* 2007). Consistent with these observations, we found no increase in mortality from non-malignant kidney disease among uranium millers and miners of Grants, New Mexico (6 observed deaths versus 7.0 expected).

4.3. Studies of New Mexico underground miners

A previous study of underground miners in New Mexico evaluated cancer and non-cancer mortality (Samet *et al* 1991). The only statistically significant excess was of lung cancer mortality (SMR 4.00; 95% CI 3.1–5.1; $n = 68$) attributed to the high concentrations of radon gas and radon decay products in unventilated underground mines and excessive tobacco use. Lung cancer increases were also seen among Navajo miners (Samet *et al* 1984a, Roscoe *et al* 1995). Increases in non-malignant respiratory diseases may have been partially due to high levels of silica dust causing pneumoconiosis and associated lung conditions (Samet *et al* 1984b). Our study of 1735 uranium miners revealed a statistically significant excess of lung cancer (SMR 2.17; $n = 95$) that was consistent with these previous investigations, as was the statistically significant increase in non-malignant respiratory disease (SMR 1.64; $n = 55$), attributable, perhaps, to silica, radon and other mine exposures and excessive tobacco use (IOM 2001). Statistically significant increases in external causes of death from accidents and suicides were seen in our study (SMR 1.65) and the previous study (SMR 1.5) of miners from New Mexico (Samet *et al* 1991) indicating the hazardous nature of underground mining and, perhaps, the characteristics of persons who choose mining as a profession.

4.4. Studies of cohorts exposed to uranium

During the early years of uranium processing, enrichment, manufacturing and milling, aboveground workers had the potential to inhale or ingest uranium dust with minimal exposure to radon gas (UNSCEAR 2008). Well over 120 000 of these workers have been studied and, overall, no consistent elevations in cancer risk were observed (Harley *et al* 1999, Royal Society 2001, IOM 2001, McGeoghegan and Binks 2000a, 2000b, 2006). Studies of workers with estimates of organ doses from uranium intakes also failed to find clear evidence of dose-response relationships (Dupree *et al* 1995, Boice *et al* 2006a, 2006b). In contrast to these negative studies of cancer risk among workers exposed to uranium dust and compounds, studies of underground uranium miners have revealed consistent and substantial increases in lung cancer attributed to radon gas and its decay products (NRC 1999).

4.5. Strengths and limitations

Strengths of our occupational study include the cohort design, the complete roster of all workers employed by a large uranium milling and mining company, and the long follow-up of the workers of up to 50 yrs. We also were able to distinguish between workers employed as underground miners, uranium millers or in both occupations. Limitations of the study include the relatively small number of workers within specific exposure categories and the lack of measurements of actual radiation exposure. Smoking histories also were not known.

Although the number of workers was relatively small (2930 overall and 2745 alive in 1979), the follow-up was long with 65% followed for more than 30 yrs after date of first employment and 38% followed for more than 40 yrs. Further, the number of deaths was sufficient to reveal increases for several causes of death; for example, among uranium miners we found statistically significant elevations of two-fold or less for lung cancer, non-malignant respiratory disease and cirrhosis of the liver.

For non-miners, the sample size was also sufficient to rule out relatively small increases in risk. For example, the SMR for total cancer, based on 56 deaths, was 0.94 (95% CI 0.71–1.22), indicating that with 95% confidence mortality elevations greater than 1.22 can be excluded. Relatively low SMRs for most diseases of *a priori* interest could be excluded, i.e., the upper 95% confidence limit was 1.38 for lung cancer, 1.81 for non-malignant respiratory disease and 2.09 for liver cirrhosis.

Although there were no measurements of individual exposures to uranium, silica, vanadium, radon, radium or other radionuclides, we could classify workers with regard to type of employment (underground mine and/or uranium mill), length of employment and, based on job title, likely exposure to ore or uranium processing activities. These occupational classifications allowed us to infer risks associated with specific types of exposures. For example, the statistically significant increase in lung cancer was restricted to workers employed as underground miners exposed to radon and radon decay products, whereas the non-mining population was not at statistically significant increased risk of dying from any cause. Thus, our study provides little support for the hypothesis that non-mining jobs may increase cancer risk. Furthermore, there was no evidence that those employed in non-mining jobs for greater than 5 yrs (i.e., for those who might have received the greatest exposure to uranium ore and mill effluents) experienced greater risks than those potentially exposed for shorter times.

Exposure misclassification is possible because employment in other regions of the country was not generally known. Prior work for other companies was not always recorded, and work histories after leaving the Grants, New Mexico area were in large part not available. The sample of worker records sent to NIOSH, for example, indicated that up to 17% of the millers might have had unrecognised employment underground as uranium miners. Such unrecognised underground exposures to radon and radon progeny could be substantial with cumulative concentrations over 100 WLM (Boice *et al* 2007b), compared with the yearly non-occupational exposure to radon of about 0.2 WLM. In addition to work as underground miners, some millers were also found to have worked at other uranium mills in Arizona, Colorado and other states.

Low risks for heart disease and cerebrovascular disease are often reported in occupational studies and ascribed to the ‘healthy worker effect’ associated with selection for employment and for continued employment (Monson 1986, Howe *et al* 1988). The healthy worker effect often diminishes with time, especially for cancer deaths. While a healthy worker effect was suggested among millers who had a lower risk of death from heart disease compared with the general population, no similar effect was seen among miners.

The study is of mortality and not incidence of disease for which the number of events and quality of diagnoses would be expected to be higher. Most of the diseases of interest, e.g., lung cancer and bone cancer, however, have a high fatality rate so that mortality would reflect incidence fairly closely. Diseases that have a low fatality rate can be evaluated in mortality studies, although the statistical power to identify a significant increase in risk might be lower than for an incidence survey because of the smaller number of events.

Because of the mobility of the workforce, mortality rates for the entire United States were used to compute expected numbers of deaths since use of New Mexico rates likely would have overestimated the SMRs. Many workers after terminating employment left New Mexico and spent substantial portions of their lives living in other states. Just over 55% of the 818 deaths occurring after 1978 happened outside the state of New Mexico. Because New Mexico rates of mortality are generally lower than for the United States as a whole, the computed expected numbers accordingly would be lower and the SMRs higher than if based on comparisons with the United States. The all-cause SMR among all workers based on New Mexico rates was 1.19 compared with the SMR of 1.15 based on United States rates, although there were wider differences for specific cancer sites such as of the lung. A 'true' SMR is likely somewhere between that computed using New Mexico rates and that computed using United States rates. Fortunately, comparisons did not differ greatly and no changes in study conclusions would have resulted had New Mexico mortality rates been used.

Tobacco use was not known for individual workers. This important carcinogenic exposure causes nearly 90% of all lung cancers, and significant percentages of cancers of the kidney, oral cavity and pharynx and non-malignant respiratory disease (Surgeon General 2004, ACS 2008). Previous studies of workers occupationally exposed to uranium in New Mexico indicate that they tend to be heavy smokers (Samet *et al* 1991), although not the Navajo miners (Samet *et al* 1984a, Roscoe *et al* 1995).

The mortality before 1979 from all causes (SMR 1.24 based on US rates and 1.09 based on NM rates, $n = 185$) was similar to that after 1978 (SMR 1.15). However, SMRs for specific causes of death could not be determined because of the incomplete collection of death certificates in the early years before the National Death Index began. Although death certificates were sought for all 185 deaths occurring before 1979, information on state of death was so incomplete that only 105 (or 56.8%) certificates were obtained. Most of the acquired death certificates were from the state of New Mexico (75 or 71.4%); the other certificates resulted from requests made to 26 other states. Most of these early deaths with known causes were due to car and mine accidents, gun shot wounds and homicides ($n = 40$ or 21.6%). Lung cancer deaths were elevated, i.e., 14 lung cancer deaths occurred in contrast to 9.8 expected computed based on the person-years of observation between date of first employment to January 1, 1979. There was only one death each attributed to kidney cancer and leukaemia and there was no deaths from lymphoma. The consistency of the pre-1979 findings with those for deaths after 1978, i.e., no apparent increase overall and only lung cancer being significantly elevated, indicates that the incomplete cause of death information for these early deaths and their exclusion from study is unlikely to have biased study conclusions with regard to late effects from mining or milling exposures.

4.6. Conclusions

Consistent with prior studies of underground miners in New Mexico, the lung cancer excess among miners in our study is likely due to radon and radon decay products. In contrast, exposure to uranium dust and other mill products had little or no effect upon disease rates, consistent with current understanding (ATSDR 1999, IOM 2001, IARC 2001). The absence of statistically significant excesses of leukaemia is as expected since uranium ore and mill products are not very radioactive and the emission of penetrating gamma radiation is low. This is one of the few studies of both uranium miners and uranium millers within the same workforce and the patterns of cancer clearly differ. Underground uranium miners were exposed to high levels of radon decay products and lung cancer resulted, but no other malignancy. Uranium millers were exposed to uranium dust, ore and mill effluents, but exposure to this heavy metal and mill processes did not increase the number of lung cancers or non-malignant diseases of the respiratory system and urinary tract. Our study adds to the growing body of evidence that uranium ore and uranium compounds are not human carcinogens, and that, in comparison to radon, uranium dust is not a major health hazard.

Acknowledgments

We thank the Homestake Mining Company of California for providing the employee rosters and work history records and for financial support. The authors are also grateful to the NIOSH staff who searched their files and provided copies of employment records from previous studies of uranium millers and miners for a sample of the uranium mill workers from New Mexico. The results presented herein represent the conclusions and opinions solely of the authors. Its publication does not imply endorsement by any of the acknowledged agencies or individuals.

References

Agency for Toxic Substances and Disease Registry (ATSDR) 1999 *Toxicological Profile for Uranium* (Atlanta, GA: US) Department of Health and Human Services, Public Health Service. Available at www.atsdr.cdc.gov/toxprofiles/tp150.html Accessed November 14, 2007

American Cancer Society (ACS) 2008 *Cancer Facts and Figures 2008* (Atlanta, GA: American Cancer Society)

Archer V E, Gillam J D and Wagoner J K 1976 Respiratory disease mortality among uranium miners *Ann. New York Acad. Sci.* **271** 280–93

Auvinen A *et al* 2002 Uranium and other natural radionuclides in drinking water and risk of leukemia: a case-cohort study in Finland *Cancer Causes Control* **13** 825–29

Auvinen A *et al* 2005 Radon and other natural radionuclides in drinking water and risk of stomach cancer: a case-cohort study in Finland *Int. J. Cancer* **114** 109–13

Boice J D Jr, Bigbee W L, Mumma M T and Blot W J 2003b Cancer incidence in municipalities near two former nuclear materials processing facilities in Pennsylvania *Health Phys.* **85** 678–90

Boice J D Jr, Bigbee W L, Mumma M T and Blot W J 2003c Cancer mortality in counties near two former nuclear materials processing facilities in Pennsylvania *Health Phys.* **85** 691–700

Boice J D, Cohen S S, Mumma M T, Dupree Ellis E, Eckerman K F, Leggett R W, Boecker B B, Brill A B and Henderson B E 2006a Mortality among radiation workers at Rocketdyne (Atomics International), 1948–1999 *Radiat. Res.* **166** 98–115

Boice J D, Cohen S S, Mumma M T, Dupree Ellis E, Eckerman K F, Leggett R W, Boecker B B, Brill A B and Henderson B E 2006b Mortality among radiation workers at Rocketdyne (Atomics International), 1948–1999 (erratum) *Radiat. Res.* **166** 566

Boice J D Jr, Mumma M, Schweitzer S and Blot W J 2003a Cancer mortality in populations living near uranium mining and milling activities in Texas, 1950-2001 *J. Radiol. Prot.* **23** 247–62

Boice J D Jr, Mumma M T and Blot W J 2007a Cancer and noncancer mortality in populations living near uranium and vanadium mining and milling operations in Montrose County, Colorado, 1950–2000 *Radiat. Res.* **167** 711–26

Boice J D Jr *et al* 2007b Mortality among residents of Uravan, Colorado who lived near a uranium mill, 1936–1984 *J. Radiol. Prot.* **27** 299–319

Canu I G, Ellis E D and Tirmarche M 2008 Cancer risk in nuclear workers occupationally exposed to uranium-emphasis on internal exposure *Health Phys.* **94** 1–17

Darby S C *et al* 1996 Radon and cancers other than lung cancer in underground miners: a collaborative analysis of 11 studies *J. Natl Cancer Inst.* **87** 378–84

Dupree E A, Watkins J P, Ingle J N, Wallace P W, West C M and Tankersley W G 1995 Uranium dust exposure and lung cancer risk in four uranium processing operations *Epidemiology* **6** 370–5

Eidson A F 1994 The effect of solubility on inhaled uranium compound clearance: a review *Health Phys.* **67** 1–14

Eidson A F and Mewhinney J A 1980 *In vitro* solubility of yellowcake samples from four uranium mills and the implications for bioassay interpretation *Health Phys.* **39** 893–902

Environmental Protection Agency 2007 *EPA Region 6 Superfund Program* Homestake Mining Company, Grants, New Mexico, Site ID: 0600816, EPA Publication Date October 2, 2007. Available at http://www.epa.gov/earth1r6/6sf/pdffiles/0600816.pdf Accessed November 7, 2007

Fry S A 1998 Studies of US radium dial workers: an epidemiological classic *Radiat. Res.* **150** S21–9

Harley N H *et al* 1999 *Depleted Uranium: A Review of The Scientific Literature As It Pertains to Gulf War Illness* (Santa Monica, CA: Rand)

Hornung R W and Meinhardt T J 1987 Quantitative risk assessment of lung cancer in US uranium miners *Health Phys.* **52** 417–30

Howe G R, Chiarelli A M and Lindsay J P 1988 Components and modifiers of the healthy worker effect: evidence from three occupational cohorts and implications for industrial compensation *Am. J. Epidemiol.* **128** 1364–75

Institute of Medicine (IOM) 2001 Committee on the health effects associated with exposures during the Gulf War *Depleted uranium, pyridostigmine bromide, sarin, vaccines* (*Gulf War and health* vol 1) (Washington, DC: National Academy Press)

International Agency for Research on Cancer (IARC) 2001 *Ionizing radiation, 2: some internally deposited radionuclides* (*IARC Monographs On the Evaluation of Carcinogenic Risks to Humans* vol 78) (Lyon: IARC)

Kurttio P *et al* 2002 Renal effects of uranium in drinking water *Environ. Health Perspect.* **110** 337–42

Kurttio P *et al* 2003 Renal effects of uranium in drinking water (erratum) *Environ. Health Perspect.* **111** 632

Kurttio P *et al* 2005 Bone as a possible target of chemical toxicity of natural uranium in drinking water *Environ. Health Perspect.* **113** 68–72

Kurttio P *et al* 2006a Kidney toxicity of ingested uranium from drinking water *Am. J. Kidney Dis.* **47** 972–82

Kurttio P *et al* 2006b Well water radioactivity and risk of cancers of the urinary organs *Environ. Res.* **102** 333–8

Leggett R W 1989 The behavior and chemical toxicity of U in the kidney: a reassessment *Health Phys.* **57** 365–83

Lubin J H *et al* 1995 Lung cancer in radon-exposed miners and estimation of risk from indoor exposure *J. Natl Cancer Inst.* **87** 817–27

Lundin F D Jr, Wagoner J K and Archer V E 1971 Radon daughter exposure and respiratory cancer. Quantitative and temporal aspects *National Institute for Occupational Safety and Health and National Institute of Environmental Health Sciences joint Monograph No. 1* (Washington, DC: US Department of Health, Education, and Welfare, Public Health Service)

Marsh G M *et al* 1998 OCMAP-PLUS: a program for the comprehensive analysis of occupational cohort data *Occup. Environ. Med.* **40** 351–62

Mason T J, Fraumeni J F Jr and McKay F W Jr 1972 Uranium mill tailings and cancer mortality in Colorado *J. Natl Cancer Inst.* **49** 661–4

McDiarmid M A *et al* 2007 Health surveillance of Gulf War I veterans exposed to depleted uranium: updating the cohort *Health Phys.* **93** 60–73

McGeoghegan D and Binks K 2000a The mortality and cancer morbidity experience of workers at the Capenhurst uranium enrichment facility 1946-95 *J. Radiol. Prot.* **20** 381–401

McGeoghegan D and Binks K 2000b The mortality and cancer morbidity experience of workers at the Springfields uranium production facility, 1946-95 *J. Radiol. Prot.* **20** 111–37

McGeoghegan D and Binks K 2006 The mortality and cancer morbidity experience of workers at the Springfields uranium production facility, 1946-95 (erratum) *J. Radiol. Prot.* **26** 455

Monson R R 1986 Observations on the healthy worker effect *J. Occup. Med.* **28** 425–33

Morgan M V and Samet J M 1986 Radon daughter exposures of New Mexico U miners, 1967–1982 *Health Phys.* **50** 656–62

National Council on Radiation Protection and Measurements (NCRP) 1993 Radiation protection in the mineral extraction industry *NCRP Report No. 118* (Bethesda, MD: National Council on Radiation Protection and Measurements)

National Research Council (NRC) 1999 *Committee on the Biological Effects of Ionizing Radiations. Radon (BEIR VI)* (Washington, DC: National Academy Press)

National Research Council (NRC) 2006 *BEIR VII: Health Risks From Exposure to Low Levels of Ionizing Radiation* (Washington, DC: National Academy Press)

Pinkerton L E, Bloom T F, Hein M J and Ward E M 2004 Mortality among a cohort of uranium mill workers: an update *Occup. Environ. Med.* **61** 57–64

Priest N D 2001 Toxicity of depleted uranium *Lancet* **357** 244–6

Roscoe R J 1997 An update of mortality from all causes among white uranium miners from the Colorado plateau study group *Am. J. Ind. Med.* **31** 211–22

Roscoe R J, Deddens J A, Salvan A and Schnorr T M 1995 Mortality among Navajo uranium miners *Am. J. Public Health* **85** 535–40

Royal Society 2001 *The Health Hazards of Depleted Uranium Munitions, Part I* (London: Royal Society)

Russell J J, Kathren R L and Dietert S E 1996 A histological kidney study of uranium and non-uranium workers *Health Phys.* **70** 466–72

Samet J M, Kutvirt D M, Waxweiler R J and Key C R 1984a Uranium mining and lung cancer in Navajo men *N. Engl. J. Med.* **310** 1481–4

Samet J M, Morgan M V, Buechley R W and Key C R 1983 Studies of Grants, New Mexico, Uranium miners: status as of December, 1982 Epidemiology applied to health physics *Proc. 16th Midyear Topical Mtg of the Health Physics Society (Albuquerque, New Mexico, Jan. 1983)* pp 444–54

Samet J M *et al* 1984b Prevalence survey of respiratory abnormalities in New Mexico uranium miners *Health Phys.* **46** 361–70

Samet J M *et al* 1991 Lung cancer mortality and exposure to radon progeny in a cohort of New Mexico underground uranium miners *Health Phys.* **61** 745–52

Surgeon General 2004 *The Health Consequences of Smoking: A Report of the Surgeon General* (Rockville, MD: Department of Health and Human Services)

Taylor D M and Taylor S K 1997 Environmental uranium and human health *Rev. Environ. Health* **12** 147–57

Thun M J *et al* 1985 Renal toxicity in uranium mill workers *Scand J. Work Environ. Health* **11** 83–90

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2000 *UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes Sources and effects of ionizing radiation. Vol I: Sources, Vol II: Effects E.00.IX.4* (New York: United Nations)

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2008 *UNSCEAR 2006 Report* Annex A *Epidmiological Studies of Radiation and Cancer* (New York: United Nations)

Wagoner J K, Archer V E and Gillam J D 1975 Mortality of American Indian uranium miners *Proc. 11th Int. Cancer Congr.* vol 3, ed P Bucalossi, U Veronesi and N Cascinelli (Amsterdam: Excerpta Medica International Congress Services No. 351) pp 102–7

Wagoner J K *et al* 1965 Radiation as the cause of lung cancer among uranium miners *N. Engl. J. Med.* **273** 181–8

Waxweiler R J *et al* 1983 Mortality patterns among a retrospective cohort of uranium mill workers, epidemiology applied to health physics *Proc. 16th Midyear Topical Meeting of the Health Physics Society (Albuquerque, New Mexico, Jan. 1983)* pp 428–35

Whittemore A S and McMillan A 1983 Lung cancer mortality among US uranium miners: a reappraisal *J. Natl Cancer Inst.* **71** 489–99

Appendix 24

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

August 6, 1999

MEMORANDUM TO: Docket File 40-8584

FROM: Elaine Brummett, Project Manager
Uranium Recovery and
Low Level Waste Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

E. Brummett

SUBJECT: ENVIRONMENTAL ASSESSMENT REGARDING LICENSE RENEWAL AND THE RECLAMATION DESIGN FOR THE KENNECOTT URANIUM COMPANY'S SWEETWATER URANIUM MILL SITE IN WYOMING

The U.S. Nuclear Regulatory Commission (NRC) is considering a request to renew NRC Source Material License SUA-1350 to authorize the licensee, Kennecott Uranium Company (KUC), to resume commercial milling operations at the Sweetwater facility as proposed in its letter of June 11, 1997, and according to the Operations Plan submitted September 18, 1997, as amended. KUC also requested approval to reclaim the mill facility, existing and proposed new tailings impoundments, and the proposed evaporation ponds, according to the 1997 Reclamation Plan, as amended. The Sweetwater uranium mill site is located in Sweetwater County, Wyoming.

An Environmental Assessment (EA) was performed by the NRC staff in support of its review of KUC's license renewal for operation and the amendment request for the reclamation plan, in accordance with the requirements of 10 CFR Part 51. The conclusion of the EA is a Finding of No Significant Impact for the proposed licensing actions. The EA was provided to the docket file on June 25, 1999. After reviewing additional information, a slight revision was made to Sections 4.4.2 and 8.0 with no change to the conclusion. The revised version is provided as an attachment to this memorandum to be placed in the licensee's docket file.

Docket No. 40-8584
License No. SUA-1350

Attachment: As stated

ENVIRONMENTAL ASSESSMENT FOR SOURCE MATERIAL LICENSE SUA-1350, RENEWAL FOR OPERATIONS AND AMENDMENT FOR THE RECLAMATION PLAN

(Revision 1)

SWEETWATER URANIUM COMPANY
SWEETWATER URANIUM MILL
SWEETWATER COUNTY, WYOMING

JULY 1999

DOCKET NO. 40-8584

U.S. Nuclear Regulatory Commission
Office of Nuclear Material Safety
and Safeguards
Division of Waste Management

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1.0 INTRODUCTION

With the 1999 renewal of license SUA-1350 for the restart of the Sweetwater Uranium Mill, the U.S. Nuclear Regulatory Commission (NRC) will be using the Performance-Based License Condition (PBLC) format. This license format change was requested by the Kennecott Uranium Company (KUC) by letter dated June 11, 1997, and documented by proposed draft license conditions submitted February 3, 1999. Under Performance-Based Licensing, the licensee has the burden of ensuring the proper implementation of the PBLCs. The licensee may:

- Make changes in the facility or process, as presented in the application,
- Make changes in the procedures presented in the application, or
- Conduct tests or experiments not presented in the application, without prior NRC approval, if the licensee ensures that the following conditions are met:

    (1) The change, test, or experiment does not conflict with any requirement specifically stated in this license (excluding material referenced in the PBLC), or impair the licensee's ability to meet all applicable NRC regulations;

    (2) There is no degradation in the essential safety or environmental commitments in the license application, or provided by the approved reclamation plan; and

    (3) The change, test, or experiment is consistent with the NRC's conclusions regarding actions analyzed and selected in the Environmental Assessment (EA).

Otherwise, the licensee is required to submit an application for a license amendment from the NRC. The licensee's determinations regarding whether the above conditions are satisfied will be made by a Safety and Environmental Review Panel (SERP).

The SERP shall consist of a minimum of three individuals. One member of the SERP shall have expertise in management and shall be responsible for managerial and financial approval changes; one member shall have expertise in operations and/or construction and shall have expertise in implementation of any changes; and, one member shall be the corporate radiation safety officer or equivalent. Additional members may be included in the SERP, as appropriate, to address technical aspects in several areas, such as health physics, ground water hydrology, surface water hydrology, specific earth sciences, and others. Temporary members, or permanent members other than the three identified above, may be consultants.

The licensee shall maintain records until license termination of any changes made pursuant to the PBLC. These records shall include written safety and environmental evaluations, made by the SERP, that provide the basis for determining that the change complies with the requirements referred to in the above conditions. The licensee shall furnish an annual report to the NRC that describes such changes, tests, or experiments, including a summary of the safety and environmental evaluation of each. In addition, the licensee shall annually submit any pages of its license application that have been revised to reflect changes made under this condition.

The licensee submitted its standard operating procedure (SOP) for operation of the SERP on February 25, 1999. The NRC staff reviewed this document and determined that the SERP should operate as the NRC intended.

NRC's inspection function remains unchanged with the administration of Performance-Based Licensing. Operational changes, regulatory commitments, and record keeping requirements implemented through the PBLC are subject to NRC inspection and possible enforcement actions.

To support the decision-making process concerning the request for resumption of mill operation and approval of the reclamation plan (stabilization of impoundments and decommissioning of land and buildings), the NRC staff has prepared this Environmental Assessment (EA) to ascertain the mitigation efforts and likely impacts to the environment from the proposed activities. The staff also has prepared a Safety Evaluation Report (SER) to document the mitigation of health impacts related to the proposed activities, and a Technical Evaluation Report (TER) to document the technical review of the reclamation plan.

1.1 Background Information

The Sweetwater Uranium Project (Site), as defined by the proposed NRC bonded area (Figure 7, KUC, 1998f), covers approximately 1432 acres, consisting of a mill, ancillary buildings, existing tailings impoundment, and the area of proposed impoundments, evaporation ponds, and diversion channels. Bordering the Site is an overburden soil pile and an uranium ore pit. The Site is operated by KUC under NRC Source Materials License SUA-1350. The license was obtained in February 1979, to permit processing of uranium ore. The mill was constructed in 1979 and 1980, and processed ore mined from an adjacent open pit from February 1981 through April 1983. The 60-acre below-grade impoundment was partially filled with tailings.

The mill has been in standby status since cessation of operation, and staff were retained to maintain the facility and perform environmental monitoring. Current license conditions authorize operation of an ion exchange uranium recovery facility and disposal of a limited amount of byproduct material originating from off-site, but ore may not be processed.

The licensee requested restart of the mill by letter dated March 9, 1993, with submittal of the Radiation Safety Program and Standard Operating Procedures (SOPs) revised for operation of the mill. On August 4, 1993, the licensee submitted the "Conceptual Design - Tailings Management Study." To also support the restart of mill operations, KUC submitted: 1) Revised Radiation Safety Program (KUC, 1994a) that was approved April 18, 1994; 2) Revised Environmental Monitoring Manual (KUC, 1994b); and 3) Revised Environmental Report (ER) (KUC, 1994c), subsequently modified based on comments from NRC staff, including addenda on aquifer information (KUC, 1995e), Background Ground Water Quality and Detection Standards (KUC, 1996a) approved May 28, 1998; and Regional Seismicity (KUC, 1996b) approved February 12, 1997. The environmental monitoring issues were closed with submittal of revisions to Section 5 of Volume VII of the Final Design (KUC 1998e,g).

The licensee also provided a Reclamation Plan for the existing impoundment, future impoundments, and for the mill facility, a final design for construction of up to 6 tailings impoundments and up to 10 evaporation ponds, and a Facility Operations Plan in 1997 and

1998. Based primarily on NRC staff comments, KUC revised and clarified these submittals (see Section 12 for details). The NRC staff has reviewed these documents and is now completing the written evaluation to accompany the license amendment for restart of the mill and eventual reclamation and decommissioning of the Site.

The actual resumption of mill operations would be conditional on: 1) a 90-day notice to NRC; 2) completion of the pre-operational inspection; and 3) resolution of any associated safety issues. The inspection will confirm that operating procedures are in place, the facility was constructed as designed, pre-operational testing was completed, and that approved radiation safety and environmental monitoring programs are in place. Due to the recent low price for uranium, the mill is not expected to resume operations until the year 2000 or later.

1.2 Proposed Action

KUC, operator and manager of the Sweetwater Site for the Green Mountain Mining Venture (GMMV), is proposing to process uranium ore mined from a deposit owned by the GMMV in Green Mountain (the Jackpot Mine), and approximately 62.7 km (39 miles) north of the Site. The proposed mill operation could last for 20 years and the final design contains plans to construct up to 6 new tailings impoundments and 10 evaporation ponds. Approval is being considered for construction of one new impoundment and up to eight evaporation ponds at this time. The licensee would request approval of the other structures, if warranted by extended mill operation. The new impoundment(s) is to cover approximately 40 acres. The contiguous evaporation ponds will cover 10 acres each. The existing below-grade tailings impoundment will be reclaimed according to the approved reclamation plan, but if the impoundment is reused during mill operation, additional design justification must be provided.

The milling operation involves grinding uranium ore, dissolving the uranium, and separating uranium from the solution and tailings (sandy residue/waste). The mill circuit (see Section 3 for details) is similar to the original 1981 operation, except: 1) some process water is recycled back into the mill circuit; 2) the ore grade is higher; and 3) the mine is farther away. The impact of these changes were assessed as discussed below under ground-water impacts, environmental monitoring, and transportation accidents, respectively. The area of the licensed Site will increase by approximately 30 percent with the proposed design (Figure 5-9 in Volume VII of Final Design, KUC, 1998g), and this impact was also considered.

Milling operations are expected to begin when it is economically feasible. The mill will operate 24 hours per day, 365 days per year, over its expected life of 20 years. Mill throughput is expected to range from 2,500 to 3,500 tons (dry weight) of ore per day, with an average rate of 3,000 tons per day. The mill is expected to yield about 1,859,748 kg (4,100,000 pounds) of product (yellowcake) annually, and the licensee will be limited to this amount of yellowcake by license condition.

The reclamation of the impoundments involves placing a 6-m (20 to 21-foot) thick soil cover over the tailings followed by riprap (rock) for erosion protection. Decommissioning the mill and land would include demolition of buildings and disposal of contaminated debris, equipment, and soil in the impoundment (see Section 6 for details).

1.3 Review Scope

1.3.1 Federal and State Authorities

NRC source material licenses are issued under Title 10, Code of Federal Regulations, Part 40 (10 CFR Part 40). As stated in 10 CFR 40.3, "A person subject to the regulations in this part may not receive title to, own, receive, possess, use, transfer, provide for long-term care, deliver or dispose of byproduct material or residual radioactive material, as defined in this part, or any source material after removal from its place of deposit in nature, unless authorized in a specific or general license issued by the Commission ...." Source material is defined under 10 CFR 40.4 as (1) uranium or thorium, or any combination thereof, in any physical or chemical form; or (2) ores which contain by weight 0.05 percent or more of uranium, thorium, or any combination thereof. In addition, the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA), as amended, requires persons who conduct uranium source material operations to obtain a byproduct material license to own, use, or possess tailings and wastes generated by the operations (including above-ground wastes from in situ operations).

This EA has been prepared under 10 CFR Part 51, "Licensing and Regulatory Policy and Procedures for Environmental Protection," which implements NRC's environmental protection program under the National Environmental Policy Act (NEPA) of 1969. In accordance with 10 CFR Part 51, an EA serves to: (a) briefly provide sufficient evidence and analysis for determining whether to prepare an environmental impact statement (EIS) or a finding of no significant impact (FONSI); (b) facilitate preparation of an EIS when one is necessary; and (c) aid the NRC's compliance with NEPA when an EIS is not necessary.

Impacts from the commercial scale operation of the site were previously evaluated in the Final Environmental Statement (FES) (NRC, 1978). Should the NRC issue a FONSI based on this EA, a renewed commercial source material license would be issued to KUC.

Other Federal agencies are involved with certain aspects of the Site activities. For example, KUC consulted the U.S. Environmental Protection Agency (EPA) concerning modification of an existing source (tailings impoundment) and construction of a new source under authorization of 40 CFR Part 61. Also, the State of Wyoming Department of Environmental Quality (DEQ) administers and implements the State's environmental protection rules and regulations. The licensee has committed to comply with all applicable Federal regulations, as well as State regulations.

1.3.2 Basis of NRC Review

The NRC, Division of Waste Management, staff has assessed the environmental impacts associated with the renewal of KUC's license for commercial operation of the mill and reclamation of the facility, as proposed, and documented the results of the assessment in this report. The staff performed this appraisal in accordance with the requirements of 10 CFR Part 51.

In conducting its assessment, the staff considered the following:

- Information contained in the previous environmental evaluations of the Sweetwater project;

- Information contained in KUC's amended renewal application, and supplementary information;
- Information contained in land use and environmental monitoring reports;
- Personal communications with staff for the Sweetwater facility, State of Wyoming, and Federal agencies (see Section 9); and
- Information derived from NRC staff site visits and inspections of the Site.

2.0 SITE DESCRIPTION

2.1 Location

The Sweetwater Uranium Site is located in Sweetwater County, Wyoming, in the Red Desert, approximately 68 km (42 miles) northwest of Rawlins, WY. Site access is provided by the paved Minerals Exploration Road connecting Highway 287 with the Wamsutter - Jeffery City road (Figure 2.1).

The facility is constructed on privately owned land. The land consists of two tracts totaling about 1975 acres. The Site covers more than 1000 acres and includes an open mine pit, overburden pile, mill, associated buildings, and a tailings impoundment (Figure 2.2). Additional acreage related to the project is held by a combination of unpatented lode claims and mill sites totaling 822 unpatented mill sites and 62 unpatented mining claims.

2.2 Climate and Weather

The climate of the Site vicinity is determined by its location in a high elevation desert basin, with the following general features: abundant sunshine, little rainfall occurring primarily in the warmer months, moderate to high wind speeds, and a large diurnal variation in temperature.

The Red Desert is the lowest region of the Continental Divide and provides a convenient passageway for cold arctic air masses and so cold air tends to collect in the bottom of the basin, affecting temperature and wind patterns. Winters are relatively long and cold, and summers are relatively short. The average frost-free season in Rawlins is 106 days. Winds also display diurnal variability with calm conditions prevailing near sunrise and wind speeds peaking in mid-afternoon.

Severe weather potential is relatively low in the Red Desert, with the exception of windstorms and severe cold. The potential for thunderstorm-associated severe weather, such as tornadoes, hail, and heavy rains, is lower in the Red Desert than in the eastern third of Wyoming because the Red Desert has low atmospheric moisture. Average hourly wind speeds of 64.4 km/hr (40 mph) or greater have been reported at the site every month except July. The strongest average hourly wind speed reported at the site from 1980 through 1993 was 90 km/hr (56 mph) in January 1987.

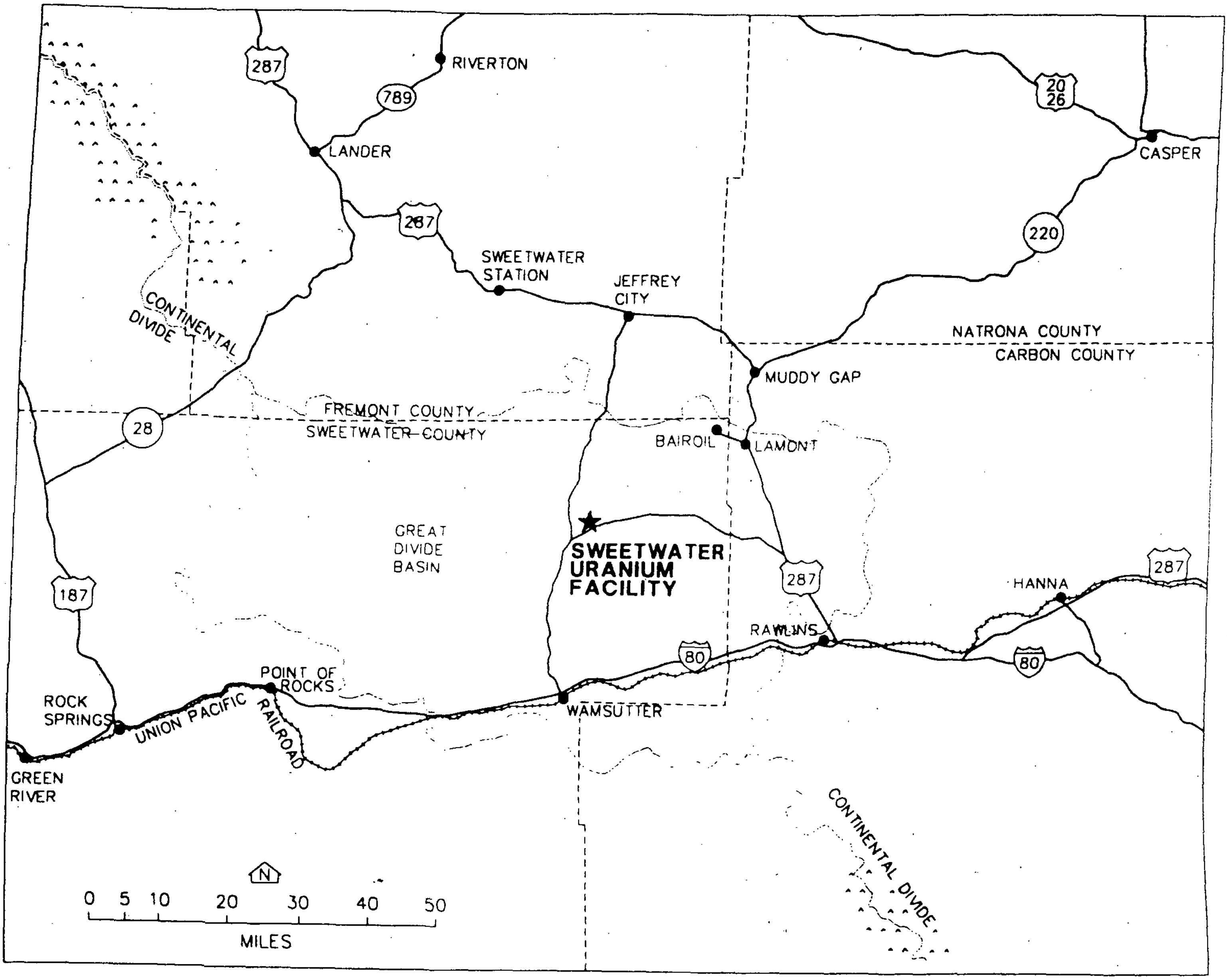

Figure 2.1
Location of the Sweetwater Uranium Facility

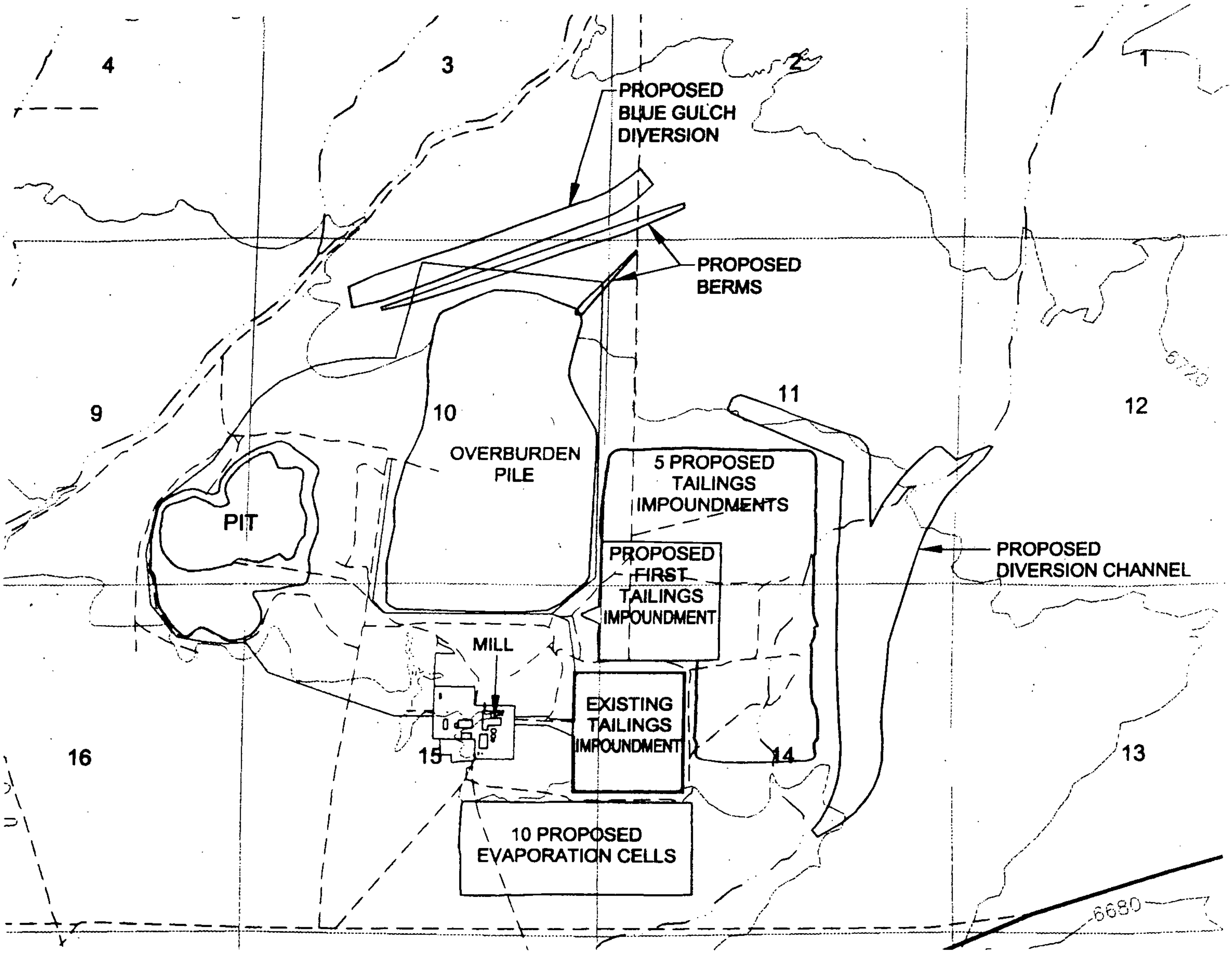

Figure 2.2
Sweetwater Facility and Proposed Impoundment and Ponds

Thunderstorms are common in the spring and summer in Wyoming in general. As a rule, however, related precipitation is light in the site area, typically a few hundredths of an inch. Heavy local storms occur which can produce 2.5 to 5.1 cm (1 or 2 inches) of rainfall. The 6-hour probable maximum precipitation (PMP) at the site is 26.7 cm (10.5 inches), according to the U.S. Department of Commerce's Hydrometeorological Report No. 55-A (1988).

2.3 Geology

2.3.1 Regional and Local Geology

The Site is located in south-central Wyoming in the Red Desert area of the Great Divide Basin. The present configuration of the Great Divide Basin is a result of tectonic activity associated with the Laramide orogeny (Late Cretaceous). In Early Cenozoic time, erosion of the Sweetwater, Rawlins, Rock Springs, and Wind River Uplifts supplied sediments to the basin. The coarser clastics came from the north and east of the basin as movement of the uplifts continued until Middle Cenozoic time. In the late Middle Cenozoic, volcanic debris consisting of tufts and tufaceous material was introduced into the basin. Subsequent regional uplift caused erosion and exhumation of the basin, which defined its present form.

Deposits in the basin consist of conglomerates, sandstones, siltstones, mudstones, and lignitic and subbituminous coals. All of these rocks are of continental origin and were deposited under fluvial, lacustrine, and paludal conditions. The Tertiary rocks have been divided into six formations, the oldest being the Fort Union Formation of Paleocene age that is only known from drilling records. The Fort Union is unconformably overlain by interfingering sediments of Eocene age of the Green River, Wasatch, and Battle Spring Formations. These beds are conformably overlain by the Eocene Bridger Formation, which in turn is unconformably overlain by the Brown's Park Formation of Oligocene to Miocene age. Holocene alluvium consisting of sands, silts, and gravels covers much of the present surface.

The uranium deposits in the area are contained in the Battle Spring Formation, which outcrops partially in the Site area. It consists of interfingered beds of arkosic sandstone, siltstone, and mudstone. The sandstones are generally fine-to-coarse grained, poorly sorted, and slightly clayey. These sandstones often grade into interchannel deposits of siltstone and mudstone. The uranium contained in the Battle Spring Formation was previously mined and milled at the Sweetwater site, however, the current application indicates that the mill will process ore from the Jackpot mine in near-by Green Mountain.

The surface at the Site is covered by thin Holocene alluvium derived from the immediate underlying Battle Spring Formation. The sandstones in this formation generally form lenses or channels that are enclosed by finer clastics. Beds of impermeable, finer clastics are found throughout the stratigraphic interval underlying the mill and tailings impoundment. No fractures, joint patterns or faults have been observed in the vicinity of the tailings impoundment. Results of bores drilled in 1976 and 1982 showed the upper 1.2 to 3.0 m (4 to 10 feet) of soil to contain silty fine sands of the topsoil series. Below this, the soils grade transitionally to poorly-to-moderately-indurated siltstones and sandstones.

2.3.2 Seismicity

The small amount of historical data and the fact that recorded events report only moderate intensities can be at least partially attributed to the sparse population in the area. However, in recent years, a network of seismic recording stations has been established across most of the western United States. This network affords a way of recording and locating seismic activity instrumentally, without relying upon the subjective reports of the general populace. Earthquakes with magnitudes too small for humans to detect are easily recorded on a seismograph, and the frequency of such small earthquakes may indicate the relative seismicity of an area, even within a relatively short period. Although the network has been in existence since about 1960, the low frequency and low magnitude of the earthquakes recorded instrumentally in Wyoming support the historical belief that Wyoming is a relatively quiescent seismic area.

Horizontal accelerations at the site corresponding to two conceptual level maximum credible earthquake magnitudes were determined by the licensee (KUC, 1993b). For the Green Mountain segment of the South Granite Mountains Fault, at a distance of 40 km (24.8 miles) and a magnitude of 6.75, the horizontal acceleration at the site is 0.14 g. For the random earthquake, at a distance of 24 km (14.9 miles) and a magnitude of 6.5, the horizontal acceleration at the site is 0.18 g. The higher of these two values, 0.18 g was used in the conceptual design of the tailings impoundments.

In the "Revised Addendum to the Revised Environmental Report -Regional Seismicity" (KUC, 1996b), KUC revised the methodology to assume that a magnitude 6.25 earthquake occurs 15 km (9.3 miles) from the Site, and took the median ground motion from the Campbell attenuation model, yielding a value of 0.15 g. The Chicken Springs fault was also analyzed. The staff determined that the estimated peak ground acceleration (PGA) of 0.22 g for the Site, from a magnitude 6.5 event 49 km (30.5 miles) away on the Chicken Springs fault system, conservatively estimates the seismic hazard.

2.4 Water Resources

2.4.1 Surface Water

The Great Divide Basin is an internally drained basin defined by a bifurcation of the Continental Divide. The Site lies in the east-central portion of this basin in the ephemeral Battle Spring Draw watershed. The Battle Spring Draw watershed empties into Battle Spring Flat, a playa located approximately 9.7 km (6 miles) southwest of the site.

There is very little surface water in the Great Divide Basin. Some shallow perennial lakes are located a few miles south of the Site in Chain Lakes Flat, which is near the center of the basin. Heavy precipitation can cause some surface flow in draws; however, these flows are infrequent, since average annual precipitation is only about 12.7 to 15.2 cm (5 to 6 inches). No surface drainage leaves the basin.

2.4.2 Ground Water

Hydrogeologic units that occur beneath the Site and vicinity include the following: recent alluvial, windblown, and lake deposits; the Eocene Battle Spring Formation; the Paleocene Fort

Union Formation; and the Cretaceous Lance Formation. These units are classified as aquifers and depending on their hydrologic characteristics, yield ground water to wells and springs. The Battle Spring and Wasatch Formations are the two most important aquifers in the Great Divide Basin.

The Site is located within a closed ground-water system. The low point of this ground-water basin lies within the 1981-m (6500-foot) contour located south and southwest of the site. Ground water moves toward the center of the basin and discharge occurs principally in the playa lakes to the south (Chain Lakes) and southwest (Battle Spring Flat) of the site. Since the Basin is also closed topographically, the discharged water is ponded, and most of this water is lost to evaporation. In addition, there is some discharge from springs near Battle Spring and Chain Lakes Flats. This water is also subject to evaporation.

The Battle Spring Aquifer is recharged mainly by infiltration of precipitation in its outcrop area near the perimeter of the Great Divide Basin. Precipitation may also seep into the aquifer in smaller amounts throughout the basin, especially in areas where sand dunes directly overlie the surface.

Regional wells are completed in either the Battle Spring or Wasatch Formations. The Battle Spring Formation underlies the site and interfingers with the Wasatch Formation southwest of the site. Uses of these aquifers include potable water supplies for industry, stock watering, domestic, and miscellaneous. All non-Kennecott water uses within a 16.1-km (10-mile) radius of the site are for stock watering purposes. These are owned by the Bureau of Land Management (BLM), the State of Wyoming, and private parties. There are no non-Kennecott domestic or potable water supplies down gradient of the Site because the 16.1-km (10-mile) radius circle encompasses the hydrologic low point of the basin, Battle Spring Flat.

2.5 Topography

The Site is located in the east-central portion of the Great Divide Basin, in an area north of the playa and alkali lakes that occupy the topographically lowest part of the basin. The relatively flat surface of the Site is broken by a few low ridges.

This basin is part of the Wyoming Basin physiographic province as defined by Fenneman (1931). The floor of the Wyoming Basin is a plateau marked by elongated ridges and isolated mountains. The Great Divide Basin is an internally drained basin bounded on most sides by major structural uplifts - the Sweetwater Uplift to the north and northeast, the Rawlins Uplift to the east and southeast, the Rock Springs Uplift to the west and the Wind River Uplift to the northwest. To the south, the Great Divide Basin is separated from the Washakie Basin by Laney Rim and Cathedral Bluffs. Elevations in the immediate project area range from 1981 to 2041m (6500 to 6700 feet) above mean sea level. The surface slope is less than one degree - about 12.2 m (40 feet) per mile.

2.6 Demography

The Sweetwater mill is located in Sweetwater County, approximately 68 km (42 miles) northwest of Rawlins, the community most likely to experience socioeconomic impacts from recommenced mill operation. Rawlins is located in Carbon County. Secondarily, Jeffrey City, in Fremont County, Sinclair, in Carbon County, and Wamsutter and Bairoil in Sweetwater County may be affected by mill operation. Bairoil is the nearest community to the Site, located approximately 36 km (22 air miles) northeast of the Site. The nearest resident is located 28 km (17 air miles) east of the Site. The 1990 census data for communities within 80 km (50 miles) of the site are: Rawlins 9380, Sinclair 500, Wamsutter 240, and Bairoil 228. These four communities are the only ones within 80 km (50 miles) of the site for which census data were provided.

2.7 Land Use

The region where the Site lies is primarily used for livestock grazing, dispersed recreation, wildlife range, oil and gas production, and mineral exploration. The rangeland surrounding the Site supports cattle, sheep, horses, and antelope. The area's climate is harsh for agriculture, with low precipitation and a short growing season. The growing season for Rawlins is approximately 100 days. Soil and climate conditions are not conducive to crop production and will most likely prevent the area from being used for any agricultural purpose except rangeland.

The primary recreational pursuits in the Great Divide Basin consist of hunting and sightseeing. Antelope, sage grouse and, to a lesser extent, mule deer are hunted in the Red Desert area. No numbers are available for area sightseers, but the remoteness of the area from large population centers limits these numbers.

3.0 PROCESS DESCRIPTION

3.1 Mill Circuit

A flow diagram of the generalized Sweetwater mill circuit is provided in this EA as Figure 3.1. Details of the circuit are provided in the figures of Appendix A to Volume VII of the Final Design (KUC, 1997f). During operations, uranium ore and other feed material are delivered to the Site by truck and placed on to the ore pad. Preliminary analyses with a beta scanner or similar type probe will determine the uranium oxide content. Front-end loaders then haul stockpiled ore to the mill grizzly for size sorting. The material that passes through the stationary grizzly will be transported to the semi-autogenous grinding (SAG) mill. The resultant slurry is pumped to a cyclone circuit to separate larger pieces that are returned to the SAG mill for further grinding. The discharge from the cyclone circuit is then pumped to the leach circuit, where the uranium materials are dissolved through the addition of a solution of sulfuric acid and sodium chlorate and steam heat. The discharge from the leach circuit is pumped to a series of six countercurrent decantation thickeners where the uranium-rich (pregnant) acid solution will be separated from the barren tailings in multiple stage thickeners. The tailings are pumped to a double-lined storage impoundment while the uranium-rich solution is filtered and then pumped to a solvent extraction system. The solution passes through a series of stages in which the dissolved uranium is transferred from the aqueous phase to an organic or solvent phase. The uranium is removed from the organic phase by ammonium sulfate and then precipitated by the injection of ammonia gas. The final precipitate, commonly called "yellowcake" (U_30_8), is washed, calcined (dried under high heat), and packed into 55-gallon steel drums. The finished product will then be shipped to a uranium hexafluoride conversion plant and eventually turned into fuel for nuclear power plants.

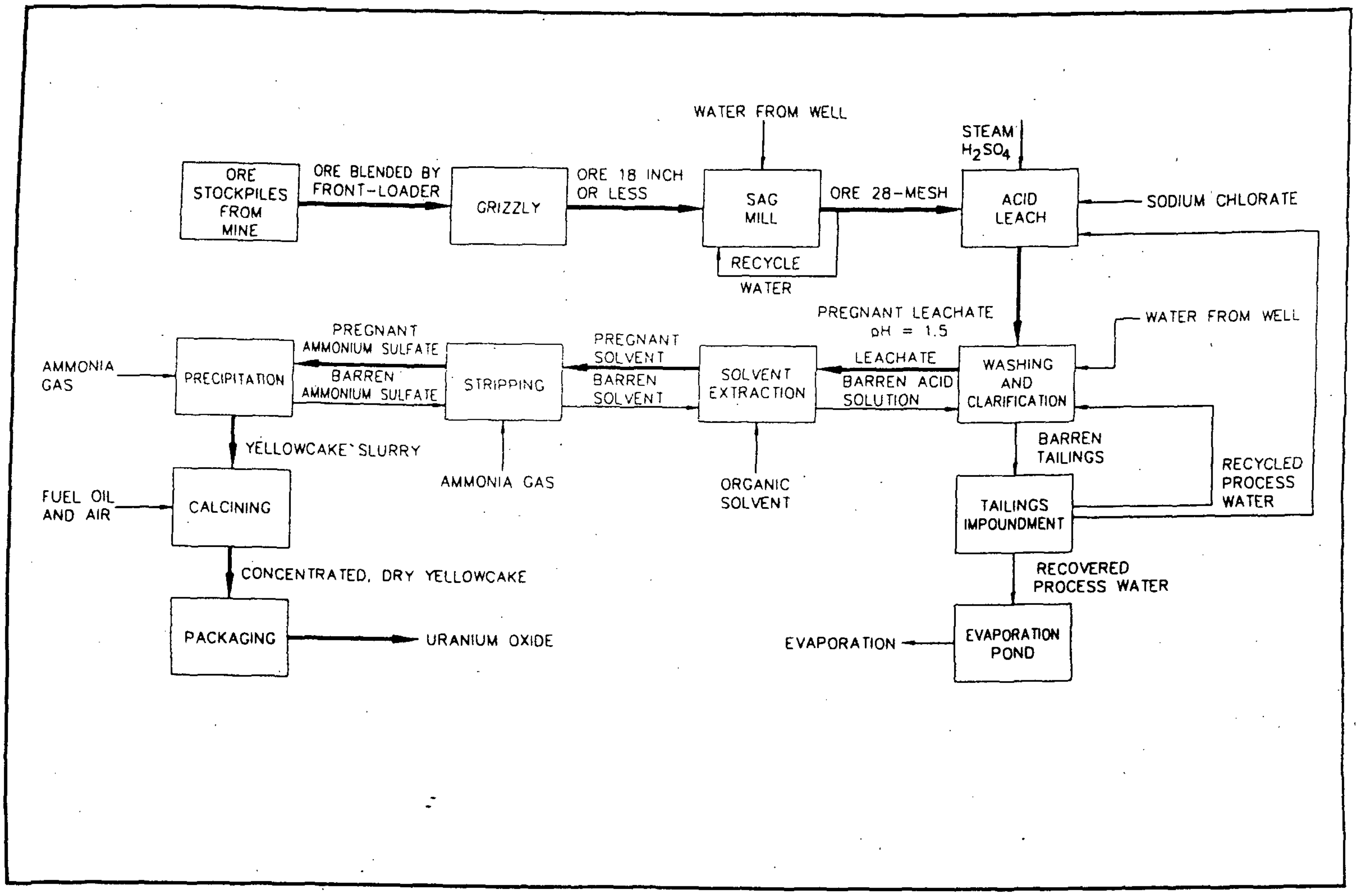

Figure 3.1
Generalized Circuit for the Sweetwater Mill

3.2 Mill Waste Disposal

Mill tailings are deposited within a tailings cell/impoundment located at the facility. The tailings, along with liquid waste, are slurried by pipeline to the impoundment system, which consists of a series of synthetically lined cells that are designed for phase construction and reclamation. The 300-acre impoundment area may contain up to six cells to provide the required adequate disposal capacity for the estimated 20-year project life. The impoundment area will be fenced to keep game animals and livestock out of the tailings impoundment.

Each of the tailings impoundments is designed to accept approximately 3,000 tons of waste per day, but only two impoundments should be in operation at a time. Each new cell will be constructed by excavating 15.2 m (50 feet) deep, and will be surrounded by 15.2-m (50-feet) high engineered embankments. Double liners with clay and composite layers, along with attendant leak-detection/recovery systems will be constructed to retard and collect seepage. A process water recovery system will be constructed on the cell bottom and on the embankment face opposite the discharge lines, at the location of the decant pool. Drains along the cell bottom and side will reduce the seepage potential. Water from the process water recovery system or the surface pump will be sent to a geomembrane-lined surge pond constructed on re-graded tailings in the existing cell for recirculating to the mill and/or evaporation. Discharge into the tailings impoundment will occur from a common center cell wall which will create a gently sloped tailings surface and a drainage divide. As each cell is filled, an additional cell will be constructed. The cover surface and side slope rock is designed to provide erosion protection for the Probable Maximum Precipitation event.

Prior to construction of any new tailings impoundments, the topsoil will be removed from the area and stockpiled for use in future reclamation activities. A diversion ditch for Battle Spring Draw will be constructed around the east edge of the impoundment area. Additionally, a new diversion ditch, lined with riprap, will be constructed to divert storm waters when a new cell is built.

KUC has committed, in its license renewal application, to returning all liquid effluents from the mill process buildings, with the exception of sanitary wastes, to the mill circuit or discharging them to the tailings impoundment. This is currently required by license condition and will continue to be so required. Non-salvageable solid wastes (e.g., filters, pumps) contaminated in the mill process, and which cannot be decontaminated below NRC unrestricted release limits, will be placed in the tailings impoundment. KUC states that void space in such material will be minimized prior to its emplacement in the impoundment.

3.3 Inspections of the Tailings Disposal System

As specified in the current license, a weekly inspection of the tailings shall be performed. During operation of the mill, visual inspections of the tailings system will be conducted during each shift by a qualified engineer or scientist (Appendix F, Volume VII, of the Final Design). Also, instrumentation installed to detect ruptures of tailings discharge and solution return lines will be used during tailings disposal operations to alert staff of problems.

4.0 EVALUATION OF ENVIRONMENTAL IMPACTS

4.1 Introduction

Operation of the mill will directly use about 640 acres of land for mill buildings, one tailings impoundment, and evaporation ponds. During operation and reclamation, effluent releases (e.g. fugitive dust, hydrocarbons, radionuclides) will be maintained at levels as low as is reasonably achievable (ALARA). Tailings, which are produced in large quantities and contained in double-lined tailings impoundments, will be reclaimed at the end of the project, in accordance with the NRC-approved reclamation plan.

Mill operations and reclamation should not have a significant impact on air and water quality. Environmental impacts estimated before the original construction of the facility were assessed (NRC, 1978) and impacts during previous operations (1981-1983) were documented in environmental reports at that time, and in the 1984 license renewal application (MEC, 1984). For example, the licensee indicated that particulate concentrations during operation are maintained below permissible standards and ALARA through prevention, entrapment, and collection. The dust collecting, venting, and fume control systems in the plant are designed to control all possible emissions when the plant is operating. In addition, the cover letter of the 1984 application indicated that environmental and economic impacts of the mining activities are unchanged from those described in the Environmental Report prepared before mill operation.

Environmental monitoring on and near the Site, as required by proposed license conditions 11.5 and 11.6, would alert the licensee to increased radiation levels so that corrective actions could be taken, as required.

4.2 Air Quality Impacts

During operation of the mill, gaseous emissions from process chemicals, fugitive dust, and radon emissions from the ore pad will occur. Gaseous emissions are expected to be mainly from the operation of heavy-duty equipment engine exhaust. The control systems used to minimize emission from the mill are incorporated into the design of the mill process and equipment. The air and gases from vessels will be passed through scrubbers to remove mists, gaseous pollutants, and dust. Gaseous effluent and dust will be discharged from high stacks in order to promote rapid dilution and dispersion.

Fugitive dust is expected to be generated by construction and earth-moving equipment during construction and covering (reclamation) of the tailings impoundment, and from soil cleanup, and by wind erosion from developed areas. Dust and radon levels will be controlled through water spraying, while the other emissions should not exceed regulatory standards. Estimates of airborne radionuclide releases caused by the resumption of mill operations and compliance with regulations were demonstrated by the licensee with the dose modeling codes MILDOS-AREA and COMPLY (Section 5.2.3, Volume VII of Final Design, KUC, 1997f).

4.3 Historical and Cultural Resources

The proposed milling operation and reclamation activities at the Site will affect additional acreage beyond that studied in 1976 for historical and cultural resources, because of the additional area to be used for construction of tailings impoundments, evaporation ponds, and a diversion channel. Therefore, an archaeological study was undertaken in 1993 to evaluate impacts on historic and prehistoric sites on the area not studied in 1976. The new study area totaled 880 acres. Additionally, 640 acres of land to be impacted by resumed mill operation, and studied in 1976, was reexamined because the state of practice for archaeological studies has improved. A Class III cultural resource inventory, including a literature search, was conducted for a total of 1,520 acres.

The 1993 inventory was executed via a series of zigzag pedestrian transects placed no more than 30 meters (98.4 feet) apart. Special attention was given to areas where subsurface cultural materials may have been exposed due to differential erosion. When a cultural item was observed, the location was marked for subsequent closer examination to determine if the object was an isolated find or if it represented a portion of an archaeological site. When a site limit was defined, an intensive inspection was carried out to locate all visible artifacts and features.

The intensive Class III cultural resource inventory resulted in three new sites, 48SW9827, 48SW9828, and 48SW9829, and five isolated finds. Only one of these sites, 48SW9829, is considered by Pronghorn Archaeological Services to be eligible for inclusion in the National Register of Historic Places. The presence of 53 to 80 cm (20.8 to 31.5 inches) of deposition on this site indicates that this site has potential to contribute additional information important to the prehistory of the area. Small, single component activity areas are critical in understanding the extent of prehistoric land use, settlement patterns, and subsistence strategies of the aboriginal occupants of the area.

The State Historic Preservation Office (SHPO) reviewed Pronghorn's 1993 results and determined that the documentation "meets the Secretary of the Interior's Standards for Archaeology and Historic Preservation," and recommended that additional testing be done on area 48W9829 if it could be impacted by construction activities (SHPO, 1993). The letter indicated that eligibility of the site remain unevaluated until then. In addition, KUC is required by license condition to perform an archeological survey and obtain approval before disturbing any previously unsurveyed areas, and to cease work if buried cultural deposits are unearthed until approval to proceed is granted by the NRC and SHPO.

On March 5, 1998, NRC staff requested BLM consultation on tribal entities to determine the absence or presence of areas of cultural significance to Native American tribes on the Sweetwater Site. The BLM replied on May 13, 1998, that of the four groups contacted, none of the entities responded with an interest in this project.

Based on the license condition and commitments made by the licensee, the NRC staff considers that historical and cultural resources will be protected from destruction or disruption by the proposed activities.

4.4 Impacts to Water Resources

4.4.1 Surface Water Impacts

The NRC staff has determined previously that the operation of the mill and reclamation of the Site will have minimal effects on the surface waters in the site vicinity (NRC, 1978). This has been recently re-confirmed based on the finding that: (1) mill effluents will not discharge to surface waters; (2) the site will not use any surface water in its milling process; (3) there will be no change in the milling process that would result in a significant change in the environmental impacts at the site; and (4) mill liquid effluents (spills) should not leave the mill area. The licensee will not use any surface water for mill operation or reclamation.

4.4.2 Ground Water Impacts

a. Existing Tailings Impoundment

The existing tailings impoundment has a single 36-mil synthetic liner that leaked several times between 1980 and 1984, and was repaired. Actions were taken to reduce the wave action that led to failure of the liner seams on the sideslopes of the tailings pond. The contamination did not leave the site but did enter the upper aquifer. An NRC-approved ground-water corrective action program is reducing the contaminated plume created by the leaks. The 1998 data from this program indicates that the contamination is in the upper 50 feet of the aquifer, all the hazardous constituents have stabilized below the standards except uranium which is confined to the northern edge of the tailings cell and radium which covers approximately 127 acres, of which nearly half is under the tailings cell. The standards will be met before license termination, and afterwards, DOE, as the site custodian, will continue ground-water monitoring to ensure the standards are maintained.

b. New Tailings Impoundment

Because of new technology and an improved design, ground water in the vicinity of the Site should not be adversely impacted by the resumption of milling operations. The new tailings impoundment will be lined with a layered system composed of two flexible membrane synthetic liners over a three-foot minimum thickness of compacted clay, as specified in Final Design Volumes I (Figure 4-1), IV, and VII (KUC, 1997g,c,f). A leak detection and recovery system installed between the two synthetic liners will be monitored regularly by the licensee. In addition, ground-water monitoring wells will be located immediately down gradient of the tailings impoundment to detect any potential ground-water contamination as early as possible, as required by 10 CFR Part 40, Appendix A, and 40 CFR 264.221.

Management of the tailings impoundment during site operations is also designed to minimize the potential for ground-water contamination. The tailings impoundment is designed to dewater tailings through the use of a process water recovery system (PWRS). The PWRS will be installed above the liner and beneath the tailings, to continually dewater the tailings above the liner. This will further protect ground water by eliminating a hydraulic head in the tailings pile which could enhance infiltration of the tailings fluid into the area surrounding the tailings pile.

Reclamation of the impoundment(s) will provide long-term ground-water protection after Site closure as the final cover will reduce rainfall infiltration to a negligible amount. This will prevent rainfall from becoming a source of leachate and building a hydraulic head that would cause the leachate to move through the tailings.

c. New Evaporation Ponds

The evaporation ponds will also have a dual synthetic liner with leak detection and recovery system, which will be installed on prepared base. Monitoring wells will be located immediately down gradient, and monitored monthly for the first year then, quarterly after the first year for indicator parameters. This sampling schedule conforms to regulatory requirements, and establishes baseline data for each well in the first year of monthly monitoring. When site operations cease, evaporation ponds will be decommissioned by evaporating all liquid, then disposing of liners and any accumulated solids in the tailings cell.

As discussed in the SER for this licensing action, the staff determined that the operational plan and liner system for both the new impoundments and the new evaporation ponds would be protective and that leakage of contaminants into ground water is unlikely. In the event of any leakage, monitoring would detect the problem so that corrective actions could be taken quickly. *In evaluating the operational plan (inspections, monitoring, design), the staff determined that it* would comply with NRC ground water regulations.

4.5 Impacts on Ecological Systems

The vegetation on approximately 350 acres will be removed over the proposed 20-year life of the project, because of tailings impoundment, evaporation pond, and diversion channel construction. Most of the Site vegetation consists of Wyoming sagebrush, big sagebrush, grasses, and a variety of forbs and other shrubs. No Federally listed endangered, threatened or candidate plant species are know to occur within the Site area. The Wyoming Natural Heritage Program has noted that only the Wyoming point-vetch (*Oxytropsis nana*), has a recent record of occurrence in the vicinity of the Site. The Wyoming point-vetch has been classified as S3, which signifies rare or local throughout its range, or found locally in a restricted range. This plant has been found approximately 11 km (7 miles) northwest of the mill site, and should not be disturbed by the proposed operations.

The ER indicates that the wildlife ecology data was updated in 1993 and included an on-site survey. The survey data covers the area within a 40-km (25-mile) radius of the Site. An October 1993 field survey was performed in order to evaluate the presence of a prairie dog community near the existing tailing impoundment. Another wildlife survey was done in 1997 (KUC, 1998c).

Large wild and domestic animals occurring on or near the survey area include: pronghorn antelope, cattle, feral horses, and sheep. The pronghorn antelope (*Antilocaprac americana*) use the area seasonally and utilize sagebrush-grasslands. The survey indicated that approximately 400 and 8000 antelope remained in the Site area during the relatively mild winter of 1975 and 1976. However, antelope migrated out the area to crucial winter ranges further south and east during the severe winter of 1983-84. Pronghorn disperse widely during the summer months. A study concluded that operation of the facility during 1980 through 1983 had no measurable impacts on pronghorn antelope, and, therefore, no mitigative actions were deemed necessary. The other large mammals are less numerous and seldom approach the Site, so they should not be adversely affected by mill operation or reclamation.

Other mammals known to be in the general Site area are: seven species of small rodents, two rabbit species, coyotes, badgers, and long-tailed weasels. These animals are not expected to be adversely impacted by Site operations. Additionally, prairie dog towns were not evident within 8 km (5 miles) of the Site. Various bird species traverse the Site and the most abundant raptor species in the region is the ferruginous hawk (see discussion below). Sage grouse have also been noted within 8 km (5 miles) of the Site. A few reptiles and amphibians occur in the general region, but there is little riparian vegetation and permanent water in the area which restricts the habitat for most of these species.

Three wildlife species, designated as endangered by the Endangered Species Act of 1973, as amended, have been identified by the U.S. Fish and Wildlife Service (FWS) as having the potential to occur in the vicinity of the Site. Theses species are the black-footed ferret (*Mustela nigripes*), bald eagle (*Haliaeetus leucocephalus*) and the peregrine falcon (*Falco peregrinus*). The back-footed ferret is exclusively associated with prairie dog towns, however, there is a marked absence of large active towns, in the general Site area. The bald eagle is known to winter within the Great Divide Basin, although no known observations have been recorded at the Site. Due to the lack of open water and potential roosting trees around the Site, bald eagles are unlikely to utilize the area, except during occasional flyovers. The peregrine falcon is also known to nest within the general region, although no observations have been recorded at the site for this species either. Due to the lack of high cliff areas within the mill region, the peregrine falcon is unlikely to nest in the area, but may occasionally cover the region in search of prey.

Certain wildlife species that may exist in the Site area and have been designated as candidate species under the Endangered Species Act were also considered. There has been no evidence of nesting trumpeter swans, white-faced ibises, harlequin ducks, or black terns. Because of a lack of suitable habitat requirements in the mill area, it seem unlikely that these species will occur. However, the ferruginous hawk, mountain plover, long-billed curlew, and loggerhead shrike have all been observed nesting in the general region. The ferruginous hawk is a common summer resident of the region. Seven observations of the hawk were documented within 8 km (5 miles) of the mill between 1988 and 1991 and ferruginous hawk nests have been found within 16 km (10 miles) of the mill. Circumstantial evidence of nesting by the long-billed curlew has been found in the region, although no nesting has ever been documented. Mountain plover and loggerhead shrike nests have been sited also in the region, however, no currently known active loggerhead shrike or mountain plover nests will be affected by mill operation or reclamation.

The 1997 study concluded that no threatened, endangered, or candidate species were found on the Site during the survey and no documentation of occurrence of any of these species on the Site was found in the records of the Wyoming Game and Fish Department.

4.6 Radiological Impacts

KUC has proposed to define two modes of activity at the mill: (1) "operational" and (2) "interim" or "standby." The operational mode is defined as any time the mill is in the normal commercial production of yellowcake, as contrasted with the interim mode which occurs when no yellowcake is produced for a period of 90 days or more. In examining potential radiological impacts, the NRC staff has chosen to address these modes separately in the following discussion. Ground-water sampling is required, as specified for each mode of operation, by license condition.

4.6.1 Operational Mode

Radiological impacts from the previous operation were evaluated (NRC, 1992) and estimated potential doses to the public were a small fraction of background which is approximately

212 mrem/yr whole body, for the region. Results from NRC-specific MILDOS-AREA dose modeling (based on expected ore grade from the Green Mountain mine), including radon, indicated effective whole body doses to the nearest resident of no more than 0.23 mrem/year; and to residents of Bairoil, the nearest community, of 0.24 mrem/year as a result of the resumption of mill operations. The effective doses in Bairoil are slightly higher due to the direction of the prevailing winds. The above-mentioned values are less than 0.25 percent (0.0025) of the corresponding 10 CFR 20 standard of 100mrem/year and about 0.14 percent (0.0014) of regional background radiation. Therefore, it can be concluded that the resumption of the mill operations, using the higher ore grade, will not result in the nearest resident or the nearest community being subject to radiation that exceeds the regulatory standard or is significantly different than background radiation.

The NRC staff has reviewed KUC's proposed operational monitoring program against the staff's recommendations in Regulatory Guide 4.14 (1980a) and considers the program acceptable. In addition, KUC will need to comply with the U.S. Environmental Protection Agency's (EPA) requirements under 40 CFR 61.252 to keep radon-222 emissions from its mill tailings pile from exceeding 20 pCi/m^2-s of radon-222.

4.6.2 Interim/Standby Mode

During the years since the 1992 EA examined potential impacts, the semi-annual effluent monitoring results and annual ALARA Audit Report indicate that the licensee has maintained potential radiation exposure levels to a reasonable level below the regulatory limits. During the current standby mode, KUC has not conducted, performed, or measured stack, surface water, soil, or vegetation samples. In addition, airborne particulate sampling is at a single location downwind of the tailings impoundment and ore stockpiles. Samples are collected semiannually and analyzed for U-nat, Ra-226, Th-230, and Pb-210. This approach has been approved by NRC staff. This level of monitoring is also considered adequate for the reclamation mode of activity.

4.6.3 Radiological Assessment

a. Off-site Impacts

The radiological impacts from milling operations at the Sweetwater site have been previously estimated (NRC, 1978) and documented in the monitoring reports during and after operation of the mill. The ground water contamination resulting from the tailings pond leakage in 1984, has not migrated off-site and the plume is maintained within 213.4 m (700 feet) of the impoundment and in the upper 80 km (50 feet) of the aquifer by pumping the water to the tailings impoundment (KUC, 1999b). The air monitoring samples for radionuclides indicate levels at a small fraction of the regulatory limits. The air sample location is on site, therefore, it is anticipated that radiation levels at the Site boundary approach background. During mill operation and reclamation, potential off-site radiation doses will be monitored and action would be taken if any radiation levels approach the regulatory limits.

b. Radiological Impact on Biota Other than Humans

Although no guidelines concerning acceptable limits of radiation exposure have been established for the protection of species other than man, it is generally agreed that the limits for humans are also conservative for other species. Doses from gaseous effluents to terrestrial biota (such as birds and mammals) are quite similar to those calculated for man and arise from the same dispersion pathways and considerations. Because the effluents of the facility will be monitored and maintained within safe radiological protection limits for man, no adverse radiological impact is expected for animals residing on or near the Site.

4.7 In-Plant Safety

The office, shop, and mill buildings have 9-kg (20-pound) portable, dry chemical fire extinguishers and all vehicles are equipped with 1.1- to 4.5-kg (2.5- to 10-pound) portable, dry chemical fire extinguishers. There are two 68-kg (150-pound) portable, dry chemical extinguishers also on site. An over-tank sprinkler system capable of foam injection is installed in the solution extraction building. Fire hydrants with 76 m (250 feet) of hose are installed every 183 m (600 feet) around the mill area. Additionally, there are fire hydrant hose stations internally in most project buildings.

An on-site Radiation Safety Officer (RSO) is part of the facility staff. A safety engineer will also be included on the staff during mill operation. At least one person trained in first aid will also be present during each work shift. The office building contains a first aid treatment room, and an ambulance is maintained on-site at all times.

The NRC, through 10 CFR Part 20 and license conditions, requires a radiological safety program that contains the basic elements needed to assure that exposures are kept ALARA. A revised radiation safety program was submitted March 13, 1994, and approved by the NRC by letter of April 18, 1994. The program includes requirements for:

- Qualified management of the radiation safety program and appropriate training of personnel;
- Written radiation procedures;
- Airborne and surface contamination sampling and monitoring;
- Internal and external radiation monitoring programs;
- An approved respiratory protection program; and
- Daily inspections of process areas and weekly inspections of general radiation control.

Also, by license condition, an annual ALARA audit report will be submitted to the NRC. The NRC considers that the proposed KUC program for in-plant safety will meet the required Federal regulations, and the radiation safety program as defined by 10 CFR Part 20. The licensee has also submitted a Radiation Protection Program for Decommissioning (KUC, Section 12 of Volume VI, Part 2, June 9, 1999). The NRC evaluation of the licensee's radiation safety program is discussed more fully in the SER.

4.8 Socioeconomic Impacts

The primary negative impact likely to occur would be due to the increased truck traffic associated with mill operations. The positive effects for the area would be an increase in jobs and tax revenues. Because there are no near-by residents, there is no one to be affected by the noise or visual impacts of proposed activities.

5.0 ENVIRONMENTAL EFFECTS OF ACCIDENTS

5.1 Failure of Storage Tanks and Piping

At the mill, tanks are used to store a variety of industrial chemicals, process fluids, and slurries, as well as flammable liquids. Various systems have been implemented to contain or direct routine or unplanned spillage. Tanks which are most likely to overflow are equipped with high-level alarms (alarm sounds in the control room) to reduce the possibility of spillage due to tank overflow. Spills resulting from the failure of any chemical holding tank would first be contained by engineered dikes or curbs and mill sumps. If the volume was too great, such as that from a rupture in one or more of the large production tanks, flow would be captured by the catchment basin.

Minor pipe or tank leakage of uranium-bearing slurries and solutions can occur at the acid leach, washing and clarification, and solvent extraction stages of the mill circuit. Human error, during the filling or emptying of tanks or the failure of valves or piping in the circuit, would result in spills which may occur periodically during operation of the mill. The entire content of any spill will be contained within the mill sumps or diked area, and would not leave the mill building. Any spillage which may occur will be pumped back into the process system.

5.2 Fires and Explosions

The solvent extraction (SX) circuit is located in a separate building and can hold up to approximately 3038.5 kg (6,700 pounds) of uranium at a time, assuming an ore grade of 0.2 percent U_3O_8. Approximately 47,312.5 L (12,500 gallons) of kerosene are contained in the SX circuit and this kerosene represents the greatest potential for a serious fire at the Site. The SX building is equipped with an automatic sprinkler system capable of foam injection, and 13.6-kg (30-pound) portable foam fire extinguishers are spaced at 15.2-m (50-foot) intervals around the area. Safety precautions are in place to ensure that a fire in one of the process tanks would be contained before other tanks are damaged. Smoke generated by a fire would be released to the atmosphere through air vents in the top of the building.

Fire is not expected to cause significant impact beyond the NRC permit area. The short-term release of smoke, soot, and unburned hydrocarbons would decrease air quality and potentially cause some damage to vegetation within the immediate vicinity of the plant, but the effects would be minimal in nature due to wind dispersion. The conservative release estimate dose is approximately 0.25 mSv/yr (25 mrem/yr).

The consequences of explosion accidents are limited by the concentration of yellowcake that can be maintained in the air of the enclosed yellowcake dryer room. The quantity of yellowcake that could be released from the room is estimated to be approximately 1 kg (2.25 pounds).

Individuals at the closest residence (28 km) could receive a 50-year committed dose to the lungs and whole body of approximately 4.9×10^{-3} and 3×10^{-6} mSv (0.49 and 3×10^{-4} mrem), *respectively. These values are significantly below the dose standards.*

5.3 Centrifuge Failure

Prior to drying, the thickened yellowcake slurry will be *dewatered* by use of a centrifuge. If the centrifuge rotor fails, it could conceivably penetrate a tank containing uranium solution or slurry, releasing radioactive materials into the interior of the mill building. The entire contents of a tank, however, will be contained within sumps and will not leave the mill building

5.4 Tailings Impoundment System Accidents

At the average estimated processing rate, approximately 125 tons per hour of sand, silt and clay-sized particles will be transported to the tailings cells through the tailings disposal system piping. *A rupture in the main tailings delivery pipe between the mill and operating tailings cell* would release material within containment berms then into sumps for reentry into the mill process circuit, or the slurry would be pumped to the tailings cell. The tailings will be pumped into an impoundment through multiple discharge laterals. The flow of any material released from the rupture of one these laterals will be toward the interior of the tailings impoundment, where it will be contained along with the existing tailings material.

The potential for seismic and flood damage to the tailings dam has been addressed in the Operational Plan and the Reclamation Plan for the Site and the impoundment design has been determined acceptable by NRC staff. A diversion channel will be built, designed for the probable maximum precipitation event, to protect the tailings impoundment dams for up to 1000 years.

A worst case scenario was used (NRC, 1980b) in assessing the potential radioactive release from a tornado strike. It was assumed that 3 days of yellowcake production at average throughput rates and an ore grade of 0.2 percent U_3O_8 (11,160 lbs/day of yellowcake x 3 days = 33,480 pounds) is not packaged in containers; an inventory of 50 tons of yellowcake is on site when a tornado strikes; and 15 percent of the contained material is released. Thus it is assumed that the tornado lifts about 21,986 kg (48,480 pounds) of yellowcake. Further, it is conservatively assumed that all of the yellowcake is in a respirable form, and that all of the material is entrained as the vortex passes over the Site.

The maximum exposure was predicted at approximately 4 km (2.5 miles) from the mill, where the 50-year committed dose to the lungs of an individual is estimated to be 1.6×10^{-5} mSv (1.60×10^{-3} mrem). For individuals at the closest residence to the Site, the 50-year committed dose was estimated to be 6.6×10^{-7} mSv (6.6×10^{-5} mrem), assuming the wind is directed that way. *These values are significantly lower that the* 40 CFR Part 190 standard for nuclear fuel cycle facilities (25 mrem annual dose equivalent), or the 10 CFR Part 20 50-year dose commitment limit.

5.5 Transportation Accidents

Transport of ore to the mill was not addressed in the ER because that aspect is not regulated by NRC. However, a truck accident along that route could contribute a minor, temporary environmental impact. The larger pieces of ore spilled during an accident can be found and retrieved. The ore fragments and dust would create small and very localized areas of elevated radiation and the effort to clean the area would be directed by the State.

During transport of the uranium product from the mill, an accident could occur in which some of the uranium oxide (U_3O_8) would be released. This is the only radioactive material expected to be transported from the Site. Because most of the radioactive decay products of uranium will have been removed in the extraction process (note: there are 14 isotopes in the uranium-238 decay chain), and because of the very slow regrowth of the gamma emitting decay products, the uranium oxide will have a very low level of radioactivity. Under the regulations of the U.S. Department of Transportation, uranium oxide is classified as low specific activity material (49 CFR Part 173, Sections 173.389C and 173.392).

The product will be packed into steel drums to a net weight of approximately 408 kg (900 pounds) and then shipped to customers. The drums will be sealed and marked as per the requirements of 49 CFR Part 173. The extent of the environmental impact of a transportation accident involving the product would be very small. Even in the case of a severe accident, only a few drums are likely to be breached. The material has a very high density (approximately 7 g/cm^3) and is not easily dispersed.

The vehicles transporting the product will be properly marked for the shipment of radioactive material. Carriers will only be used that have Spill Prevention Control and Countermeasures (SPCC) plans, trained drivers, and special procedures for transporting yellowcake.

6.0 RECLAMATION AND DECOMMISSIONING

Ground water restoration will continue to be conducted under the Corrective Action Program, as authorized by the NRC license. Mill decommissioning and tailings area reclamation are governed by NRC regulations and descriptions of these proposed activities for the Site were provided in the Final Design (KUC, 1997-1999). The Design (including the Decommissioning Plan) has been evaluated and the NRC review will be documented in a Technical Evaluation Report. Other associated Site reclamation and restoration activities for the pit and overburden pile and associated mining disturbances are regulated by the Wyoming DEQ and are not addressed in this EA.

The purpose of mill decommissioning and tailings area reclamation is defined by 10 CFR 40, Appendix A, which establishes the objective of permanent isolation of tailings and associated contamination, and to do so without ongoing maintenance. The proposed reclamation at the Site will:

- provide reasonable assurance of 1000-year control of radiological hazards,
- minimize wind and water erosion potential for the impoundment(s),

- provide a reclamation cover which will limit radon emanation, infiltration, and erosion to acceptable levels,
- ensure that reclamation measures are undertaken in a timely fashion,
- include a post-closure monitoring plan, and
- provide financial surety for decommissioning and reclamation.

Contaminated equipment will either be: 1) decontaminated so that it meets the requirements of release for unrestricted use; 2) sold or otherwise transferred to another licensee authorized to accept contaminated equipment; 3) placed for disposal in the tailings impoundment; or 4) placed for disposal in another impoundment authorized to accept 11(e)2 byproduct material. Contaminated buildings that do not meet the release requirements will be: 1) decontaminated and/or remediated so that they meet the unrestricted release requirements; 2) dismantled and placed for permanent disposal in the tailings impoundment; 3) transferred to another licensee authorized to accept contaminated materials; or 4) placed for disposal in another impoundment authorized to accept 11(e)2 byproduct material. Cleanup of contaminated soils in the mill vicinity will be conducted as per Criterion 6(6) of Part 40, Appendix A.

The impacts from the planned decommissioning of land and buildings and the reclamation of the impoundments have been addressed in previous sections of this EA. In summary, significant or long-term impacts should not occur off-site. On-site restoration will be performed to include regrading and seeding disturbed areas.

7.0 ALTERNATIVES

The action under consider action is the renewal of Source Material License SUA-1350, for restart of operations at the Sweetwater mill, as requested by KUC. The alternatives available to the NRC are to:

(1) Renew the license with such conditions as are considered necessary or appropriate to protect public health and safety and the environment; or

(2) Deny the renewal of the license.

If the existing mill were not used to process the ore from the Jackpot Mine, the potential environmental impacts discussed above would be avoided. On the other hand, to deny the renewal for operation would prevent the creation of an estimated 79 direct and indirect jobs within Fremont, Sweetwater, and Carbon Counties. It would also result in a loss of at least $755,200 per year in tax revenues.

Uranium is the only fuel used for the generation of nuclear power. It is estimated that United States (U.S.) utilities inventories of uranium oxide decreased by 2.2 million pounds or 3 percent, and U.S. supplier inventories decreased 15 percent in 1997. The United States produced a total of 8.1 million pounds of U_3O_8 equivalent in 1997, and this represents only 19 percent of the amount received by U.S. utilities (DOE, 1998). Of this national production, 14 percent came from conventional uranium mills. For the years 2002 through 2007, the utilities' reported enrichment deliveries are less than their anticipated market requirements (DOE, 1998). Based on this projected demand for uranium and the current national production levels, it is quite possible that a long-term shortage of yellowcake (uranium oxide) could develop within the U.S. in the coming years.

Based on its review of the information identified in Section 1.3.2, the NRC staff has concluded that the environmental impacts associated with the proposed actions do no warrant denial of the license renewal. It is the staff's conclusion that the impacts associated with the license renewal and reclamation plan are within the realm of impacts anticipated in the FES (NRC, 1978). Additionally, in the SER prepared for this action, the staff has reviewed the licensee's proposed action with respect to the criteria for license issuances specified in 10 CFR Part 40, section 40.32, and has no basis for denial of the proposed action.

8.0 FINANCIAL SURETY

Under 10 CFR Part 40, Appendix A, Criterion 9, licensees are required to establish a financial surety adequate to cover the estimated cost for: (1) decommissioning and decontamination of the mill and mill site; (2) reclamation of any tailings or waste disposal area; (3) ground water restoration, as warranted; and (4) the long term surveillance fee.

The surety is based on an estimate which must account for the total cost that would be incurred if an independent contractor were contracted to perform the reclamation and decommissioning work. The surety estimate must be approved by NRC and be based on an NRC-approved decommissioning and reclamation plan. The licensee must also provide the surety arrangement through a financial institution acceptable to the NRC. The licensee's surety mechanism will be reviewed by NRC annually to assure that sufficient funds are available to complete reclamation. Additionally, the amount of the surety should be adjusted annually to recognize any increases or decrease in liability resulting from inflation, changes in engineering plans, or other conditions affecting cost. The licensee will be required by license condition to maintain a financial surety arrangement in accordance with the requirement of Criterion 9.

The revised 1999 annual surety for the Sweetwater mill was reviewed by NRC staff. The amount includes funds to decommission the existing facility, complete ground-water restoration, and reclaim the existing impoundment. As required by License Condition 9.7 in the renewed license, the surety amount will be increased within three months of NRC approval of the cost estimate. For the new structures (impoundment, ponds) proposed to support renewed operation of the mill, the estimated amount for their reclamation, as approved by NRC, will be provided in the surety bond before commencement of construction of these structures.

9.0 CONSULTATION WITH AFFECTED FEDERAL AND STATE AGENCIES

As documented in the references, the NRC staff contacted representatives of the EPA, BLM, FWS, the Wyoming Fish and Game Department, the Wyoming State Historic Preservation Office, and the Wyoming DEQ regarding the proposed restart of the mill and eventual reclamation of the site. Any comments received from these agencies were adequately addressed. The licensee also contacted Federal, State, and county agencies during development of the ER. In addition to these agencies, the staff also consulted the Wyoming Outdoor Council to determine if additional concerns needed to be addressed in this EA.

10.0 FINDING OF NO SIGNIFICANT IMPACT

KUC has applied to NRC to renew Source Material License SUA-1350 to authorize the resumption of operations at the Sweetwater uranium mill, located in Sweetwater County, Wyoming. The NRC staff has reexamined actual and potential environmental impacts associated with yellowcake production at the mill site, and has determined *that* renewal of the source material license (1) will be consistent with requirements of 10 CFR Part 40; (2) will not be inimical to public health and safety; and (3) will not have long-term detrimental impacts on the environment.

Therefore, based on an evaluation of KUC's renewal request, the NRC staff has determined that the proper action is to issue a FONSI in the Federal Register. The following statements support the FONSI and summarize the conclusions resulting from the staff's environmental assessment:

- An acceptable environmental sampling program will be in place to monitor effluent releases and to detect if appropriate limits are exceeded;

- The licensee will implement an intensive, routine inspection program of the mill process building, associated facilities, and tailings retention impoundments, and conduct an annual ALARA audit program;

- Standard operating procedures will be in place for all operational process activities involving radioactive materials that are handled, processed, or stored;

- Mill tailings and process liquid effluents from the mill circuit will be discharged to a double-lined tailings impoundment, with a leak detection system;

- The licensee will implement an acceptable ground-water detection monitoring program to ensure compliance with the requirements of 10 CFR Part 40, Appendix A;

- The licensee will conduct site decommissioning and reclamation activities in accordance with NRC-approved plans; and

- Because the staff has determined that there will be no significant impacts associated with approval of the license renewal and reclamation plan amendment, there can be no disproportionately high and adverse effects or impacts on minority and low-income populations. Consequently, further evaluation of `Environmental Justice' concerns, as outlined in Executive Order 12898 and NRC's Office of Nuclear Material Safety and Safeguards Policy and Procedures Letter 1-50, Rev.1, is not warranted.

Based on these findings, the NRC staff recommends that KUC's license for the resumption of yellowcake production at the Sweetwater uranium mill be renewed. The source material license shall be based upon the licensee's renewal application, this EA, the SER, and the license conditions which address environmental issues.

1.0 CONCLUSION AND ENVIRONMENTAL LICENSE CONDITIONS

Upon completion of the environmental review of KUC's application for renewal of Source Material License SUA-1350, the NRC staff has concluded that operation and reclamation of the Sweetwater uranium mill, in accordance with the following conditions to be included in the renewed source material license, is protective of health, safety, and the environment, and fulfills the requirements of 10 CFR Part 51. Therefore, the NRC staff recommends renewal of SUA-1350 for operation, subject, in part, to the following conditions:

1. The mill production rate shall not exceed 4,100,000 pounds of yellowcake per year.

2. A. The licensee may, without prior NRC approval, and subject to the conditions specified in Part B of this condition:

   (1) Make changes in the facility or process, as presented in the application.

   (2) Make changes in the procedures presented in the application.

   (3) Conduct tests or experiments not presented in the application.

   B. The licensee shall file an application for an amendment to the license, unless the following conditions are satisfied.

   (1) The change, test, or experiment does not conflict with any requirement specifically stated in this license, or impair the licensee's ability to meet all applicable NRC regulations.

   (2) There is no degradation in the essential safety or environmental commitments in the license application, or provided by the approved reclamation plan.

   (3) The change, test, or experiment are consistent with the conclusions of actions analyzed and selected in this EA.

   C. The licensee's determinations concerning Part B of this condition, shall be made by a "Safety and Environmental Review Panel (SERP)." The SERP shall consist of a minimum of three individuals. One member of the SERP shall have expertise in management and shall be responsible for managerial and financial approval changes; one member shall have expertise in operations and/or construction and shall have responsibility for implementing any operational changes; and, one member shall be the corporate radiation safety officer (RSO) or equivalent, with the responsibility of assuring changes conform to radiation safety and environmental requirements. Additional members may be included in the SERP as appropriate, to address technical aspects such as health physics, ground water hydrology, surface-water hydrology, specific earth sciences, and other technical disciplines. Temporary members or permanent members, other than the three above-specified individuals, may be consultants.

D. The licensee shall maintain records of any changes made pursuant to this condition until license termination. These records shall include written safety and environmental evaluations, made by the SERP, that provide the basis for determining changes are in compliance with the requirements referred to in Part B of this condition. The licensee shall furnish, in an annual report to NRC, a description of such changes, tests, or experiments, including a summary of the safety and environmental evaluation of each. In addition, the licensee shall annually submit to the NRC changed pages to the Operations Plan and Reclamation Plan of the approved license application to reflect changes made under this condition.

3. Standard operating procedures (SOPs) shall be established and followed for all operational process activities involving radioactive materials that are handled, processed, or stored. SOPs for operational activities shall enumerate pertinent radiation safety practices to be followed. Operational SOPs will be available for the pre-operational inspection. Additionally, written procedures shall be established for non-operational activities to include in-plant and environmental monitoring, bioassay analyses, and instrument calibrations. An up-to-date copy of each written procedure shall be kept in the mill area to which it applies.

   All SOPs (both operational and non-operational activities) shall be reviewed and approved in writing by the RSO before implementation and whenever a change in procedure is proposed to ensure that proper radiation protection principles are being applied. In addition, the RSO shall perform a documented review of all existing operating procedures at least annually.

4. The licensee shall have an archeological survey performed prior to disturbing any previously unsurveyed areas. Such surveys shall be submitted to the NRC and the State Historic Preservation Office (SHPO) for review and approval. No such disturbance shall occur until authorization to proceed has been granted by NRC and SHPO. In addition, all work in the immediate vicinity of any buried cultural deposits unearthed during the disturbance of land shall cease until approval to proceed has been granted by the NRC and SHPO.

5. All liquid effluents from mill process buildings, with the exception of sanitary wastes, shall be returned to the mill circuit or discharged to the tailings impoundment.

6. Upon resumption of milling operations, the licensee shall implement a ground-water detection monitoring program for the tailings impoundment and evaporation ponds to ensure compliance with 10 CFR 40, Appendix A, in accordance with the "Addendum to the Revised Environmental Report, Background Ground Water Quality and Detection Standards," January 1996, as revised by the submittals of January 8, 1998, and March 25, 1999. The licensee shall conduct an environmental monitoring program in accordance with on-file standard operating procedures for environmental monitoring (Environmental Procedures, EPs), and in accordance with Table 5-2 of the Final Design Volume VII, submitted as a page change March 25, 1999.

7. During the period of mill standby, the licensee shall conduct an environmental monitoring program in accordance with on-file standard operating procedures for environmental monitoring (Environmental Procedures), and in accordance with Table 5-1 of the Final Design Volume VII, submitted as a page change March 25, 1999.

8. The licensee shall conduct a corrective action program (CAP) with the objective of returning the concentrations of chromium, natural uranium, and combined radium-226/228 to the levels referenced in "Addendum to the Revised Environmental Report, Background Ground Water Quality and Detection Standards," January 1996, as amended January 8, 1998, and approved by the NRC May 28, 1998.

12.0 REFERENCES and SUBMITTALS

Fenneman, N.M., 1931. Physiography of the Western United States, New York: McGraw-Hill.

Kennecott Uranium Company (KUC), letters and submittals to NRC:
--- Provides required submittals for resumption of operations, "Revised Radiation Safety Program and Standard Operating Procedures," March 9, 1993
---Conceptual Design - Tailings Management Study, August 4, 1993
—Page changes, Appendix C of Conceptual Design, August 17, 1993
—Revised Radiation Safety Program, March 13, 1994a
---Revised Environmental Monitoring Manual (for mill operation), June 7, 1994b
---Revised Environmental Report, August 15, 1994c
---modification to Conceptual Design for Use of Impoundment as Evaporation Pond, December 2, 1994d
---Response to the NRC's Fourteen Comments on the Conceptual Design - Tailings Management Study-Sweetwater Uranium Project, January 18, 1995a
---Evaluation of Revegetation Efforts, March 17, 1995b
—Revised page for Appendix G of ER, March 27, 1995c
---Revised MILDOS (dose modeling) tables, April 10, 1995d
---Addendum to the Revised Environmental Report - Geologic Cross Sections and Aquifer Information, August 10, 1995e
---Use of Existing Tailings Impoundment, August 22, 1995f
---Addendum to the Revised Environmental Report - Regional Seismicity, November 22, 1995g
---Addendum to the Revised Environmental Report - Background Ground Water Quality and Detection Standards, February 2, 1996a
---Revised Addendum to the Revised Environmental Report - Regional Seismicity, Sweetwater Uranium Facility, June 26, 1996b
---Final Design Volume III, Embankment Design Report, request performance-based license, withdrawal of 10-year license request, and renewal of license to allow resumption of mill operation, June 11, 1997a
---Final Design Volume II, Data Report, July 3, 1997b
---Final Design Volume IV, Liner Design Report, July 23, 1997c
---Final Design Volume V, New Impoundment Reclamation Plan, August 1, 1997d
---Final Design Volume VI, Existing Impoundment Reclamation Plan, August 20, 1997e
---Final Design Volume VII, Operations Plan, September 18, 1997f
---Final Design Volume I, Executive Summary Report, October 7, 1997g
---Tailings fluid analysis data, January 5, 1998a

---Page changes, Background Groundwater Study, January 8, 1998b
—Attached map of 1997 Wildlife Study area, January 29, 1998c
---Tailings Management - maps, March 5, 1998d
---Page changes, Volume VII, Section 5, April 13, 1998e
---Final Design Volume VI, Part 2 (Mill Decommissioning Plan) includes revised decommissioning cost estimate and proposed expanded NRC bonded-area, May 28, 1998f
---Page changes, Volume VII, Section 5, June 10, 1998g
---Page changes, Appendix D, Volume VII, Volume V and VI, June 10, 1998h
---Page change, Volume VII, Figure 5-10, July 1, 1998i
---Page changes, Volume IV and Volume VII, July 20, 1998j
---Final Design Volume VIII, response to comments, changes new pile cover to 21 feet; draft performance-based license, February 3, 1999a
—Annual Review-Corrective Action Program, Semiannual 10 CFR 40.65 Report (Airborne Effluents), Land Use Survey, and ALARA Report, February 15, 1999b
---Final Design Volume IX Response to Comments, revised cost estimates for surety, SERP SOP, February 25, 1999c
---Page changes, Volume VII, March 25, 1999d
---Page changes to Vol. I, V, VI on cost estimates and radium background, April 21, 1999e
—Page Changes to Vol. I, V, VI, VII, and IX on channel design, revised cost estimate, and deletion of references to SOPs and license conditions, June 21, 1999f.
—Page changes to Vol. IX, revised cost estimate, July 29, 1999g.

Minerals Exploration Company (MEC), application for renewal of Source Materials License SUA-1350, April 3, 1984.

State Historic Preservation Office (SHPO), Wyoming Department of Commerce, letter to NRC concerning review of the cultural resource survey report for the Sweetwater Uranium Facility (project control #1093KLK091), October 29, 1993.

U.S. Bureau of Land Management, (BLM) reply on Native American consultation, May 19, 1998.

U.S. Department of Commerce, "Probable Maximum Precipitation Estimates - United States Between the Continental Divide and the 103rd Meridian," Hydrometeorological Report No. 55-A, 1988.

U.S. Department of Energy (DOE), "Uranium Industry Annual 1997," Energy Information Administration, April 1998.

U.S. Fish and Wildlife Service, Letter to NRC indicating that the proposed activities are unlikely to adversely affect any threatened or endangered species, but expressing concern for Ra-226 and selenium levels in the environment, April 10, 1998.

U.S. Nuclear Regulatory Commission (NRC), "Final Environmental Statement Related to Operation at Sweetwater Uranium Project, Minerals Exploration Company, Docket No. 40-858,4" NUREG-0505, December 1978.

—"Radiological Effluent and Environmental Monitoring at Uranium Mills," Regulatory Guide 4.14, April 1980a.

—Final Generic Environmental Impact Statement on Uranium Milling, NUREG/CR-0706, September 1980b.

---Environmental Assessment for the Renewal of Source Material License SUA-1350, March 24, 1992.

---Letter to KUC approving the revised Radiation Safety Program, April 18, 1994.

–Letter to KUC indicating that its request to extend the license to 10 years is acceptable unless the license is renewed to resume operations. The license will not expire until final action is taken by NRC, May 16, 1997.

—Letter to BLM requesting consultation on eligible of Sweetwater Site for listing on national register of historic places, March 5, 1998.

—Letter to U.S. Fish and Wildlife Service requesting information on protected plants and animals in the Sweetwater Project area, March 5, 1998.

---Response to U.S. Fish and Wildlife Service to resolve two concerns (radium and selenium), February 19, 1999.

—Telephone conversation with R. Hoy, Wyoming Department of Environmental Quality, May 20, 1999, no comments.

–Telephone conversation with Mark Newman, Rawlins Field Office, BLM, May 24, 1999, no comments.

—Telephone conversation with Mark Theisse, Wyoming Department of Environmental Quality, May 26, 1999, no comments.

Appendix 25

Kennecott Uranium Company
Sweetwater Uranium Project
Preoperational Background Surface Radionuclide Sampling Data

Sample Location	Date	Ra-226 pCi/g	U-nat ug/g	U-nat pCi/g	U-238 pCi/gr	Th-230 pCi/g	Pb-210 pCi/g	U-238 / TH-230	TH-230 / Ra-226	U-238 / Ra-226	Comments
MA (A)	5/10/1979	0.08	0.41	0.28	0.14					1.73	Mill Area Survey
MA (B)	5/10/1979	0.49	0.73	0.49	0.25					0.50	
M-1-B(A)	5/10/1979	0.23	0.19	0.13	0.06					0.28	
M-1-B (B)	5/10/1979	0.32	0.38	0.26	0.13					0.40	
M-2-B(A)	5/10/1979	0.3	0.35	0.24	0.12					0.39	
M-2-B(B)	5/10/1979	0.16	0.47	0.32	0.16					0.99	
M-3-B(A)	5/10/1979	0.06	0.13	0.09	0.04					0.73	
M-3-B(B)	5/10/1979	0.45	0.28	0.19	0.09					0.21	
M-4-B(A)	5/10/1979	0.12	0.2	0.14	0.07					0.56	
M-4-B(B)	5/10/1979	0.64	0.76	0.51	0.26					0.40	
1A	4/13/1978	3	12	8.12	4.05	3.2	4.4	1.27	1.07	1.35	Soil Station Sampling
1B	4/13/1978	4.2	9.4	6.36	3.17	2.4	3.3	1.32	0.57	0.76	#1 same location as Air 3
2A	4/13/1978	4.2	14	9.48	4.73	2.8	2.7	1.69	0.67	1.13	
2B	4/13/1978	3.6	12	8.12	4.05	2.9	1.6	1.40	0.81	1.13	#2 same location as SVS 1
3A	4/13/1978	1	1.3	0.88	0.44	0.74	1.1	0.59	0.74	0.44	
3B	4/13/1978	0.19	1.8	1.22	0.61	0.87	0	0.70	4.58	3.20	#3 same location as SVS 2
4A	4/13/1978	1.7	3.1	2.10	1.05	1.3	2.3	0.80	0.76	0.62	
4B	4/13/1978	1.7	3.1	2.10	1.05	1.2	1.4	0.87	0.71	0.62	#4 same location as SVS 3
5A	4/13/1978	0.55	3.5	2.37	1.18	1.1	2	1.07	2.00	2.15	
5B	4/13/1978	2.2	2.8	1.90	0.95	1.3	1.8	0.73	0.59	0.43	#5 same location as SVS 5
6A	4/13/1978	1.8	4	2.71	1.35	1.6	1.9	0.84	0.89	0.75	
6B	4/13/1978	1.1	6.2	4.20	2.09	2.7	2.1	0.78	2.45	1.90	
7A	4/13/1978	1.8	2.2	1.49	0.74	2	2.2	0.37	1.11	0.41	
7B	4/13/1978	1.7	2.5	1.69	0.84	1.1	1.7	0.77	0.65	0.50	
#8	4/13/1978	2.8	2.6	1.76	0.88	3.1	1.7	0.28	1.11	0.31	
#9	4/13/1978	1.3	3.5	2.37	1.18	1.1	2	1.07	0.85	0.91	
T1-A	4/13/1978	0.13	0.46	0.31	0.16	0.31	0.41	0.50	2.38	1.19	T-series sampling
T1-B	4/13/1978	0.28	0.55	0.37	0.19	0.49	0.38	0.38	1.75	0.66	Located SW of Mill
T2-A	4/13/1978	0.55	0.53	0.36	0.18	0.28	0.35	0.64	0.51	0.33	
T2-B	6/16/1978	0.45	0.37	0.25	0.12	0.56	0.43	0.22	1.24	0.28	
T3-A	6/16/1978	0.2	0.51	0.35	0.17	0.2	0.5	0.86	1.00	0.86	
T3-B	8/29/1978	0.2	0.43	0.29	0.15	0.84	0.63	0.17	4.20	0.73	
T4-A	8/29/1978	0.05	0.57	0.39	0.19	0.14	0.25	1.37	2.80	3.85	
T4-B	8/29/1978	0.24	0.45	0.30	0.15	0.42	0.27	0.36	1.75	0.63	
T5-A	8/29/1978	0.34	0.36	0.24	0.12	0.51	0.85	0.24	1.50	0.36	
T5-B	8/28/1978	0.15	0.45	0.30	0.15	0.27	0.28	0.56	1.80	1.01	
A	9/27/1978	2	0.66	0.45	0.22	2.3	1	0.10	1.15	0.11	Center point of survey
A-1	9/26/1978	3.32	0.88	0.60	0.30	2.28	1.76	0.13	0.69	0.09	

Sample Location	Date	Ra-226 pCi/g	U-nat ug/g	U-nat pCi/g	U-238 pCi/gr	Th-230 pCi/g	Pb-210 pCi/g	U-238 / TH-230	TH-230 / Ra-226	U-238 / Ra-226	Comments
A-2	9/27/1978	4.48	0.73	0.49	0.25	2.38	3.21	0.10	0.53	0.06	Series located in T24N, R93W, Sections 10,
A-3	9/27/1978	3.53	0.57	0.39	0.19	0.95	2.02	0.20	0.27	0.05	11,14,15,22 and 23
1-C	9/26/1978	2.4									
1-E	9/27/1978	2.5									Radial survey (8 radials) from point A,
1F-1	9/27/1978	2									located approx. 800' east of mill building
1F-2	9/27/1978	1.6									(i.e. SE Mill)
1F-3	9/27/1978	1.7									
1G	9/27/1978	1.5									
1-I	9/27/1978	1.4	0.32	0.22	0.11	1.3	1.1	0.08	0.93	0.08	
1K	9/27/1978	2.2									
2-C	9/27/1978	1.2									
2-E	9/27/1978	2.3									
2-G	9/27/1978	2.1									
2-I	9/27/1978	1.7	0.54	0.37	0.18	1.2	1.2	0.15	0.71	0.11	
2-K	9/27/1978	0.55									
3-C	9/27/1978	1.2									
3-E	9/27/1978	2	0.62	0.42	0.21	1.8	1.4	0.12	0.90	0.10	
3F-1	9/27/1978	1.8									
3F-2	9/27/1978	1									
3F-3	9/27/1978	0.29									
3-G	9/27/1978	0.93									
3-I	9/27/1978	4									
3-K	9/27/1978	1.6									
4-C	9/27/1978	4.6									
4-E	9/27/1978	0.78									
4-G	9/27/1978	1.7									
4-I	9/28/1978	1									
4-K	9/28/1978	0.62									
5-C	9/27/1978	2.3									
5-E	9/27/1978	0.97									
5F-1	9/27/1978	1.5	0.93	0.63	0.31	2	1.1	0.16	1.33	0.21	
5F-2	9/27/1978	1.4	1.1	0.74	0.37	1.8	1.2	0.21	1.29	0.27	
5F-3	9/27/1978	1.4	0.74	0.50	0.25	2.1	1.2	0.12	1.50	0.18	
5-G	9/26/1978	0.36									
5-I	9/26/1978	0.24									
5-K	9/28/1978	1.2									
6-C	9/28/1978	0.95	0.6	0.41	0.20	0.97	1.1	0.21	1.02	0.21	
6-E	9/28/1978	7.3									
6-G	9/26/1978	1.5									
6-I	9/26/1978	1.4									
6-K	9/28/1978	2.3									
7-C	9/26/1978	2.8									

Sample Location	Date	Ra-226 pCi/g	U-nat ug/g	U-nat pCi/g	U-238 pCi/gr	Th-230 pCi/g	Pb-210 pCi/g	U-238 / TH-230	TH-230 / Ra-226	U-238 / Ra-226	Comments
7-E	9/29/1978	1.5									
7F-1	9/29/1978	1.4	0.6	0.41	0.20	1.6	0.82	0.13	1.14	0.14	
7F-2	9/29/1978	1.4	0.46	0.31	0.16	1.5	1.5	0.10	1.07	0.11	
7F-3	9/29/1978	1.8	0.37	0.25	0.12	1.6	0.63	0.08	0.89	0.07	
7-G	9/26/1978	0.51									
7-I	9/26/1978	0.87									
7-K	9/28/1978	1.8									
8-C	9/28/1978	1.86									
8-E	9/28/1978	2.07									
8-G	9/26/1978	1.7	0.38	0.26	0.13	1.5	1.6	0.09	0.88	0.08	
8-I	9/26/1978	0.99									
8-K	9/26/1978	1.03									
Air-1	8/28/1978	1.05	0.49	0.33	0.17	0.98	1.16	0.17	0.93	0.16	1978 Pre-Op Sampling
Air-2	8/28/1978	0.3	0.47	0.32	0.16	0.2	1.47	0.79	0.67	0.53	
Air-3	8/28/1978	1.8	0.41	0.28	0.14	1.51	2.18	0.09	0.84	0.08	
Air-4	8/28/1978	3.7	0.59	0.40	0.20	4.27	8.64	0.05	1.15	0.05	
Air-5	8/28/1978	0.3	0.37	0.25	0.12	1.42	1.33	0.09	4.73	0.42	
PRO 1A	4/13/1978	3	12	8.12	4.05	3.2	4.4	1.27	1.07	1.35	
PRO 1B	4/13/1978	4.2	9.4	6.36	3.17	2.4	3.3	1.32	0.57	0.76	
PRO 6A	4/13/1978	1.8	4	2.71	1.35	1.6	1.9	0.84	0.89	0.75	
PRO 6A	10/20/1979		3.5	2.37	1.18						
PRO 6B	4/13/1978	1.1	6.2	4.20	2.09	2.7	2.1	0.78	2.45	1.90	
AIR 1	10/20/1979		1.8	1.22	0.61						
AIR 2	10/20/1979		1.8	1.22	0.61						
AIR 4	10/20/1979		2	1.35	0.68						
PRO 6	10/20/1979		3.5	2.37	1.18						
SVS 1A	10/16/1979	2	3.9	2.64	1.32	1.8	2.4	0.73	0.90	0.66	SVS Series Sampling
SVS 1A	4/13/1978	4.2	14	9.48	4.73	2.8	2.7	1.69	0.67	1.13	Data Summary Sheet
SVS 1A	10/30/1980	1.6	3.4	2.30	1.15	1.6	2.4	0.72	1.00	0.72	Eberline Lab Data
SVS 1B	10/16/1979	2.1	4.6	3.11	1.55	1.7	0.76	0.91	0.81	0.74	Eberline
SVS 1B	4/13/1978	3.6	12	8.12	4.05	2.9	1.6	1.40	0.81	1.13	Summary Sheet
SVS 1B	10/30/1980	2	3	2.03	1.01	2.4	0.74	0.42	1.20	0.51	Eberline
SVS 2A	10/16/1979	0.63	1.1	0.74	0.37	0.82	1.8	0.45	1.30	0.59	Eberline
SVS 2A	10/16/1979	0.8		0.00	0.00	3.8	ND		4.75		Hazen Lab Data
SVS 2A	4/13/1978	1	1.3	0.88	0.44	0.74	1.1	0.59	0.74	0.44	Summary Sheet
SVS 2A	10/29/1980	0.49	0.87	0.59	0.29	0.57	0.25	0.52	1.16	0.60	Eberline
SVS 2B	10/22/1979	0.74	1.9	1.29	0.64	1.2	1.1	0.53	1.62	0.87	Eberline
SVS 2B	4/13/1978	0.19	1.8	1.22	0.61	0.87	ND	0.70	4.58	3.20	Summary Sheet
SVS 2B	10/30/1980	0.75	1.1	0.74	0.37	0.55	0.78	0.68	0.73	0.50	Eberline
SVS 3A	10/16/1979	1.4	2.3	1.56	0.78	1.2	2.2	0.65	0.86	0.55	Eberline
SVS 3A	10/16/1979	2		0.00	0.00	3.2	0.7		1.60		Hazen
SVS 3A	4/13/1978	1.7	2.1	1.42	0.71	1.3	2.3	0.55	0.76	0.42	Summary Sheet

Sample Location	Date	Ra-226	U-nat	U-nat	U-238	Th-230	Pb-210	U-238 /	TH-230 /	U-238 /	Comments
		pCi/g	ug/g	pCi/g	pCi/gr	pCi/g	pCi/g	TH-230	Ra-226	Ra-226	
SVS 3A	10/29/1980	1.2	2	1.35	0.68	0.97	1.9	0.70	0.81	0.56	Eberline
SVS 3B	10/16/1979	1.4	2	1.35	0.68	1.4	1.4	0.48	1.00	0.48	Eberline
SVS 3B	4/13/1978	1.7	3.1	2.10	1.05	1.2	1.4	0.87	0.71	0.62	Summary Sheet
SVS 3B	10/29/1980	1.5	2	1.35	0.68	1.5	1.2	0.45	1.00	0.45	Eberline
SVS 4A	10/20/1979	0.99	2.3	1.56	0.78	1.1	1.7	0.71	1.11	0.78	Eberline
SVS 4A	4/13/1978	1.8	2.2	1.49	0.74	2	2.2	0.37	1.11	0.41	Summary Sheet
SVS 4A	10/29/1980	0.41	1.4	0.95	0.47	1.1	2.3	0.43	2.68	1.15	Eberline
SVS 4B	10/20/1979	2.8	3	2.03	1.01	9.1	2.7	0.11	3.25	0.36	Eberline
SVS 4B	4/13/1978	1.7	2.51	1.70	0.85	1.1	1.7	0.77	0.65	0.50	Summary Sheet
SVS 4B	10/29/1980	0.78	1.9	1.29	0.64	0.91	0.9	0.70	1.17	0.82	Eberline
SVS 5A	10/20/1979	0.22	1.7	1.15	0.57	0.78	1.7	0.74	3.55	2.61	Eberline
SVS 5A	10/20/1979	1.2				3.5	2.4		2.92		Hazen
SVS 5A	4/13/1978	0.55	3.5	2.37	1.18	1.1	2	1.07	2.00	2.15	Summary Sheet
SVS 5A	10/29/1980	0.85	1.8	1.22	0.61	1.1	2.1	0.55	1.29	0.71	Eberline
SVS 5B	10/20/1979	0.78	1.8	1.22	0.61	1	1.1	0.61	1.28	0.78	Eberline
SVS 5B	4/13/1978	2.2	2.8	1.90	0.95	1.3	1.8	0.73	0.59	0.43	Summary Sheet
SVS 5B	10/29/1980	1.1	1.8	1.22	0.61	2.1	1.2	0.29	1.91	0.55	Eberline
SVS 6A	10/20/1979	0.59	2.6	1.76	0.88	1	1.6	0.88	1.69	1.49	Eberline
SVS 6A	10/30/1980	0.64	1.1	0.74	0.37	0.61	2	0.61	0.95	0.58	Eberline
SVS 6B	10/20/1979	0.71	2.7	1.83	0.91	2.2	0.84	0.41	3.10	1.28	Eberline
SVS 6B	10/30/1980	0.53	3.6	2.44	1.22	0.2	0.96	6.08	0.38	2.29	Eberline
SVS 7A	10/20/1979	0.52	1.3	0.88	0.44	1.7	1.3	0.26	3.27	0.84	Eberline
SVS 7A	10/30/1980	1.4	1.5	1.02	0.51	0.8	1.1	0.63	0.57	0.36	Eberline
SVS 7B	10/20/1979	0.36	1.3	0.88	0.44	1.2	0.44	0.37	3.33	1.22	Eberline
SVS 7B	10/30/1980	0.56	3.2	2.17	1.08	0.16	2.3	6.75	0.29	1.93	Eberline
SVS 8A	10/20/1979	0.57	1.3	0.88	0.44	1.8	1.2	0.24	3.16	0.77	Eberline
SVS 8A	10/30/1980	0.51	1.8	1.22	0.61	0.31	1.8	1.96	0.61	1.19	Eberline
SVS 8B	10/20/1979	0.94	1.8	1.22	0.61	1.3	0.7	0.47	1.38	0.65	Eberline
SVS 8B	10/30/1980	0.85	1.6	1.08	0.54	2.3	0.96	0.23	2.71	0.64	Eberline
SL 1	3/3/1980	1				1.5	1.8		1.50		Eberline
SL 2	3/3/1980	0.4				1.7	2.2		4.25		Eberline
SL 2-A	3/3/1980	0.6				8.7	6.4		14.50		Eberline
SL 3	3/3/1980	1				1.4	2		1.40		Eberline
SL 4	3/3/1980	2				4	3.3		2.00		Eberline
SL 5	3/3/1980	0.97				1.5	2.2		1.55		Eberline
C-1 1-A	7/16/1980										Ra-226 = 13, Likely
C-1 1-B	7/16/1980										Ra-226 = 20 not
C-1 1-C	7/16/1980										Ra-226 = 16 surface
C-1 1-D	7/16/1980										Ra-226 = 17 soils
C-1 1-E	7/16/1980										Ra-226 = 12
C-1 1-F	7/16/1980										Ra-226 = 16
C-1 1-G	7/16/1980	3.6									Eberline

Sample Location	Date	Ra-226 pCi/g	U-nat ug/g	U-nat pCi/g	U-238 pCi/gr	Th-230 pCi/g	Pb-210 pCi/g	U-238 / TH-230	TH-230 / Ra-226	U-238 / Ra-226	Comments
C-1 1-H	7/16/1980	2.8									Eberline
C-1 1-I	7/16/1980	2.9									Eberline
C-1 1-J	7/16/1980	4									Eberline
C-1 1-K	7/16/1980	3.7									Eberline
C-1 1-L	7/16/1980	7.6									Eberline
C-1 1-M	7/16/1980	5.5									Eberline
C-1 1-N	7/16/1980	3.3									Eberline
C-1 1-O	7/16/1980	2.1									Eberline
C-1 1-P	7/16/1980	2.6									Eberline
C-1 1-Q	7/16/1980	2.3									Eberline
C-1 1-R	7/16/1980	2									Eberline
C-1 1-S	7/16/1980	2.6									Eberline
C-1 1-T	7/16/1980	4									Eberline
C-1 1-U	7/16/1980	3.3									Eberline
C-1 1-V	7/16/1980	4.3									Eberline
C-1 1-W	7/16/1980	2.5									Eberline
C-1 1-X	7/16/1980	2.6									Eberline

MILL AREA AVERAGE	1.44	2.44	1.66	0.83	1.57	1.61	0.53	1.09	0.57	n = 146 (radium samples)
Std Dev	1.16	3.00	2.03	1.01	1.19	1.12	0.85	1.03	0.88	
MILL AVG	0.29	0.39	0.26	0.13					0.46	n = 10
SOIL STATION SERIES AVG	2.05	5.25	3.55	1.77	1.84	2.01	0.96	0.90	0.86	n = 16
T-SERIES AVG	0.26	0.47	0.32	0.16	0.40	0.44	0.39	1.55	0.61	n = 10
1978 MILL RADIALS	1.80	0.63	0.43	0.21	1.69	1.39	0.13	0.94	0.12	n = 56
1978/79 PRO/Air	1.92	3.32	2.25	1.12	2.03	2.94	0.55	1.06	0.59	n = 9
SVS SERIES AVG	1.21	2.69	1.82	0.91	1.61	1.53	0.57	1.32	0.75	n = 45
PIT STOCKPILE AVG	1.00				3.13	2.98		3.15		n = 6
C-1 WASTE DUMP AVG	3.43									n = 18

Note: ▨ **indicates a data population not used in the calculation of overall mean**

Appendix 26

ORIGINAL ARTICLE

Mortality among a cohort of uranium mill workers: an update

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Occup Environ Med 2004;**61**:57–64

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Accepted 27 March 2003

Aims: To evaluate the mortality experience of 1484 men employed in seven uranium mills in the Colorado Plateau for at least one year on or after 1 January 1940.

Methods: Vital status was updated through 1998, and life table analyses were conducted.

Results: Mortality from all causes and all cancers was less than expected based on US mortality rates. A statistically significant increase in non-malignant respiratory disease mortality and non-significant increases in mortality from lymphatic and haematopoietic malignancies other than leukaemia, lung cancer, and chronic renal disease were observed. The excess in lymphatic and haematopoietic cancer mortality was due to an increase in mortality from lymphosarcoma and reticulosarcoma and Hodgkin's disease. Within the category of non-malignant respiratory disease, mortality from emphysema and pneumoconioses and other respiratory disease was increased. Mortality from lung cancer and emphysema was higher among workers hired prior to 1955 when exposures to uranium, silica, and vanadium were presumably higher. Mortality from these causes of death did not increase with employment duration.

Conclusions: Although the observed excesses were consistent with our a priori hypotheses, positive trends with employment duration were not observed. Limitations included the small cohort size and limited power to detect a moderately increased risk for some outcomes of interest, the inability to estimate individual exposures, and the lack of smoking data. Because of these limitations, firm conclusions about the relation of the observed excesses in mortality and mill exposures are not possible.

In the United States, mining and milling of uranium ores to recover uranium for nuclear weapons began during World War II to support the Manhattan Project. Uranium bearing ores had been mined previously on a small scale, but mainly for the recovery of vanadium. Continued development and expansion of the industry after the war was promoted by a domestic uranium concentrate procurement programme that was established by the Atomic Energy Commission in 1947.[1] As early as 1949, health officials became concerned about the potential health risks associated with uranium mining and milling.[2]

The health risks associated with uranium mining have been extensively studied. Uranium miners have been found to have a substantially increased risk of death from lung cancer, which is associated with cumulative exposure to radon decay products.[3–5] Excess mortality from non-malignant respiratory diseases has also been found.[6] However, existing data concerning the health effects of uranium milling are limited. Waxweiler and colleagues reported a significantly increased risk of "other non-malignant respiratory disease" (standardised mortality ratio (SMR) = 2.50; observed (obs) = 39) among 2002 workers at seven uranium mills in the Colorado Plateau.[7] This category included emphysema, fibrosis, silicosis, and chronic obstructive pulmonary disease. Non-significant excesses were observed for lymphatic and haematopoietic malignancies other than leukaemia after 20 years latency (SMR = 2.3; obs = 6) and chronic renal disease (SMR = 1.67; obs = 6). In an earlier overlapping study of 662 uranium mill workers, Archer and colleagues observed an excess risk of mortality from lymphatic and haematopoietic malignancies other than leukaemia (SMR = 3.92; obs = 4).[8] Limited data from morbidity studies suggest that uranium millers may have an increased risk of pulmonary fibrosis[2] and renal tubular injury.[9]

The primary exposures of interest in uranium mills are uranium, silica, and vanadium containing dusts. Inhalation of uranium dust may pose an internal radiation hazard as well as the potential for chemical toxicity. High concentrations of radon and radon decay products, similar to the levels found in underground uranium mines, are not expected in the mills.

Because of continuing concern about the health effects of uranium milling, we extended the follow up of the cohort described by Waxweiler and colleagues.[7] The present report describes the mortality experience of the cohort through 21 additional years of observation. In addition, the risk of end stage renal disease was evaluated among the cohort.

Uranium milling process

The primary function of uranium mills is to extract and concentrate uranium from uranium containing ore to produce a semi-refined product known as yellowcake. Yellowcake is a chemically complex mixture of diuranates, basic uranyl sulphate, and hydrated uranium oxides that contains 80–96% uranium as U_3O_8, UO_3, and/or ammonium diuranate.[10] Yellowcake is used commercially to manufacture nuclear fuel for nuclear power and national defence purposes.

Conventional mills process uranium bearing ores from underground or open-pit mines. Until the mid-1970s, all yellowcake in the United States was produced at conventional uranium mills.[11] The main stages of the process in conventional mills involved: (1) ore handling and preparation; (2) extraction; (3) concentration and purification; and (4) precipitation, drying, and packaging. So-called "upgrader" facilities processed virgin ore that was initially too low in uranium content to process economically in a uranium mill. At an upgrader, a series of crushing, grinding, and chemical separation steps were employed to "upgrade" the percent

Main messages

- Potential exposures among uranium mill workers that may be associated with adverse health effects include uranium, silica, and vanadium containing dusts.
- We observed a statistically significant increase in mortality from non-malignant respiratory disease and non-significant increases in mortality from lymphatic and haematopoietic malignancies other than leukaemia, lung cancer, and chronic renal disease. These findings were consistent with our a priori hypotheses.
- The SMRs for lung cancer and emphysema among men hired before 1955, when exposures to uranium, silica, and vanadium were presumably higher, were significantly increased and greater than the SMRs observed among men hired in 1955 or later. However, mortality for causes of death observed to be in excess did not increase with employment duration.
- Limitations include a lack of smoking data, small cohort size and limited power to detect a moderately increased risk for some outcomes of interest, and the inability to estimate individual exposures to uranium, silica, and vanadium.

uranium contained in the final product, which was sent to a uranium mill for further processing. Unlike conventional uranium mills, upgrader facilities did not carry out concentration and purification of the uranium, and precipitation, drying, and packaging of yellowcake. In this paper, the term "mill" will be used in reference to both conventional uranium mills and upgrader facilities.

METHODS

Cohort description

The cohort was assembled from the personnel records obtained from the companies operating seven uranium mills (five conventional uranium mills and two upgraders). The original cohort described by Waxweiler and colleagues, which is referred to hereafter as the Waxweiler cohort, included 2002 men who had worked for at least one day after 1 January 1940, worked for at least one year in uranium mills, and never worked in underground uranium mines.[7] Because some of the work histories in the Waxweiler cohort were found to be coded inaccurately, we recoded all work histories. We also reviewed documentation from the original study to identify men who met the original cohort criteria, but had been omitted. Personnel records were obtained and work histories updated for cohort members who were still employed in 1971 when the personnel records were originally microfilmed. After re-coding the work histories, we limited the cohort to men who met the original cohort criteria, had never worked in an above-ground or underground uranium mine, and had worked for at least one year in the seven uranium mills before the personnel records were originally microfilmed in 1971 while the mills were operating to recover uranium and/or vanadium concentrates. The final cohort included 1485 men, 1438 (96.8%) of whom were in the Waxweiler cohort. Of the 564 workers not included in the current study, 103 (18.3%) worked in uranium mines, 318 (56.4%) never worked in one of the seven mills comprising the study, 141 (25.0%) worked for less than one year in the seven mills when they were operating, and one (0.2%) was excluded because the work history was incomplete. One woman whose gender was coded incorrectly in the Waxweiler cohort was also excluded.

Follow up

The vital status of all persons in the cohort was determined until 31 December 1998. Follow up included inquiry through the Social Security Administration, Internal Revenue Service, US Postal Service, National Death Index (NDI), and state bureaus of motor vehicles. Death certificates were obtained from state vital records offices for some deceased members of the cohort and coded by a trained nosologist according to the revision of the International Classification of Diseases in effect at the time of death. The causes of death for other deceased members of the cohort were obtained from the NDI.

To identify cohort members with treated end stage renal disease, the cohort was linked with the End Stage Renal Disease (ESRD) Program Management and Medical Information System (PMMIS) by name, social security number, and date of birth. The ESRD PMMIS is maintained by the Health Care Financing Administration (HCFA) and includes all individuals who received Medicare covered renal replacement therapy (dialysis or transplant) in 1977 or later. Approximately 93% of ESRD patients in the United States are included in the ESRD PMMIS.[12]

Analysis

The mortality experience of the cohort was analysed with the use of the National Institute for Occupational Safety and Health (NIOSH) modified life table analysis system (LTAS).[13 14] Each cohort member accumulated person-years at risk (PYAR) for each year of life after 1 January 1940 or completion of the one year eligibility period, whichever was later, until the date of death for deceased cohort members, the date last observed for persons lost to follow up, or the ending date of the study (31 December 1998) for cohort members known to be alive. Cohort members known to be alive after 1 January 1979 (the date that the NDI began) and not identified as deceased were assumed to be alive as of 31 December 1998. The PYAR were stratified into five year intervals by age and calendar time and were then multiplied by the appropriate US gender, race, and cause specific mortality rates to calculate the expected number of deaths for that stratum. The resulting expected numbers were summed across strata to obtain cause specific and total expected number of deaths. The ratio of observed to expected number of deaths was expressed as the standardised mortality ratio (SMR). Ninety five per cent confidence intervals (CI) were computed for the SMRs assuming a Poisson distribution for observed deaths. The mortality analysis was repeated using Colorado, New Mexico, Arizona, and Utah state mortality rates to generate expected numbers of deaths. In addition to analyses of underlying cause of death, all causes listed on the death certificate were analysed using multiple cause mortality methods described by Steenland and colleagues.[15] Multiple cause analyses are particularly important for diseases that may be prevalent at death but that are not the underlying cause of death.[15] In analyses using state or multiple cause mortality rates, person-years at risk started to accumulate on 1 January 1960, when the rates were first available, or completion of the one year eligibility period, whichever was later.

The end stage renal disease experience of the cohort was analysed using methods described by Calvert and colleagues.[16] Briefly, the modified life table analysis system was used to calculate PYAR, expected number of individuals developing ESRD, and standardised incidence ratios (SIRs) for ESRD. Since the ESRD PMMIS is considered incomplete prior to 1977, cohort members who died before this date were excluded from the ESRD analysis. PYAR for cohort members who were alive on 1 January 1977 began to accumulate on this date. Cohort members accumulated PYAR until the first service date for those with ESRD, the date of death for deceased cohort members, the date last observed for those lost to follow up, or the ending date of the study for those known to be alive. The first service date for ESRD, which generally represents the date on which renal replacement therapy began, was used as a surrogate for the date of onset of ESRD. After the PYAR were stratified into five year intervals by age and calendar time, the PYAR were multiplied by the appropriate US ESRD incidence rates to calculate the expected number of cases for that stratum. The US incidence rates were developed by NIOSH from the HCFA PMMIS data and US census data as described elsewhere.[16] The expected number of treated ESRD cases in all strata were summed to yield the total expected number. The ratio of the observed to expected number of treated ESRD cases was expressed as the standardised incidence ratio (SIR). The SIR for four major categories of ESRD (systemic, non-systemic, other, and unknown) were also calculated.

We stratified SMRs and SIRs by duration of employment (1–2, 3–9, 10+ years), time since first employment (latency) (0–9, 10–19, 20+ years), and year of first employment (<1955, 1955+). In general, the cut points for duration of employment and time since first employment were retained from the original study; however, we lowered the cut point between the lowest and middle duration of employment categories so that the number of deaths in each category would be more similar. The cut point for year first employed was selected a priori based on the assumption that exposures in the earlier years (when there was little emphasis on dust control) would be higher than in later years. Duration of employment was based on employment in the seven cohort mills while they were operating to produce uranium and/or vanadium concentrates and included employment that occurred prior to the start of the follow up period. The analyses were repeated restricting the cohort to those who had worked in a conventional mill and to those who had worked in a conventional mill that produced both vanadium and uranium concentrates. Because of the potential impact of exposures encountered during other employment in the uranium industry, SMRs and SIRs were also conducted restricting the cohort to those without such employment. All analyses were done using the PC version of the LTAS[17] (http://www.cdc.gov/niosh/ltindex.html). Testing for heterogeneity and trend in the SMRs used the methods of Breslow and Day.[18]

Based on previous studies and the known toxic effects of uranium and silica, the a priori outcomes of interest in this study included non-malignant respiratory disease, chronic renal disease, lung cancer, and lymphatic and haematopoietic cancer other than leukaemia. Within the major category of non-malignant respiratory disease, the minor category "pneumoconiosis and other respiratory diseases" was of a priori interest.

Table 1 Characteristics of the study population

No. of workers	1485
Excluded from analysis*	1
Person-years at risk	49925
Mill type	
Conventional mill only	1412 (95.1%)
Upgrader only	44 (3.0%)
Both	28 (1.9%)
Vital status as of 31 Dec 1998	
Alive	656 (44.2%)
Dead	810 (54.6%)
Unknown	18 (1.2%)
Year of birth	1921 median 1872–1951 range
Year of first employment†	
Prior to 1955	799 (53.8%)
1955 or later	685 (46.2%)
Duration of employment†	
1–2 years	634 (42.7%)
3–9 years	547 (36.9%)
10 + years	303 (20.4%)
Time since first employment†	
<10 years	76 (5.1%)
10–19 years	128 (8.6%)
20+ years	1280 (86.3%)

*Missing date of birth.
†Employment in the seven mills while operating to produce uranium and/or vanadium concentrates.

RESULTS

A total of 1484 men contributing 49 925 person-years were included in the study. Table 1 presents the distribution of the cohort by vital status, plant type (conventional mill, upgrader), duration of employment, time since first employment, and first year of employment. Race was unknown for 642 (43.3%) members of the cohort. Because all workers of known race were white, workers of unknown race were classified as white in the analysis. In the total cohort, 656 (44.2%) men were alive, 810 (54.6%) were deceased, and 18 (1.2%) were lost to follow up. Causes of death were obtained from death certificates or the NDI for 794 (98.0%) of the individuals known to be deceased. Deaths with missing causes of death were included in the other and unknown causes category. The duration of employment of the cohort is relatively short with a median of 3.6 (range 1–36.3) years. Over half of the cohort was first employed prior to 1955. The median time since first employment, based on employment in the seven mills while they were operating, is 37 years.

Almost all of the workers and person-years were from conventional uranium mills. Of the 1440 men who were employed at conventional mills, 1263 (87.7%) were employed at mills that recovered vanadium, 145 (10.1%) were employed at mills that did not recover vanadium, and 32 (2.2%) were employed both at mills that recovered vanadium and mills that did not recover vanadium. Among the entire cohort, 83 (5.6%) men had also been employed in other aspects of the uranium industry according to their employment application or other employment records.

Table 2 shows the results of the analysis for all causes of death. Mortality from all causes was less than expected, which is largely accounted for by fewer deaths from heart disease than expected. Mortality from all malignant neoplasms was also less than expected. Among the outcomes of a priori interest, a statistically significant increase in mortality from non-malignant respiratory disease (SMR = 1.43; 95% CI 1.16 to 1.73; obs = 100) and non-significant increases in mortality from trachea, bronchus, and lung cancer (SMR = 1.13; 95% CI 0.89 to 1.41; obs = 78), lymphatic and haematopoietic malignancies other than leukaemia (SMR = 1.44; 95% CI 0.83 to 2.35; obs = 16), and chronic renal disease (SMR = 1.35; 95% CI 0.58 to 2.67; obs = 8) were observed. The excess in mortality from lymphatic and haematopoietic malignancies was due to an excess in mortality from lymphosarcoma and reticulosarcoma (SMR = 1.74; 95% CI 0.48 to 4.46; obs = 4) and Hodgkin's disease (SMR = 3.30; 95% CI 0.90 to 8.43; obs = 4). Within the major category of non-malignant respiratory disease, mortality from emphysema (SMR = 1.96; 95% CI 1.21 to 2.99; obs = 21) and pneumoconioses and other respiratory disease (SMR = 1.68; 95% CI 1.26 to 2.21; obs = 52) was significantly increased. Among outcomes other than those of a priori interest, non-significant increases in mortality from other and unspecified cancers (SMR = 1.59; 95% CI 0.98 to 2.43; obs = 21) and accidents (SMR = 1.26; 95% CI 0.93 to 1.68;

Table 2 Uranium mill workers' mortality (since 1940, US referent rates): update of cohort to 1998

Underlying cause of death (ICD9 code)*	Obs	Exp	SMR	95% CI
All causes	810	877.66	0.92‡	0.86 to 0.99
All cancers (140–208)	184	204.12	0.90	0.78 to 1.04
Buccal and pharyngeal CA (140–149)	2	5.06	0.40	0.05 to 1.43
All digestive CA (150–159)	33	53.18	0.62§	0.43 to 0.87
Oesophagus (150)	1	5.06	0.20	0.01 to 1.10
Colon (152–153)	12	18.96	0.63	0.33 to 1.11
Rectal (154)	2	4.77	0.42	0.05 to 1.51
Liver and biliary (155–156)	4	5.04	0.79	0.22 to 2.03
Pancreas (157)	6	10.30	0.58	0.21 to 1.27
All respiratory CA (160–165)	78	72.29	1.08	0.85 to 1.35
Trachea, bronchus, and lung (162)	78	68.93	1.13	0.89 to 1.41
Male genital CA (185–187)	15	19.67	0.76	0.43 to 1.26
All urinary CA (188–189)	5	11.03	0.45	0.15 to 1.06
Kidney (189.0–189.2)	4	4.96	0.81	0.22 to 2.06
Leukaemia/aleukaemia (204–208)	5	7.62	0.66	0.21 to 1.53
Lymphatic and haematopoietic CA other than leukaemia (200–203)	16	11.08	1.44	0.83 to 2.35
Lymphosarcoma and reticulosarcoma (200)	4	2.29	1.74	0.48 to 4.46
Hodgkin's disease (201)	4	1.21	3.30	0.90 to 8.43
Other lymphatic and haematopoietic CA (202–203)	8	7.57	1.06	0.46 to 2.08
Other/unspecified CA (194–199)	21	13.20	1.59	0.98 to 2.43
Tuberculosis (001–008)	2	3.88	0.52	0.06 to 1.86
Diabetes mellitus (250)	10	14.60	0.68	0.33 to 1.26
Heart disease (390–398, 402, 404, 410–414, 420–429)	293	349.10	0.84§	0.75 to 0.94
Ischemic heart disease (410–414)	236	280.07	0.84§	0.74 to 0.96
Other circulatory disease (401, 403, 405, 415–417, 430–459)	69	83.06	0.83	0.65 to 1.05
Non-malignant respiratory disease (460–519)	100	70.16	1.43§	1.16 to 1.73
Pneumonia (480–486)	25	23.76	1.05	0.68 to 1.55
Chronic and unspecified bronchitis (490–491)	2	2.20	0.91	0.11 to 3.28
Emphysema (492)	21	10.72	1.96§	1.21 to 2.99
Pneumoconioses and other respiratory disease (470–478, 494–519)	52	30.87	1.68§	1.26 to 2.21
Non-malignant digestive disease (520–579)	23	36.91	0.62‡	0.39 to 0.94
Non-malignant genitourinary disease (580–629)	13	13.03	1.00	0.53 to 1.71
Acute renal disease (580–581, 584)	1	1.16	0.86	0.02 to 4.79
Chronic renal disease (582–583, 585–587)	8	5.91	1.35	0.58 to 2.67
Ill defined conditions (780–796, 798–799)	4	8.01	0.50	0.14 to 1.28
Accidents (E800–E949)	47	37.23	1.26	0.93 to 1.68
Violence (E950–E978)	18	17.73	1.02	0.60 to 1.60
Suicide (E950–E959)	15	14.19	1.06	0.59 to 1.74
Homicide (E960–E978)	3	3.54	0.85	0.18 to 2.48
Other and unknown causes	27†	14.04	1.92§	1.27 to 2.80

*International Classification of Disease codes, 9th revision.
†Includes 16 observed deaths with missing death certificates.
‡95% confidence interval excludes the null value (1.0).
§99% confidence interval excludes the null value (1.0).

obs = 47) were observed. The observed other and unspecified cancers were metastatic cancers of unknown primary site. Mortality from all digestive cancers was significantly less than expected (SMR = 0.62; 95% CI 0.43 to 0.87; obs = 33).

An analysis was also conducted (not shown) using US rate files for 1960 to 1999 which have 99 causes of death instead of 92 because these rate files include more detailed categories of non-malignant respiratory disease and slightly different categories of malignancies of the lymphatic and haematopoietic system. Of the 1484 cohort members, 89 (6.0%) were not included in this analysis because they had either died or were lost to follow up before 1960. Only one death from silicosis (SMR = 5.93; 95% CI 0.15 to 32.94) and two deaths from pneumoconioses other than silicosis and asbestosis (SMR = 2.29; 95% CI 0.28 to 8.25) were observed. The remainder of the excess in non-malignant respiratory disease mortality was due to a significant excess in mortality from emphysema (SMR = 1.83; 95% CI 1.10 to 2.86) and other respiratory diseases (SMR = 1.62; 95% CI 1.19 to 2.15). Most of the observed deaths from other respiratory diseases were due to chronic obstructive lung disease. In the category of malignancies of the lymphatic and haematopoietic system other than leukaemia, mortality was significantly increased for Hodgkin's disease (SMR = 4.01; 95% CI 1.09 to 10.25, obs = 4) and non-significantly increased for non-Hodgkin's lymphoma (SMR = 1.25; 95% CI 0.54 to 2.46; obs = 8).

In order to evaluate whether regional variations in mortality rates could explain the findings, analyses were conducted using state rates as the comparison population (table 3). State rates are not available before 1960 so men who had either died or were lost to follow up before 1960 were also excluded from this analysis. The excess in mortality from cancer of the trachea, bronchus, and lung (SMR = 1.51; 95% CI 1.19 to 1.89) based on state rates was statistically significant and greater than the excess based on US rates since 1960 (SMR = 1.13; 95% CI 0.89 to 1.42). In contrast, the excess in mortality from emphysema (SMR = 1.25; 95% CI 0.75 to 1.95) and other respiratory diseases (SMR = 1.35; 95% CI 0.99 to 1.79) was less than the excess based on US rates. Mortality from chronic renal disease was not increased based on state rates (SMR = 1.02; 95% CI 0.33 to 2.39; obs = 5) and was similar to that based on US rates since 1960 (SMR = 1.00; 95% CI 0.32 to 2.35). This is in contrast to the excess in mortality from chronic renal disease observed based on US rates since 1940.

Tables 4 and 5 show mortality according to duration of employment and time since first employment for selected causes of death based on US rates. Overall mortality was highest among those with the shortest duration of employment and lowest among those with the longest duration of employment. Similar trends with duration of employment were observed for mortality from lung cancer, non-malignant

Table 3 Uranium mill workers' mortality (since 1960) from selected causes of death (state referent rates): update of cohort to 1998

Underlying cause of death (ICD9 code)*	Obs	Exp	SMR	95% CI
All respiratory CA (160–165)	75	51.98	1.44‡	1.13 to 1.81
Trachea, bronchus, and lung (162)	75	49.73	1.51‡	1.19 to 1.89
Leukaemia/aleukaemia (204–208)	5	6.51	0.77	0.25 to 1.80
Lymphatic and haematopoietic CA other than leukaemia (200–203)	15	9.58	1.57	0.88 to 2.58
Non-Hodgkin's lymphoma (200, 202)	8	5.71	1.40	0.60 to 2.76
Hodgkin's disease (201)	4	0.94	4.24†	1.15 to 10.84
Myeloma (203)	3	2.93	1.02	0.21 to 3.00
Other/unspecified CA (187, 194–199)	22	11.93	1.84‡	1.16 to 2.79
Non-malignant respiratory diseases (460–519)	94	79.32	1.19	0.96 to 1.45
Chronic and unspecified bronchitis (490–491)	1	2.74	0.36	0.01 to 2.03
Emphysema (492)	19	15.22	1.25	0.75 to 1.95
Asbestosis (501)	0	0.12	0.00	0.00 to 30.62
Silicosis (502)	1	0.45	2.22	0.06 to 12.36
Other pneumoconioses (500, 503, 505)	2	0.40	5.04	0.61 to 18.19
Other respiratory diseases (470–478, 494–499, 504, 506–519)	47	34.86	1.35	0.99 to 1.79
Non-malignant genitourinary disease (580–629)	10	10.51	0.95	0.46 to 1.75
Acute renal disease (580–581, 584)	1	0.79	1.26	0.03 to 6.99
Chronic renal disease (582–583, 585–587)	5	4.89	1.02	0.33 to 2.39

*International Classification of Disease codes, 9th revision.
†95% confidence interval excludes the null value (1.0).
‡99% confidence interval excludes the null value (1.0).

respiratory disease, and emphysema. A positive trend between mortality and duration of employment was not observed for any of the selected causes of death except other and unspecified cancers. The excess in mortality from Hodgkin's disease was confined to 20 years or more since first employment. Mortality from Hodgkin's disease was significantly increased over sevenfold among this group, but the confidence interval around the point estimate was wide (95% CI 1.96 to 18.40).

Mortality was also examined (not shown) by date of hire (pre-1955 versus 1955 or later). There appeared to be a relation between an earlier date of hire and increased mortality from trachea, bronchus, and lung cancer (prior to 1955: SMR = 1.34, 95% CI 1.02 to 1.74; 1955 or later: SMR = 0.79, 95% CI 0.49 to 1.21). Mortality from emphysema was also higher among men hired prior to 1955 (SMR = 2.22; 95% CI 1.29 to 3.56; obs = 17) than among men hired in 1955 or later (SMR = 1.30; 95% CI 0.36 to 3.33; obs = 4), but mortality from pneumoconiosis and other respiratory disease was similar among men hired prior to 1955 (SMR = 1.69; 95% CI 1.17 to 2.36) and men hired in 1955 or later (SMR = 1.68; 95% CI 0.99 to 2.65).

Analyses of multiple causes of death and end stage renal disease incidence were conducted to further evaluate the risk of renal disease among the cohort. The risk of chronic renal disease mortality was not increased (SMR = 1.05; 95% CI 0.69 to 1.54, obs = 26) in the multiple causes of death analysis. The risk of treated end stage renal disease was less than expected overall (SIR = 0.71; 95% CI 0.26 to 1.55, obs = 6). The risk of treated end stage renal disease of unknown aetiology was increased (SIR = 2.73; 95% CI 0.56 to 7.98, obs = 3). This finding was based on three observed cases and the confidence interval was wide. The primary cause of renal failure was missing in the ESRD PMMIS for two of the three observed cases, raising the possibility that these cases were misclassified. Death certificates were available for these cases; renal disease was mentioned on the death certificate for both, but not a specific type or aetiology of renal disease.

Similar results were obtained when the cohort was restricted to men who were employed in conventional mills and when the cohort was restricted to men who were employed in conventional mills that produced both uranium and vanadium concentrates. Results were also similar when

Table 4 Uranium mill workers' mortality (since 1940) from selected causes of death by duration of employment (US referent rates): update of cohort to 1998

	Duration of employment (years)			
Underlying cause of death	1–2 SMR (obs)	3–9 SMR (obs)	⩾10 SMR (obs)	
All deaths	1.01 (352)	0.91 (295)	0.80 (163)†	‡
All cancers	0.94 (75)	0.91 (68)	0.83 (41)	
Trachea, bronchus, and lung CA	1.35 (36)	1.27 (32)	0.58 (10)	‡
Lymphatic and haematopoietic CA other than leukaemia	1.38 (6)	1.22 (5)	1.90 (5)	
Lymphosarcoma and reticulosarcoma	2.15 (2)	1.15 (1)	2.03 (1)	
Hodgkin's disease	1.91 (1)	4.25 (2)	4.57 (1)	
Other lymphatic and haematopoietic CA	1.03 (3)	0.73 (2)	1.56 (3)	
Other/unspecified CA	1.16 (6)	1.65 (8)	2.19 (7)	
Non-malignant respiratory disease	1.99 (53)†	1.12 (29)	1.02 (18)	‡
Emphysema	2.69 (11)†	1.79 (7)	1.11 (3)	
Pneumoconioses and other respiratory diseases	2.53 (29)†	1.07 (12)	1.35 (11)	
Chronic renal disease	1.27 (3)	1.33 (3)	1.53 (2)	

*95% confidence interval excludes the null value (1.0).
†99% confidence interval excludes the null value (1.0).
‡Test for trend p value <0.05.

Table 5 Uranium mill workers' mortality (since 1940) from selected causes of death by length of time since first employment (US referent rates): update of cohort to 1998

Underlying cause of death	Time since first employment (years) <10 SMR (obs)	10–19 SMR (obs)	⩾20 SMR (obs)
All deaths	0.95 (68)	0.87 (125)	0.93 (617)
All cancers	0.62 (7)	0.88 (25)	0.92 (152)
Trachea, bronchus, and lung CA	0.36 (1)	1.45 (13)	1.12 (64)
Lymphatic and haematopoietic CA other than leukaemia	1.35 (1)	0.00 (0)	1.72 (15)
Lymphosarcoma and reticulosarcoma	3.33 (1)	0.00 (0)	2.24 (3)
Hodgkin's disease	0.00 (0)	0.00 (0)	7.19 (4)**
Other lymphatic and haematopoietic CA	0.00 (0)	0.00 (0)	1.18 (8)
Other/unspecified CA	0.00 (0)	1.21 (2)	1.76 (19)*
Non-malignant respiratory disease	1.32 (4)	1.48 (11)	1.42 (85)**
Emphysema	2.39 (1)	2.21 (4)	1.89 (16)*
Pneumoconioses and other respiratory diseases	3.73 (2)	2.24 (4)	1.61 (46)**
Chronic renal disease	3.95 (3)	1.23 (1)	0.92 (4)

*95% confidence interval excludes the null value (1.0).
**99% confidence interval excludes the null value (1.0).

the cohort was restricted to men without known employment in other aspects of the uranium industry.

DISCUSSION

Uranium exposure presents both chemical and radiological hazard potentials. Both the chemical and radiological toxicity are influenced by the biological solubility of a given uranium compound. Poorly soluble uranium compounds are cleared slowly from the lungs and pose a potential internal radiation hazard. More soluble compounds are absorbed rapidly from the lungs, decreasing the radiation hazard, but increasing the potential for renal toxicity.[19 20] In the ore handling and preparation areas of the mills, the uranium in ore dusts consists mostly of insoluble uranium oxides with a relatively small fraction of the more soluble uranium compounds. The potential for exposure to the long lived alpha emitters (uranium-238, uranium-234, thorium-230, radium-226, and lead-210) is greatest in these areas of the mill. In the yellowcake drying and packaging areas of the mill, the uranium in yellowcake consists of a complex mixture of uranium compounds of varying solubility. The composition and solubility of the yellowcake product depends on the drying temperature employed.[19 21] In mills that dry the product at relatively low temperatures (100–150℃), the yellowcake product is high in ammonium diuranate $[(NH_4)_2U_2O_7]$ which is highly soluble in lung fluids; in mills that dry the product at relatively high temperatures (370–538℃), the yellowcake is high in uranium oxide (U_3O_8) which is mostly insoluble in lung fluids.[21 22] Based on available data on drying temperatures and drying equipment, four of the five conventional mills in this study used relatively high drying temperatures. The fifth mill did not prepare a dried yellowcake product; rather, it produced filter press cake or a uranium product liquor, depending on the year of operation. Accordingly, most mill workers in this study worked in mills that probably produced yellowcake of relatively low solubility.

Both human and animal data suggest that insoluble uranium compounds and thorium accumulate in the tracheobronchial lymph nodes.[23–26] Because of this, it has been suggested that studies of early uranium workers evaluate the effects on lymphatic tissues.[25] In the previous study of workers at the mills in this study, a significant increase in mortality from lymphatic and haematopoietic malignancies other than leukaemia was observed after 20 years latency, based on six deaths.[7] We also found an excess in mortality from lymphatic and haematopoietic malignancies other than leukaemia but the magnitude of the excess was less than the excess observed in the previous study. The observed excess was due to an excess in both Hodgkin's disease mortality and lymphosarcoma and reticulosarcoma mortality based on four observed deaths each. The ability to evaluate exposure response relations, using duration of employment as a surrogate of exposure, was limited by the small number of observed deaths from these cancers. Of the eight observed deaths due to Hodgkin's disease, lymphosarcoma, and reticulosarcoma in this study, three were observed in the previous study and one was observed in the study by Archer and colleagues.[8]

Hodgkin's disease and non-Hodgkin's lymphoma, a group of lymphomas which includes lymphosarcoma and reticulosarcoma, have not been clearly linked to radiation.[27 28] Data on the risk of death from Hodgkin's disease and non-Hodgkin's lymphoma among uranium or thorium workers are limited. An increased risk of Hodgkin's disease mortality and lymphosarcoma and reticulosarcoma mortality has been observed among uranium processing workers at the Fernald Feed Materials Production Center near Cincinnati, Ohio (SMR = 2.04, 95% CI 0.74 to 4.43, obs = 6; and SMR = 1.67, 95% CI 0.72 to 3.29, obs = 8, respectively)[29] and thorium processing workers (SMR = 1.64, 95% CI 0.33 to 4.79, obs = 3; and SMR = 1.14, 95% CI 0.23 to 3.34, obs = 3, respectively),[30] but not among uranium processing workers at the Y-12 plant at Oak Ridge, Tennessee[31] and Mallinckrodt Chemical Works in St Louis, Missouri[32] or among a combined cohort of uranium and other miners from 11 studies.[33] Hodgkin's disease mortality and incidence and non-Hodgkin's lymphoma incidence was associated with cumulative external radiation dose among workers at the Springsfield uranium production facility; the effects of internal exposures were not evaluated.[34] In general, these studies, like the current study, are limited by the small number of deaths from Hodgkin's disease and non-Hodgkin's lymphoma among exposed workers.

A new finding in this update not previously reported was a small increase in mortality from cancer of the trachea, bronchus, and lung, particularly relative to state rates. We also observed an increased risk of mortality from non-malignant respiratory disease. Mortality from lung cancer was higher based on state rates than US rates, whereas mortality from non-malignant respiratory disease was lower based on state rates than US rates. This is consistent with the relatively low smoking attributable mortality and relatively high chronic obstructive lung disease mortality in Arizona, Colorado, and New Mexico compared to other states.[35] The reason for the discrepancy in smoking-attributable mortality and chronic obstructive lung disease mortality in many inland western states is unknown. However, the results suggest that regional differences in mortality may explain, in part, the observed excess in non-malignant respiratory disease mortality based on US rates.

The excess in both lung cancer mortality and emphysema mortality was greater among workers hired prior to 1955, when there was little emphasis on dust control and exposures to uranium and silica containing dusts were presumably higher. However, mortality from lung cancer and non-malignant respiratory disease was inversely related to duration of employment. We found no evidence that workers who were hired prior to 1955 were more likely to be short term workers. The inverse relation between lung cancer and emphysema mortality and duration of employment in this study may be a reflection of the healthy worker survivor effect, in which individuals who remain in the workforce over time tend to be healthier than those who leave.[36] Duration of employment may also be a poor surrogate of exposure in this study since exposures are thought to have varied considerably by mill area and over time.

Some data suggest that uranium workers other than miners may be at increased risk of lung cancer[29 31] and non-malignant respiratory disease.[37] Uranium ore dust has been shown to induce pulmonary lesions in animals[23 38 39] and lung cancer in rats.[40] Silica exposure has been reported to lead to the development of silicosis, emphysema, obstructive airways disease, and lymph node fibrosis.[41] Although the carcinogenicity of silica continues to be debated in the scientific community, several investigators have showed an increased risk of lung cancer among workers exposed to silica.[42–44] Vanadium containing compounds have known acute respiratory effects,[45] but it is less clear whether exposure to vanadium can lead to chronic non-malignant respiratory disease.[45 46] In this study, we only observed three deaths from silicosis and unspecified pneumoconioses. The majority of the excess in non-malignant respiratory disease mortality was due to mortality from emphysema and other respiratory disease.

Other potential explanations also exist for the observed excesses in mortality from lung cancer and non-malignant respiratory disease mortality. Smoking data are not available for this cohort, and differences in smoking habits between the cohort and the general population may partially explain the excesses observed. White men in the Colorado Plateau uranium miners cohort were heavy smokers,[6 47] but it is unknown whether the smoking habits of uranium mill workers who never worked underground in uranium mines would be similar to these miners. Even if the mill workers in this study were more likely to smoke than the general population, other investigators have shown that smoking is unlikely to account for SMRs above 1.3 for lung cancer and other smoking related diseases.[48] Other potential factors that may contribute to these excesses include unknown employment in underground uranium mines and employment in other mines with increased levels of radon and radon decay products. It is unlikely that the cohort included many mill workers who also worked as uranium miners. Mill workers who also worked in uranium mines were identified by reviewing the work history records and by matching the cohort to a NIOSH file of over 18 000 uranium miners. All identified uranium miners were excluded from the final cohort. However, members of the cohort may have been more likely to work in other types of mines than the general population.

We found a small non-significant excess in chronic renal disease when using US rates as a comparison; this excess was not apparent when only deaths between 1960 and 1998 were analysed (both underlying cause and multiple cause). Renal effects have been observed among silica exposed workers. Goldminers and industrial sand workers exposed to silica have been found to be at excess risk of death from renal disease and to have increased renal disease incidence.[16 49 50] Low level β_2 microglobulinuria and aminoaciduria has been observed among uranium mill workers exposed to soluble uranium compounds at a mill not in the current study,[9] but little data on chronic renal disease mortality among uranium workers exist. An increase in mortality from chronic nephritis (SMR = 1.88; 95% CI 0.75 to 3.81) was observed among uranium processing workers at Mallinckrodt, based on six observed deaths.[32] An excess in chronic renal disease mortality has been observed among uranium miners (SMR = 1.6; 95% CI 0.7 to 3.0, obs = 9), but the observed excess was not related to duration of employment.[6]

This study may have underestimated the risk of ESRD and renal disease mortality associated with uranium milling. We observed an excess in chronic renal disease mortality during the follow up period 1940–59, but not during the follow up period 1960–98. This suggests that the exclusion of cohort members who died or were lost to follow up prior to 1960 may have been a significant limitation in our ability to evaluate the risk of ESRD and chronic renal disease mortality using multiple cause of death data. Because the cohort is relatively old, approximately 22% of the cohort was excluded from the analysis of ESRD because they died or were lost to follow up before the ESRD PMMIS is first considered complete, which also reduced the statistical power of the ESRD analysis. In addition, the majority of the mill workers in this study were probably exposed to relatively insoluble forms of uranium. The risk of renal disease may be higher in mills using relatively low drying temperatures where the potential for exposure to soluble forms of uranium is greater. The study evaluated chronic renal disease mortality and ESRD and was not able to evaluate the risk of less severe renal effects.

In conclusion, we observed an excess in mortality from haematopoietic and lymphatic malignancies other than leukaemia, trachea, bronchus, and lung cancer, non-malignant respiratory disease, and chronic renal disease. Some of these excesses were based on a small number of deaths and the confidence intervals around the point estimates were wide. Limitations include the lack of smoking data, small cohort size and limited power to detect a moderately increased risk of some of the a priori outcomes of interest, and the inability to evaluate exposure-response relations using individual estimates of exposure to uranium, silica, and vanadium. Because of these limitations and the lack of a positive trend between the observed excesses and duration of employment, firm conclusions about the relation of the observed excesses and mill exposures are not possible.

ACKNOWLEDGEMENTS

This study was funded in part by the United States Army Center for Health Promotion and Preventive Medicine (the former United States Army Environmental Hygiene Agency) and the United States Department of Energy.

We gratefully acknowledge the dedication of Ms Chris Gersic who carefully recoded and updated the work histories for this study. We also thank Mr Frank McGinley and Mr Bill Chenoweth for providing valuable information on mill operations and job titles and the companies participating in the study for assisting us in obtaining and understanding work history records.

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REFERENCES

1 **Albrethsen H Jr**, McGinley FE. *Summary history of domestic uranium procurement under U.S. atomic energy commission contracts: final report.* Grand Junction, CO: Department of Energy, 1982.
2 **Holaday DA**, David WD, Doyle HN. An interim report of a health study of the uranium mines and mills by the Federal Security Agency, Public Health Service, Division of Occupational Health and the Colorado State Department of Public Health (May 1952). In: Eischstaedt P, ed. *If you poison us: uranium and native Americans.* Santa Fe, NM: Red Crane Books, 1994.
3 **Lubin JH**, Boice JD Jr, Edling C, *et al.* Lung cancer in radon-exposed miners and estimation of risk from indoor exposure. *J Natl Cancer Inst* 1995;**87**:817–27.
4 **Committee on Health Risks of Exposure to Radon, National Research Council**. *Health effects of exposure to radon (BEIR VI).* Washington, DC: National Academy Press, 1999.
5 **Hornung RW**. Health effects in underground uranium miners. *Occup Med* 2001;**16**:331–44.
6 **Roscoe RJ**. An update of mortality from all causes among white uranium miners from the Colorado Plateau study group. *Am J Ind Med* 1997;**31**:211–22.
7 **Waxweiler RJ**, Archer VE, Roscoe RJ, *et al.* Mortality patterns among a retrospective cohort of uranium mill workers. In: *Epidemiology Applied to Health Physics, Proceedings of the Sixteenth Midyear Topical Meeting of the Health Physics Society.* Albuquerque, New Mexico, 9–13 January 1983:428–35.
8 **Archer VE**, Wagoner JK, Lundin FE Jr. Cancer mortality among uranium mill workers. *J Occup Med* 1973;**15**:1, 11–14.
9 **Thun MJ**, Baker DB, Steenland K, *et al.* Renal toxicity in uranium mill workers. *Scand J Work Environ Health* 1985;**11**:83–90.
10 **Fisher DR**, Stoetzel GA. *Radiological health aspects of uranium milling.* Pacific Northwest Laboratory for the United States Department of Energy. PNL-4606 USUR-04. Springfield, VA: NTIS, 1983.
11 **White WS**. *Directory and profile of licensed uranium recovery facilities.* United States Nuclear Regulatory Commission (USNRC). Ref. no. NUREG/CR-2869 ANL/ES-128, Rev. 1, 1984.
12 **US Renal Data System**. *USRDS 1999 annual data report.* Bethesda, MD: National Institutes of Health, National Institute of Diabetes and Digestive and Kidney Diseases, April 1999.
13 **Waxweiler RJ**, Beaumont JJ, Henry JA, *et al.* A modified life table analysis system for cohort studies. *J Occup Med* 1983;**25**:115–24.
14 **Steenland K**, Beaumont J, Spaeth S, *et al.* New developments in the life table analysis system of the National Institute for Occupational Safety and Health. *J Occup Med* 1990;**32**:1091–8.
15 **Steenland K**, Nowlin S, Ryan B, *et al.* Use of multiple-cause mortality data in epidemiologic analyses: US rate and proportion files developed by the National Institute for Occupational Safety and Health and the National Cancer Institute. *Am J Epidemiol* 1992;**136**:855–62.
16 **Calvert GM**, Steenland K, Palu S. End-stage renal disease among silica-exposed gold miners: a new method for assessing incidence among epidemiologic cohorts. *JAMA* 1997;**277**:1219–23.
17 **Steenland K**, Spaeth S, Cassinelli R 2nd, *et al.* NIOSH life table program for personal computers. *Am J Ind Med* 1998;**34**:517–18.
18 **Breslow NE**, Day NE. Comparisons among exposure groups. In: Heseltine E, ed. *Statistical methods in cancer research. Volume II. The design and analysis of cohort studies.* IARC (International Agency for Research on Cancer) Scientific Publication No. 82. New York: Oxford University Press, 1987:69.
19 **United States Nuclear Regulatory Commission, Office of Standards Development**. *Health physics surveys in uranium mills.* Regulatory guide 8.30, June 1983.
20 **Spoor NL**, Hursh JB. Protection criteria. In: Hodge NC, Stannard JN, Hursh JB, eds. *Uranium, plutonium and transplutonic elements.* New York, Heidelberg, Berlin: Springer-Verlag, 1973:241–70.
21 **Spitz HB**, Simpson JC, Aldridge TL. *Analysis of uranium urinalysis and in-vivo measurement results from eleven participating uranium mills.* United States Nuclear Regulatory Commission (USNRC). Ref No. NUREDG/CR-2955 PNL-4550, 1984.
22 **Breitenstein BD**, Fisher DR, Hoenes GR, *et al.* *Occupational exposures to uranium: processes, hazards, and regulations.* Pacific Northwest Laboratory and Hanford Environmental Health Foundation. Ref No. PNL-3341 USUR-01 UC-41, 1981.
23 **Leach LJ**, Yuile CL, Hodge HC, *et al.* A five year inhalation study with natural uranium oxide (UO_2) dust. II. Postexposure retention and biologic effects in the monkey, dog and rat. *Health Phys* 1973;**25**:239–58.
24 **Mausner LF**. Inhalation exposures at a thorium refinery [note]. *Health Phys* 1982;**42**:231–6.
25 **Keane AT**, Polednak AP. Retention of uranium in the chest: implications of findings in vivo and postmortem. *Health Phys* 1983;**44**:391–402.
26 **Singh NP**, Bennett DB, Wrenn ME. Concentrations of α-emitting isotopes of U and Th in uranium miners' and millers' tissues. *Health Phys* 1987;**53**:261–5.
27 **Committee on the Biological Effects of Ionizing Radiation, National Research Council**. *Health risks of exposure to low levels of ionizing radiation (BEIR V).* Washington, DC: National Academy Press, 1990.
28 **United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)**. *Sources and Effects of Ionizing Radiation.* UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. New York: United Nations, 2000.
29 **Ritz B**. Radiation exposure and cancer mortality in uranium processing workers. *Epidemiology* 1999;**10**:531–8.
30 **Liu Z**, Lee T, Kotek TJ. Mortality among workers in a thorium-processing plant—a second follow-up. *Scand J Work Environ Health* 1992;**18**:162–8.
31 **Loomis DP**, Wolf SH. Mortality of workers at a nuclear materials production plant at Oak Ridge, Tennessee, 1947–1990. *Am J Ind Med* 1996;**29**:131–41.
32 **Dupree-Ellis E**, Watkins J, Ingle JN, *et al.* External radiation exposure and mortality in a cohort of uranium processing workers. *Am J Epidemiol* 2000;**152**:91–5.
33 **Darby SC**, Whitley E, Howe GR, *et al.* Radon and cancers other than lung cancer in underground miners: a collaborative analysis of 11 studies. *J Natl Cancer Inst* 1995;**87**:378–84.
34 **McGeoghegan D**, Binks K. The mortality and cancer morbidity experience of workers at the Springsfield uranium production facility, 1946–95. *J Radiol Prot* 2000;**20**:111–37.
35 **Weinhold B**. Death out West: the link to COPD. *Environ Health Perspect* 2000;**108**:A350.
36 **Arrighi HM**, Hertz-Picciotto I. The evolving concept of the healthy worker survivor effect. *Epidemiology* 1994;**5**:189–96.
37 **Wilson J**. An epidemiologic investigation of nonmalignant respiratory morbidity in a uranium mill. Presented at the American Public Health Association Conference, November 1983.
38 **Cross FT**, Pamer RF, Busch RH, *et al.* Development of lesions in syrian golden hamsters following exposure to radon daughters and uranium ore dust. *Health Phys* 1981;**41**:135–53.
39 **Cross FT**, Pamer RF, Filipy RE, *et al.* Carcinogenic effects of radon daughters, uranium ore dust and cigarette smoke in beagle dogs. *Health Phys* 1982;**42**:33–52.
40 **Mitchel REJ**, Jackson JS, Heinmiller B. Inhaled uranium ore dust and lung cancer risk in rats. *Health Phys* 1999;**76**:145–55.
41 **International Agency for Research on Cancer (IARC)**. *IARC monographs on the evaluation of carcinogenic risks to humans: silica, some silicates, coal dust and para-aramid fibrils.* Volume 68. Lyon, France: World Health Organisation, IARC, 1997.
42 **Steenland K**, Sanderson W. Lung cancer among industrial sand workers exposed to crystalline silica. *Am J Epidemiol* 2001;**153**:695–703.
43 **Finkelstein MM**. Silica, silicosis, and lung cancer: a risk assessment. *Am J Ind Med* 2000;**38**:8–18.
44 **Checkoway H**, Heyer NJ, Seixas NS, *et al.* Dose-response associations of silica with nonmalignant respiratory disease and lung cancer mortality in the diatomaceous earth industry. *Am J Epidemiol* 1997;**145**:680–8.
45 **Hryhorczuk DO**, Aks SE, Turk JW. Unusual occupational toxins. *Occup Med* 1992;**7**:567–86.
46 **Barceloux DG**. Vanadium. *J Toxicol Clin Toxicol* 1999;**37**:265–78.
47 **Hornung RW**, Meinhardt TJ. Quantitative risk assessment of lung cancer in U.S. uranium miners. *Health Phys* 1987;**52**:417–30.
48 **Siemiatycki J**, Wacholder S, Dewar R, *et al.* Degree of confounding bias related to smoking, ethnic group, and socioeconomic status in estimates of the associations between occupation and cancer. *J Occup Med* 1988;**30**:617–25.
49 **Steenland K**, Brown D. Mortality study of gold miners exposed to silica and nonasbestiform amphibole minerals: an update with 14 more years of followup. *Am J Ind Med* 1995;**27**:217–29.
50 **Steenland K**, Sanderson W, Calvert GM. Kidney disease and arthritis in a cohort study of workers exposed to silica. *Epidemiology* 2001;**12**:405–12.

Appendix 27

KENNECOTT URANIUM COMPANY		CGL = Chemical & Geological Laboratories				ELI = Energy Laboratories, Inc.									*Revised*						
SWEETWATER TAILINGS CELL		CLI = Core Laboratories, Inc.				MEC = Minerals Exploration Company									*08/22/97*						
Surface Water Analysis																					
WYDEQ III Livestock Standard		1980	1981	1983	1984	1985	1986		1987	1988	1989	1990	1991	1992			1993		1994		1995
	Std	12/30/80	12/17/81	8/16/83	6/4/84	8/1/85	4/11/86	7/10/86	7/6/87	7/12/88	3/29/89	6/12/90	10/31/91	4/14/92	8/11/92	10/22/92	7/1/93	9/23/93	3/24/94	7/28/94	3/31/95
FIELD DATA mg/l:		(CGL)	(MEC)	(CGL)	(CLI)	(CLI)	(CLI)	(CLI)	(CLI)	(CLI)											
Temperature (C)			5					16.8	18.6	18.5	6.2	13.8				11.3	18.6	15.8	3.2	21.3	2
pH (Std. Units)			0.9					1.76	1.72	2.16	2.18	2.19				2.4	2.2	2.1	3	2.4	2.33
Cond (umho/cm)			15800					11300	9200	8009	3560	5290				13930	12450	13140	14700	12510	11310
TDS								1000+	1000+	1000+	1000+	1000+				6980	6180	6590	8010	6210	5650
MAJOR IONS mg/l:																					
Alk-CaC03		0	50	0	-5	0	-1	0	1	-1	0	0	0	0	0	0	0	0	0	0	0
Bicarbonate (HCO3)		0		0	-1	0	0	0			0	0	0	0	0	0	0	0	0	0	0
Calcium (Ca)		158	126.7	370	420	472	519	502	497	510	320	478	580	588	726	529	445	449	423	421	348
Carbonate (CO3)		0		0	-1	0	0	0			0	0	0	0	0	0	0	0	0	0	0
Chloride (Cl)	**2000**	28	39.5	160	200	140	215	183	200	244	139	479	551	538	49.4	532	460	558	661	579	445
Fluoride (F)		0.45	0.5	0.09	0.22	8	5.4	0.3	14.5	11.9	-0.1	-0.1	0.1	84.7	-0.1	0.18	-0.1	0.11	0.13	0.1	0.12
Magnesium (Mg)		10		164	192	230	125	310	350	220	220	513	566	580	632	699	548	729	578	810	761
Nitrate-N (NO2)	**10**	0.11	ND	23.33	17.5	29.3	11.6	25	24	0.5	1.12	5.09	-0.01	146	97.1	-0.1	-0.1	0.2	2.7	0.14	0.27
Potassium (K)		3	1.4	42	44	45	96	53	61	63	29	41.2	10.8	14.3	9.17	5	2.9	0.9	1	1.1	0.87
Silica (SiO2)		18.6	186.4	496	556	527	523	435	43	79	364	618	681	745	393	631	554	615	476	495	338
Sodium (Na)		337	99.8	166	184	225	232	283	258	302	180	596	680	683	777	669	465	663	682	627	541
Sulfate (SO4)	**3000**	1090	9529	7400	6200	9200	8880	10400	10400	12600	5743	12760	14084	13850	13300	14793	10701	12976	12145	13539	11000
NON-METALS:																					
Cyanide (CN)											-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005
PHYSICAL PROPERTIES:																					
Cond (umho/cm)		3075	15800	11000	10870	10830	11360	11800			7872	13611	13752	1420	12449	13115	12560	13928	14313	13085	11823
pH (units)	**-2**	2.3	0.9	1.4	1.8	1.7	1.82	1.9			2.3	1.97	2.57	2.23	2.24	2.34	2.58	2.46	2.43	2.48	2.7
TDS @ 180°	**5000**	1322	12958	9640	10580	14178	13990	14100	14700	16600	8464	19352	20408	21061	19300	21140	15441	17532	16887	17665	14566
TRACE METALS mg/l:																					
Aluminum (Al)	**5**	15.7	151.4	312	360	375	378		423	567	320	485	818	874	979	906	676	854	863	912	800
Arsenic (As)	**0.2**	-0.01	0.288	0.78	0.326	0.18	0.23	0.36	0.126	0.447	0.223	0.41	0.26	0.46	0.4	0.02	0.14	0.16	0.12	0.114	0.099
Barium (Ba)					0.052	0.01	0.01				-0.1	-0.1	-0.1	-0.1	0.37	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Beryllium (Be)											0.16	0.24	0.23	0.23	-0.01	0.26	0.23	-0.01	0.31	0.22	0.19
Boron (B)	**5**	-1	0	0.19	0.13	0.15	-0.1	-0.1	3	0.75	-0.1	0.1	0.13	-0.1	0.15	-0.1	3.98	4.5	3.08	1.9	0.78
Cadmium (Cd)	**0.05**	-0.01	-0.005	0.02	-0.01	0.23	-0.01	0.03	0.05		-0.005	0.024	0.093	-0.005	0.021	-0.005	-0.005	-0.005	-0.005	-0.01	0.07
Chromium (Cr)	**0.05**	0.06	1.7	3.59	-0.05	1.7	3.1	0.56	2.48	35	1.5	2.45	3.65	2.86	3.79	3.36	3.75	3.3	3.08	2.25	2.52
Cobalt (Co)	**1**														2.085	1.78	2.55	6.65	2.45	-	1.47
Copper (Cu)	**0.5**	0.04	0.9	1.09	0.86	1.1	1.1	1.2	1.5	1.46	0.76	1.31	2.11	2.28	2.79	2.41	2.48	2.82	1.73	1.83	1.88
Iron (Fe)		32.5		898	836	815	830	750	1290	1550		1297	1676	1703	638	1540	1256	1478	1125	991	840
Lead (Pb)	**0.1**	-0.05	0.8	0.66	0.48	0.33	0.49	0.42	-0.05	0.4	0.05	0.11	0.39	-0.01	-0.01	-0.01	-0.01	0.41	-0.01	-0.01	-0.01
Manganese (Mn)		0.82	23.2	19	26.9	26	26.6	27.7	30	48.7	22	46.2	74.87	62.9	83.9	72.2	66.7	76	65.4	63.1	62.2
Mercury (Hg)	**0.005**	-0.001	-0.005	-0.0004	-0.0004	0.0004	0.0043	-0.0004	-0.0004	-0.0004	-0.001	-0.001	-0.002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002
Molybdenum (Mo)		-0.1	0.1	-0.1	-0.1	-0.02	-0.02	-0.02	0.3	-0.5	-0.01	0.01	0.04	0.11	0.33	-0.01	-0.01	-0.01	-0.01	-0.1	-0.01
Nickel (Ni)		0.07	1.3	1.91	0.93	1.1	1.2	1.2	1.8	2.33	1.1	2.68	3.93	3.69	5.08	4.14	4.95	5.73	4.35	4.06	3.6
Selenium (Se)	**0.05**	-0.01	0.032	0.02	0.012	0.009	0.029	0.023	0.002	0.424	0.262	0.531	0.44	0.614	0.426	0.62	0.608	0.618	0.385	0.847	0.349
Silver (Ag)						-0.02	-0.02				-0.01	0.01	0.02	2.05	-0.01	0.12	-0.01	-0.01	-0.01	-0.01	-0.01
Thallium (Tl)											-0.015	0.49	-0.015	-0.015	-0.015	-0.015	-0.015	-0.015	-0.015	-0.015	-0.015
Vanadium (V205)	**0.1**	0.41	2.8	2.91	2.72	3.1	4.3	4.7	7.6	9.64	2.5	2.04	2.06	2.05	2.38	1.93	2.1	1.89	1.5	1.2	1.14
Zinc (ZN)	**25**	1.11	31	1.7	1.72	3.1	2.1	2.2	3	4	1.9	4.03	6.02	5.72	7.02	6.45	6.38	7.71	6.67	5.95	5.9
RADIOMETRIC pCi/l:																					
Uranium, natural	**3385**	3012.7	3100.1	3046.5	3047	44	2006	2832	5416	4690 (0.2)	2269	8023	7777 (0.2)	7212	8480	6177	9030	10507	9864	10311	9242
Radium 226		114	99.14	102	59	11.2	41.9	25	13	12.7	303	439	126	70.1	74.4	54.7	38.1	40.4	53.9	112	25.7
Radium 226 Error Estimate		3	2.09	12	2	0.5	9	5.1	0.8	1	8.3	9.6	4.4	2.9	7.6	2.5	3.1	1.8	3.3	6	2.1
Radium 228											15.1	-1	15.8	1.8	4.2	5.8	9	3.5	9.6	7.6	-1
Radium 228 Error Estimate											+/- 2.0		+/- 2.1	+/- 0.7	+/- 0.9	+/- 0.7	+/- 2.9	+/- 0.9	+/- 9.4	+/- 5.4	
Combined Ra226/228	**5**										318.1	439	141.8	71.9	78.6	60.5	47.1	43.9	63.5	119.6	25.7
Radon 222																					
Radon 222 precision (±)																					
Thorium 230		1.24	3035	864	23567	6857	18461	39334	11000	15200	11521	2831	2820	19310	18700	5487	9880	3266	650	4136	28217
Thorium-230 Error Estimate		+/- 68	+/- 6.93	+/- 1195	+/- 1717	+/- 68		+/- 337	+/- 77	+/- 105	+/- 195	+/- 45.1	+/- 14	+/- 105	+/- 119	+/- 44	+/- 104	+/- 54	+/- 403	+/- 371	+/- 623
Lead (Pb210)		394	1541	513	2850	2598.6	2134	1890	1440	2	76.9	90.9	-1	6.3	5.4	5	-1	-1	3.5	9	1.8
Lead 210 Error Estimate		+/- 20	+/- 37	+/- 5	+/- 52	+/- 160	+/- 8	+/- 124	+/- 89	+/- 1.1	+/- 5.3	+/- 8.7		+/- 0.8	+/- 3.8	+/- 0.7			+/- 2.1	+/- 8.1	+/- 1.1
Polonium (Po210)		64	361	640	1581	476	176	782	1.8	17.5											
Polonium 210 Error Estimate		+/- 11	+/- 25	+/- 7	+/- 40	+/- 8	+/- 14	+/- 29	+/- 0.6	+/- 1.1											
Gross Alpha	**15**										14093	3325	3000	20000	27300	5541	9919	3312	718	4276	28244
Gross Alpha Error Estimate											+/- 119	+/- 58	+/- 55	+/- 400	+/- 165	+/- 74.4	+/-99	+/- 58	+/- 26.8	+/- 22	+/- 168
QUALITY ASSURANCE DATA:																					
A/C Balance				51.4	49.1	57.86	12.69					1.115	0.964	1.033	1.13	1.037	1.064	0.999	1.044	1	1.02
(Energy Labs Inc unless noted)																					

KENNECOTT URANIUM COMPANY																	
SWEETWATER TAILINGS CELL																	
Surface Water Analysis																	
WYDEQ III Livestock Standard		1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
	Std	6/22/96	6/3/97	6/2/98	6/2/99	6/6/00	6/5/01	6/12/02	6/4/03	6/15/04	6/7/05	6/6/06	6/4/07	5/13/08	6/9/09	6/7/10	6/7/11
FIELD DATA mg/l:																	
Temperature (C)		17.1	18	14	14	16	10	12	14	16	14	27.2	4	4.2	12.3	14.8	16
pH (Std. Units)		2.53		2.8	2.8	2.7	2.8	2.8	2.8	16.2	2.1	2.78	3.34	3.1	7.8	2.8	3.2
Cond (umho/cm)		13400	11200	11600	13000	9000	1200	9600	10400	9000	8000	12550	10140	9860	11610	10950	12170
TDS		6690															
MAJOR IONS mg/l:																	
Alk-CaC03		0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
Bicarbonate (HCO3)		0	0	-0.1	-0.1	-0.1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
Calcium (Ca)		707	389	378	431	410	469	410	459	470	436	501	549	486	436	419	447
Carbonate (CO3)		0	0	-0.1	-0.1	-0.1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
Chloride (Cl)	**2000**	628	502	503	574	607	610	680	678	820	651	683	649	695	786	704	828
Fluoride (F)		26.5	24	24.1	25.1	30.4	36.5	42.4	43.7	38.4	16	44.9	13.5	0.2	0.2	0.2	0.2
Magnesium (Mg)		1010	880	830	880	931	1130	992	1130	1300	1140	1290	1110	1080	1040	827	952
Nitrate-N (NO2)	**10**	0.3	1.86	0.14	1.1	0.83	0.67	0.4	2.4	0.17	-0.1	0.3	0.5	0.3	0.3	0.6	-0.1
Potassium (K)		0.7	1.03	1	1.9	0.5	0.7	-1	1.5	1	-0.5	1.4	5.3	5.9	5	3.9	4.4
Silica (SiO2)		364	252	237	232	188	175	151	138	130	119	117	105	48	103	77.4	167
Sodium (Na)		870	606	607	651	657	733	724	801	810	726	725	743	829	998	846	1060
Sulfate (SO4)	**3000**	14281	13120	12300	12200	11500	13100	12500	13400	14000	12500	13500	10300	9950	10600	8670	10600
NON-METALS:																	
Cyanide (CN)		-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005	-0.005
PHYSICAL PROPERTIES:																	
Cond (umho/cm)		12495	11800	12600	12900	14300	14000	14200	14100	14100	13600	13200	11500	12100	12700	10800	11700
pH (units)	**-2**	2.55	2.61	2.82	2.81	2.83	2.81	2.83	2.88	2.95	2.94	3.09	3.37	3.55	3.01	3.19	3.16
TDS @ 180°	**5000**	19167	15900	18700	18600	19900	19400	20400	20100	21000	19100	18100	13600	14800	15200	12900	13900
TRACE METALS mg/l:																	
Aluminum (Al)	**5**	920	974	1000	1150	916	1220	1150	1250	1300	1230	1060	554	495	495	508	533
Arsenic (As)	**0.2**	0.097	0.068	0.081	0.073	0.078	0.039	0.036	0.023	0.06	0.027	0.019	0.012	0.017	0.009	0.017	0.037
Barium (Ba)		-0.1	-0.1	-0.1	-0.1	0.89	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Beryllium (Be)		0.3	0.24	0.24	0.26	0.27	0.2	0.32	0.18	0.25	0.33	0.35	0.2	0.18	0.15	0.17	0.34
Boron (B)	**5**	-0.1	0.56	-0.1	0.75	-0.1	0.5	0.63	-0.22	-0.1	0.3	0.4	0.4	0.4	-0.1	-0.1	0.4
Cadmium (Cd)	**0.05**	0.11	0.028	0.022	0.02	0.038	0.019	0.034	0.02	0.03	0.019	0.017	0.014	0.028	0.018	0.014	0.024
Chromium (Cr)	**0.05**	3.21	2.38	2.12	2.23	2.35	1.83	2.47	1.31	2	1.7	1.44	0.55	0.24	0.31	0.25	0.44
Cobalt (Co)	**1**	2.19	1.83	2.47	1.69	2.07	1.95	2.78	1.87	3	2.63	2.96	2.09	2.21	2.03	2.13	2.2
Copper (Cu)	**0.5**	2.55	2	1.93	1.8	2.03	1.54	2.04	1.76	1.9	1.64	1.54	0.58	0.44	0.49	0.43	0.71
Iron (Fe)		874	722	573	418	348	313	250	232	230	139	115	59.5	135	134	108	171
Lead (Pb)	**0.1**	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.02	-0.01	-0.01	-0.01	0.02	-0.01	-0.01	-0.01	-0.01
Manganese (Mn)		82.4	80	76	78.6	79.5	61.7	94	70.4	110	84.4	94.4	67.4	79.6	80.2	67.8	72.1
Mercury (Hg)	**0.005**	-0.0002	-0.0002	-0.0002	-0.0002	0.0006	-0.0002	0.0005	-0.0004	0.0005	-0.0002	-0.0002	-0.0002	-0.0004	-0.0004	-0.0002	0.0007
Molybdenum (Mo)		-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.04	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
Nickel (Ni)		5.37	4.3	5.7	4	6.16	4.6	7.01	5.79	7.2	6.8	6.92	4.39	4.97	5.52	4.69	4.89
Selenium (Se)	**0.05**	0.608	0.888	0.655	0.641	0.706	0.591	0.618	0.579	0.24	0.534	0.461	0.414	0.287	0.256	0.198	0.327
Silver (Ag)		-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.05	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
Thallium (Tl)		-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.16	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
Vanadium (V205)	**0.1**	1.37	1.4	0.87	0.75	0.57	0.4	0.5	0.3	0.2	0.2	0.2	-0.1	-0.1	-0.1	-0.1	-0.1
Zinc (ZN)	**25**	0.79	6.68	7.48	6.99	7.65	5.8	9.19	11.6	9.5	8.25	7.48	5.72	4.75	6	5.07	5.18
RADIOMETRIC pCi/l:																	
Uranium, natural	**3385**	8973	8400	10800	11200	12000	12300	12321.4	12000	11000	10300	11100	8530	6350	7980	6420	10900
Radium 226		55.3	60.6	45.8	567	83.1	59.8	55.9	69.8	46.2	23.8	1.5	20.2	25.2	10	7.6	5.7
Radium 226 Error Estimate		1.9	2.6	2	2.3	3	2.3	2.3	2.5	2.2	1.8	0.4	1.7	0.9	0.68	0.55	0.61
Radium 228		6.7	-1	1.9	2.9	3.6	1.9	-1	-1	-1	-1	8.9	-1	2.3	1.3	1.6	0.8
Radium 228 Error Estimate		+/- 0.5		+/- 1.1	+/- 0.5	+/- 0.2	+/- 1.0					+/-1.1		0.7	0.9	0.8	1
Combined Ra226/228	**5**	62	60.6	47.7	569.9	86.7	61.7	55.9	69.8	46.2	23.8	10.4	20.2	27.5	11.3	9.2	6.5
Radon 222																	
Radon 222 precision (±)																	
Thorium 230		7550	4526	6360	2340	11500	9440	3250	1890	2110	1650	1620	671	216	361	283	214
Thorium-230 Error Estimate		+/- 160	+/- 86	+/- 108	+/- 44.1	+/- 212	+/- 78	+/- 30.3	+/-19.7	+/- 34.9	+/-24.3	+/-113	+/-58.2	7.9	71.7	28.5	27.2
Lead (Pb210)		7.9	6.6	-1	5	-1	-1	-2.7	-2.7	-1	-1	-1	-1	1.9	6.2	5.7	1.6
Lead 210 Error Estimate		+/- 0.9	+/- 2.3		+/- 1.8									9.6	2.4	6.1	0.9
Polonium (Po210)											-	-	-	-	-		
Polonium 210 Error Estimate																	
Gross Alpha	**15**	16600	274	300	261	162	149	124	212	222	83.3	127	43.9	83.4	48.8	39.8	8
Gross Alpha Error Estimate		+/- 130	+/- 9.4	+/- 10.7	+/- 9.9	+/- 6.0	+/- 6.4	+/- 5.0	+/-7.2	+/- 10.9	+/- 5.3	+/-6.0	+/-2.0	3.3	3	2.7	0.8
QUALITY ASSURANCE DATA:																	
A/C Balance		1.02	0.96	1.2	1.2	1.35	1.17	1.19	1.09	1.17	1.22	1.07	1.01	2.66	-1.87	-2.9	-4.96
(Energy Labs Inc unless noted)																	

Appendix 28

Kennecott Uranium Company

Radon Emissions Estimates

Natural and Man Induced (Excluding Uranium Mining and Processing) Radon Emissions (Estimate Does Not Include Indoor Radon Emissions in Homes, Offices etc)

Radon Source	Emission Rate	Emission Rate Unit	Extension		Extension Unit	Extension	Extension Unit	Extension	Extension Unit	Total United States Emission	Unit	Surface Air Volume	Unit	Surface Air Concentration	Unit	Data Source
Natural Sources																
Terrestial Radon Flux	0.5	pCi/m2-sec	7.80E+12		square meters					1.23E+08	Curies/year	1.00E+18	Cubic meters	1.23E+02	picoCuries/meters3	NUREG/CR-0573 A Radiological Assessment of Radon-222 Released from Uranium Mills and Other Natural and Technologically Enhanced Sources
Evapotranspiration	0.56	meters3/meter2	7.80E+12		square meters	2.00E-09	Curies/Liter			8.74E+06	Curies/year	1.00E+18	Cubic meters	8.74E+00	picoCuries/meters3	NUREG/CR-0573 A Radiological Assessment of Radon-222 Released from Uranium Mills and Other Natural and Technologically Enhanced Sources
Subtotal										1.32E+08	Curies/year			1.32E+02	picoCuries/meters3	
Anthropogenic (Not Including Uranium Mining and Processing) Sources																
Tillage of Agricultural Land	0.5	pCi/m2-sec (Terrestial radon flux)	1.52E+12	[4]	Square meters of tilled land (19.5% of U.S. land surface - 2002)	0.13	Additional Radon-222 above natural flux released by tillage			3.12E+06	Curies/year	1.00E+18	Cubic meters	3.12E+00	picoCuries/meters3	NUREG/CR-0573 A Radiological Assessment of Radon-222 Released from Uranium Mills and Other Natural and Technologically Enhanced Sources
Burning of Natural Gas	20	PicoCuries per Liter (Average concentration of Radon-222 in natural gas)	2.28E+13	[1]	Cubic feet (Annual consumption of natural gas in the United States - 2009)					1.29E+04	Curies/year	1.00E+18	Cubic meters	1.29E-02	picoCuries/meters3	United States Department of Energy(DOE)/Energy Information Administration (EIA)/NUREG/CR-0573 A Radiological Assessment of Radon-222 Released from Uranium Mills and Other Natural and Technologically Enhanced Sources
Coal Fired Power Plants (Direct Combustion of Coal)	5.994E-13	Curies per gram (Average Radon-222 activity in coal)	1.00E+09	[2]	Short tons (Annual consumption of coal in the United States - 2009)					5.44E+02	Curies/year	1.00E+18	Cubic meters	5.44E-04	picoCuries/meters3	United States Department of Energy(DOE)/Energy Information Administration (EIA)/NUREG/CR-0573 A Radiological Assessment of Radon-222 Released from Uranium Mills and Other Natural and Technologically Enhanced Sources
Releases from Fly Ash	0.04	Fraction of coal burned that is flyash	1.00E+09	[2]	Short tons (Annual consumption of coal in the United States - 2009)	0.2	Emanation coefficient of flyash	5.994E-13	Curies per gram (Average Radium-226 activity in coal)	2.88E+02	Curies/year	1.00E+18	Cubic meters	2.88E-04	picoCuries/meters3	United States Department of Energy(DOE)/Energy Information Administration (EIA)/NUREG/CR-0573 A Radiological Assessment of Radon-222 Released from Uranium Mills and Other Natural and Technologically Enhanced Sources
Phosphate Fertilizer Use	3.90E-04	Curie per metric ton (Radon-222 release rate per metric ton of fertilizer)	2.96E+08	[3]	Metric Tons (Total phosphate fertilizer applied in the United States from 1900 to 2007)					1.15E+05	Curies/year	1.00E+18	Cubic meters	1.15E-01	picoCuries/meters3	United States Environmental Protection Agency (EPA)/ NUREG/CR-0573 A Radiological Assessment of Radon-222 Released from Uranium Mills and Other Natural and Technologically Enhanced Sources
Subtotal										3.25E+06	Curies/year			3.25E+00	picoCuries/meters3	
Total:										1.35E+08	Curies/year			1.35E+02	picoCuries/meters3	

Note: This assessment does not include radon emissions from other difficult to quantify sources such as geothermal energy fields, flaring of natural gas during oil and gas drilling operations, use of well water, and any open pit and underground mines.

This spreadsheet duplicates the calculations for the selected items shown as done previously in NUREG/CR-0573 A Radiological Assessment of Radon-222 Released from Uranium Mills and Other Natural and Technologically Enhanced Sources with coal, natural gas, tilled land and phosphate fertilizer data updated from United States government (Energy Information Agency (EIA), United States Department of Agriculture (USDA) and Enviornmmental Protection Agency (EPA) sources.

Additional References:

[1] http://www.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

[2] http://www.eia.doe.gov/cneaf/coal/quarterly/html/t32p01p1.html

[3] http://www.epa.gov/rpdweb00/tenorm/fertilizer.html

[4] http://www.ers.usda.gov/publications/eib14/

Appendix 29

A FRAMEWORK FOR FINE-SCALE COMPUTATIONAL FLUID DYNAMICS AIR QUALITY MODELING AND ANALYSIS

Alan H Huber
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1. INTRODUCTION

High-fidelity fine-scale Computational Fluid Dynamics (CFD) simulation of pollutant concentrations within roadway and building microenvironments is feasible using high performance computing. Unlike currently used regulatory air quality models, fine-scale CFD simulations are able to account rigorously for topographical details such as terrain variations and building structures in urban areas as well as their local aerodynamics and turbulence. Thermal heat fluxes may be added to terrain and building surfaces to simulate the thermal atmospheric boundary layer and their influences on pollution transport and dispersion. The results of these CFD simulations can both be directly used to better understand specific case studies as well as be used to support the development of better-simplified algorithms for adoption into other modeling systems.

This paper discusses a framework for fine-scale CFD modeling that may be developed to complement the present Community Multi-scale Air Quality (CMAQ) modeling system which itself is a computational fluid dynamics model. A goal of this presentation is to stimulate discussions on what is "Computational Fluid Dynamics" modeling and how can it evolve to support the critical needs for modeling human exposures to air pollutants. Related mathematical equations and their solutions cannot begin to be covered herein and thus no equations are presented.

2. BACKGROUND

Modern day CFD has evolved much since Sir Isaac Newton's physical equations and the evolution of the Navier-Stokes equation for fluid flow due to advancing computational hardware and software.. The Navier-Stokes equation is the general basis for all CFD applications, for example, from weather prediction to vehicular aerodynamics design. The Navier-stokes equation is non-linear and any solution will depend on initial boundary conditions. Practical CFD solutions require both simplifying assumptions and numerical approximations. In practice, solutions for specific fluid flow problems result from calculations of a system of fluid flow and conservation equations generally cast as the Navier-Stokes equations.

While reasonable models can be developed for most physical processes in the atmosphere, their application in a numerical model is limited by the grid scale. The Navier-Stokes equations are a deterministic system. Practical solutions require a sub-grid scale model for turbulence. As computer capacities advance the scale where turbulence is modeled can be reduced and the application of higher order numerical methods can presumably support more accurate turbulence models. Understanding turbulence remains one of the greatest challenges in physics. It is very important not to confuse turbulence with randomness that may be produced by numerical solutions due to numerical errors or other model inadequacies.

3. AIR QUALITY MODELING AND HUMAN EXPOSURE.

3.1 Challenge to Relate to Human Exposure Assessment

Air Quality in the ambient environment is strongly influenced by emissions, the physical environment, and the state of the atmosphere influencing transport and dispersion. Pollution concentrations potentially contributing to human exposure may be considered composed of a regional background concentration due to long range transport, regional scale mixing, and specific local microenvironmental concentrations as depicted in Figure 1. Often it is the concentrations within a few microenvironments that dominate a profile of total human exposure. A human is only exposured to what can possibly contact his body.

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Figure 1. Depiction of local microenvironments plus regional background air concentrations.

The science of human exposure assessment in support of health risk assessment to pollution requires concentrations that are both temporally and spatially resolved to estimate direct contact with the human body. Ott (1995) identified four questions that exposure science should address in support of human health risk analysis: a) how many people are exposed? b) what is the level of each person's exposure? c) what are the causes of exposure? d) how can exposures be altered efficiently? Additional overviews on issues linking environmental concentrations to profiles of human exposure may be found, for example, in Özkaynak (1999) and McCurdy (2000). There are challenges for the air quality modeling community for linking concentration to temporal and spatial scales associated with profiles of human exposure relevant to supporting health risk assessments.

3.2 The Present CMAQ Modeling System

The CMAQ model has been designed to approach air quality as a whole by including state-of-the-science capabilities for modeling multiple air quality issues (Byun and Schere; 2006, 2004). CMAQ was designed to have multi-scale multi-pollutant capabilities so that separate models are not needed for urban and regional air quality modeling. Various chemical and physical processes thought to be important for understanding atmospheric trace gas transformations and distributions are modeled. The CMAQ modeling system links models for meteorology, emissions, and air quality on a common temporal and spatial scale. It produces air quality concentrations resolved at its applied grid resolution. Regional air quality applications are normally applied at grid resolutions larger than 10 km. Urban applications are applied at smaller grid scales but there is a meaningful limit due to the sub-grid scale process models. The present framework of the CMAQ modeling system well supports environmental issues where its grid-averaged concentration is applicable. For example, regional emission control strategies are especially applicable while specific profiles of human exposure concentrations are not. The system may presently be useful for estimating profiles of human exposure for pollutants having course temporal and spatial distributions at or above the grid scale.

3.3 Potential Framework for Interfacing CMAQ CFD with Fine-scale CFD Models

With ever increasing computational capacities the ability of extending or interfacing CMAQ to spatially finer-scales is becoming practical. Finer temporal scales are a greater challenge. Traditionally, fine-scale CFD software uses finite volume numerical method to best accommodate complex geometries and unstructured grids. CMAQ software uses finite difference methods which must use a structured grid. Extending to finer scales is most meaningful where there are significant sub-grid inhomogeneities to the present CMAQ grid scales and where supporting information is available at the finer scales. In principal, the fine-scale finite volume numerical methods can be interfaced with the present CMAQ-type grid system. An extension of CMAQ to already existing fine-scale CFD code with advanced chemistry and physical processes models is envisioned as the complete way to proceed. Further scoping of the related issues is needed and justified to extend CMAQ's capabilities to model human exposure profiles. This challenge is presented now to start the discussions with hope it may lead sooner to a working plan.

An interim alternative to full implementation of an extension of CMAQ to fine-scales would be when needed to run a fine-scale model separate from CMAQ but pass resulting useful information between the two model codes. The larger CMAQ grid scale could be used to form the external boundary conditions for the fine-scale model through driving wind fields and adding background pollutant concentrations for the fine-scale model. Likewise, output from the highly resolved fine-scale model could pass improved local scale winds (and other atmospheric state variables) along with pollutant concentrations generated from internal emissions into the CMAQ model.

Meeting the challenges of extending a CMAQ-like air quality modeling system to fine scales is the natural way to support total human exposure modeling. In rural areas without significant buildings or variation in landuse characteristics, if necessary, more simplifying methods may be applicable. The CMAQ sub-grid may be carefully linked for simple situations with an analytical plume model. For example, applications of EPA's AERMOD (Cimorelli et al., 2005) model on the fine "local" scale may be interfaced with and driven by the wind field from a regional grid model. This should work well where there are only a few significant sources and/or no significant complications due to buildings or other structures influencing pollution transport and dispersion. AERMOD cannot be expected to be applicable within an urban environment. Earlier applications applying adjustments to analytical plume models (for example; Huber; 1988, 1989) found limited success for isolated clusters of simple-shaped buildings.

3.4 Fine-scale CFD Models for Exposure Factors.

Fine-scale CFD models can support the development and application of human exposure factors without interfacing to a CMAQ-type air quality modeling system. This would especially be applicable to the simulation of exposure profiles from sources within the fine-scale model domain. Human exposure models apply human exposure factors principally based on observations of relationships between pollutant concentrations at human contact and concentrations at surrounding points in the ambient environment, often a single neighborhood monitor. The CFD model can be used to develop databases to complement the dearth of exposure measurements and ambient measurements that exist in all urban areas. Measurements from field case studies are more limited than desired to support the development of human exposure profiles. The time has come for field measurements to support the evaluation of fine-scale CFD simulations so there is a reliable model for developing expanded databases to support human exposure assessments.

4. PRESENT EXAMPLES OF FINE-SCALE CFD MODELS AND THEIR APPLICATIONS

The US Environmental Protection Agency (EPA) has a project using FLUENT CFD software to develop applications for urban environments. A goal has been to demonstrate best practices for using CFD as a tool for estimating potential human exposures to local sources of toxic air contaminants in geometrically complex environments. FLUENT (2005) is a general purpose CFD software system with options for developing new and expanded applications through use of user defined functions. Examples of this work can be found, for example, in Huber et al. (2004, 2006) and Tang et al. (2006). To date the project has focused on steady-state solutions to the Reynolds-Averaged Navier-Stokes (RANS) equations with the widely used k-ε turbulence models. Ongoing developments are being extended to include unsteady solutions and higher order turbulence models as well. In any case, the fine-scale RANS models are most appropriate for interfacing with a CMAQ-like air quality model. Much has been learned and we are now ready to begin to determine how best to interface with the framework of a CMAQ-like larger grid modeling system.

A few example study cases are presented below to show the high-fidelity that is presently possible. While there is no thermal heating for these cases, methods have been developed for adding heat fluxes to any grid face or volume. These examples show that urban building environments may be specifically modeled within 1-4 km^2 at very fine scales to sufficiently resolve the significant features in the wind field to support simulation of steady-state pollution transport and diffusion distributions. Special source emissions and effects from moving vehicles may be added to these steady-state simulations. There is a growing literature with similar examples. For example, Kondo et al. (2006) demonstrates application of a multi-scale CFD model. Multi-scale CFD for this application is a nested regional meteorological model at 3 grid resolutions and a separate fine-scale CFD air quality model to estimate concentrations in the neighborhood of a major roadway. The state-of-art and science for applying fine-scale CFD models is rapidly growing. Just a taste of what is possible could be provided herein.

Test cases have been developed for Manhattan, NY. The building and terrain geometry was licensed from Vexcel Corporation. Test cases were run with boundary inlet winds set at S(180), SW(225), W(270), NW(315), and N(360). The 20 million cell solution is rich with fine-scale detailed structure in the wind distribution. Figure 3 shows a nearly 4 km^2 building domain and surface grid placed on a larger model domain including terrain.

A 20 million cell unstructured grid was constructed with 1-2 m size near the building surfaces to larger than 10 m far away from the buildings within a 1 km deep atmosphere-like boundary layer. The domain is oriented as depicted by the 3-axes displayed in Figures 3 and 4 (red arrow pointing East, green arrow pointing North). Figure 4 shows vertical velocity on several horizontal slice-planes through a volume study zone (defined as a 1.8 km by 0.8 km horizontal area through the full 1 km vertical domain depth). Vertical velocity is minimal near the top of the 1 km deep domain (not shown). Vertical velocities were observed to be generally largest in the windward half of the study planes or specifically near tall building faces such as shown near the tall Empire State building.

The patterns of horizontal winds near the surface have winds oriented in all directions making it hard for an isolated local bystander to estimate the boundary wind direction or even which way the winds would blow on the neighboring block. Simulations are being examined to determine "bulk" flow parameters. The horizontal wind velocities were area-averaged at z= 5, 10, 25, 60, 85, 110, 160 and 210 m above ground level (AGL) and compared with the inlet boundary conditions. Figure 5a shows the urban canopy effect. At 210 m (most buildings are lower) the wind speed nearly equals the inlet value accept for the N case. The average wind direction is strongly influenced below 25 m. This is very useful information for supporting the development of reliable site-specific urban canopy models.

Figures 6 and 7 show that there are variations in the wind patterns due to influences from specific buildings. There tends to be downward mass flow along windward building faces and upward mass flow along leeward building faces. Pollutants are naturally transported within the wind fields. Figure 7 shows how the shape and direction of a pollution plume may vary within the same wind field. The visualized plume represents the outer boundary from point emissions. Plume differences have been found to be significant for even minor changes in the emission location.

A CFD model of a 1 km^2 urban residential Baltimore, MD neighborhood with building and street geometry has been developed to support a study of human exposure from local street emissions. The digital model has sub-meter accuracy based on analyses of aerial and ground photographs. Methods have been developed to simulate time-averaged roadway turbulence and

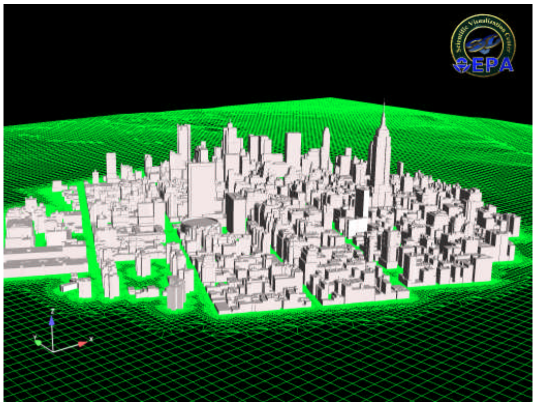


Figure 3. Model domain with surface grid.

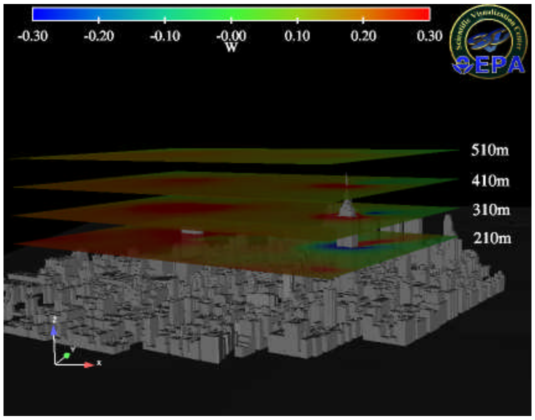
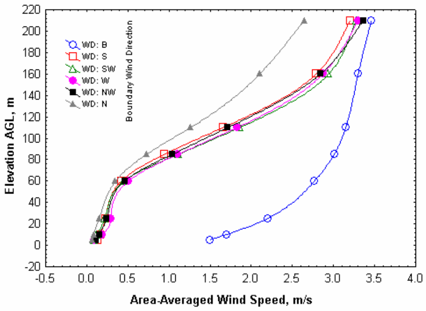


Figure 4. Horizontal planes displaying vertical velocity.

a) Wind speed



b) Wind direction

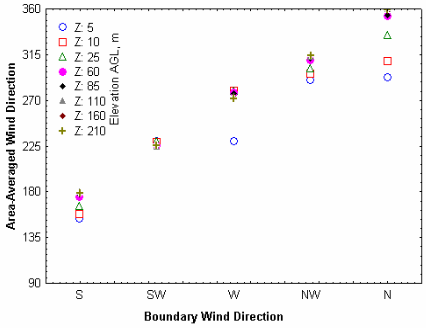


Figure 5. a) Area-averaged wind speed. Blue circles (B) plot the inlet wind profile b) Wind direction.

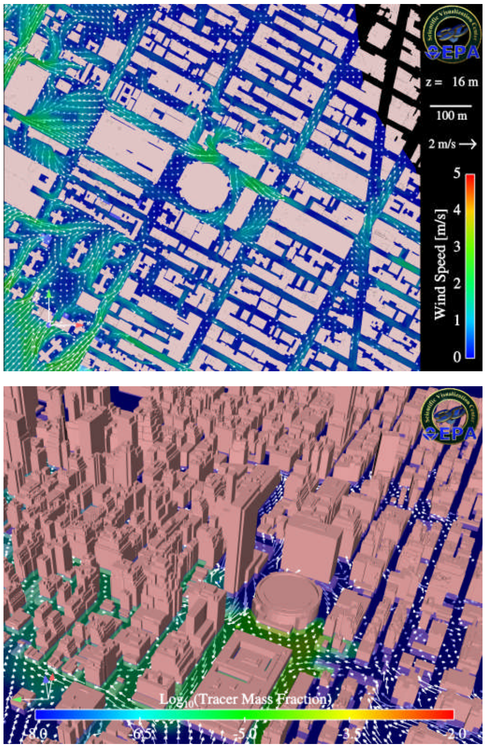


Figure 6. Surface winds (Top) and with concentration from a point source (Bottom) for the SW case.

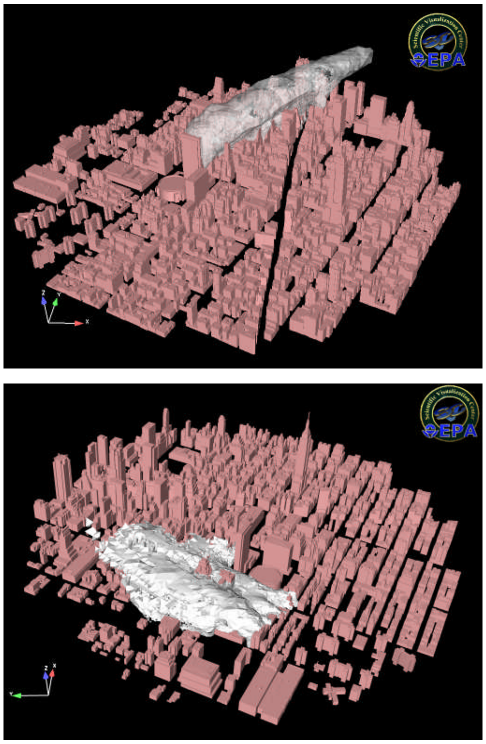
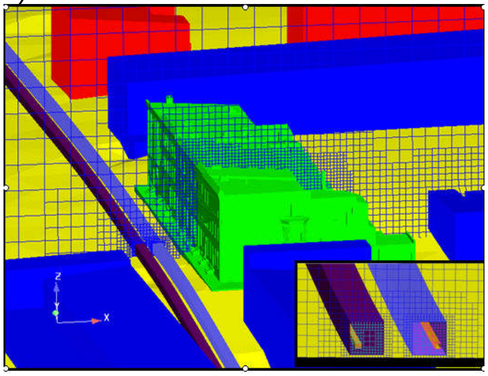


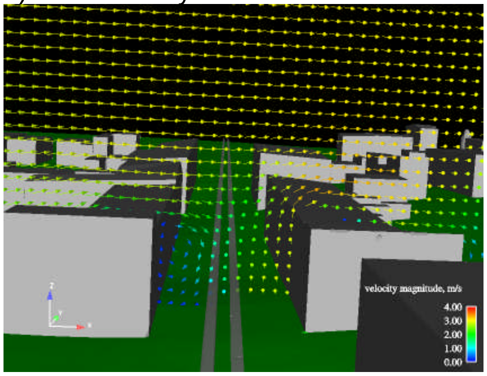
Figure 7. Top and Bottom picture shows a plume initiated from different point locations but within an identical wind field.

mobile source emissions based on Kastner-Klein et al. (2003) and Di Sabatino et al. (2003). Figure 8a below shows a vertical cross section slice of the domain grid with higher resolution near the building faces. This figure also shows the vehicle effects box (source of momentum and TKE within blue and purple boxes and shown expanded in the insert) and the smaller vehicle emissions box (yellow and orange shown in the insert) both running along a street. Ambient winds are from

a) Grid resolution



b) Wind velocity



c) Concentration

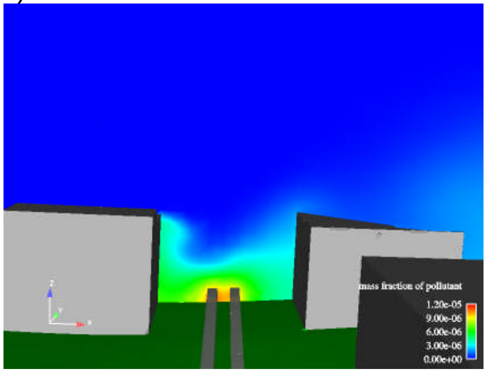


Figure 8. View of modeling a) domain grid resolution including the vehicle effects box along the roadway and vehicle emissions source box within b) wind and c) concentration.

left to right. Vehicle traffic is simulated assuming two lanes of one-way traffic at 20 mph.

There is a recirculation flow induced with the street canyon zone being displayed (Figure 8b) and the resulting concentration pattern (Figure 8c). For example, simulations for a few select wind directions can be used to study mobile source pollutants near the street and inside the adjacent buildings throughout the domain. This project is being completed to demonstrate how CFD simulations may be applied to model human exposure to mobile source emissions within specific neighborhoods.

5. SUMMARY STATEMENT

Fine-scale CFD models can be both interfaced with and applied independent of a larger scale grid model to support the development of human exposure factors and human exposure profiles dominated by local source emissions. Advances in computing hardware and software make it possible and increasingly more practical to consider extending present CMAQ-like air quality models to increasingly finer scales. The methods are all scaleable to larger domains as computing capacities grow. Routine fine-scale CFD modeling of air quality will happen.

Acknowledgements. Dr. Matt Freeman (Lockheed-Martin Operations Support) and Dr. Wei Tang (National Research Council Research Associate at the US EPA and now Lockheed-Martin Operations Support) are acknowledged for their support of the CFD applications and visualizations. Drs. Walter Schwarz, Brian Bell, and Karl Kuhlert (Fluent, Inc) are acknowledged for their support in developing CFD application using FLUENT. Scientific visualization and high performance computing were provided through support from the US EPA's Environmental Modeling and Visualization Laboratory. Additional computing support was provided through collaboration with Michael Lazaro and the Argonne National Laboratory, Laboratory Computing Resource Center.

Disclaimer. The research presented here was performed under the Memorandum of Understanding between the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) and under agreement number DW13921548. This work constitutes a contribution to the NOAA Air Quality Program. Although it has been reviewed by EPA and NOAA and approved for publication, it does not necessarily reflect their policies or views

References

Byun, D. W, and K. L. Schere (2006). Review of the Governing Equations, Computational Algorithms, and Other Components of the Models-3 Community Multiscale Air Quality (CMAQ) Modeling System, ASME. J Applied Mechanics Reviews **59(2):** 51-77.

Byun, D. W. and K. L. Schere (2004). EPA's Third Generation Air Quality Modeling System: Description of the Models-3 Community Multiscale Air Quality (CMAQ) Model, ASME J of Applied Mechanics Reviews.

Cimorelli, A. J.; Perry, S. G.; Venkatram, A.; Weil, J. C.; Paine, R. J.; Wilson, R. B.; Lee, R. F.; and Peters, W. D. (2005). AERMOD: A dispersion model for industrial source applications. Part 1: General model formulation and boundary layer characterization. Journal of Applied Meteorology, **44**: 682-692.

Di Sabatino, S., P. Kastner-Klein, R. Berkowicz, R.E. Britter, and E. Fedorovich (2003). The modelling of turbulence from traffic in urban dispersion models – Part I: Theoretical considerations. Environ. Fluid Mech. **3**, 129–143.

FLUENT (2005). FLUENT 6.2 User's Guide. Fluent Inc, Lebanon, NH.

Huber A.H., (1988): Performance of a Gaussian model for centerline concentrations in the wake of buildings. Atmospheric Environment 22:1039-1050.

Huber A. H., (1989): The influence of building width and orientation on plume dispersion in the wake of a building. Atmospheric Environment 23:2109-2116.

Huber, A.H., Tang, W., Flowe, A., Bell, B., Kuehlert, K., and Schwarz, W. (2004). Development and applications of CFD simulations in support of air quality studies involving buildings. 13th Joint Conference on the Applications of Air Pollution Meteorology with the Air & Waste Management Association, (CD-ROM) Vancouver, British Columbia, Canada, August 23-27, 2004.

Huber A., M. Freeman, R. Spencer, W. Schwarz, B. Bell, and K. Kuehlert (2006). Development and Application of CFD Simulations Supporting Urban Air Quality and Homeland Security. Presented at the AMS Sixth Symposium on the Urban Environment, Atlanta, GA, Jan 30 – Feb 2, 2006. http://ams.confex.com/ams/Annual2006/techprogram

Kastner-Klein, P., E. Fedorovich, M. Ketzel, R.Berkowicz and R.Britter (2003). The Modelling of Turbulence from Traffic in Urban Dispersion Models – Part II: Evaluation Against Laboratory and Full-Scale Concentration Measurements in Street Canyons. Environ. Fluid Mech. **3**, 145–172.

Kondo, H., K. Asahi, T. Tomizuka, M. Suzuki (2006). Numerical analysis of diffusion around a suspended expressway by a multi-scale CFD model. Atmos. Environ. **40**: 2852-2859.

McCurdy, T. (2000). Conceptual basis for multi-route intake dose modeling using an energy expenditure approach. Journal of Exposure Analysis and Environmental Epidemiology **10**: 86-97.

Ott, W. (1995). Human exposure assessment: the birth of a new science. Journal of Exposure Analysis and Environmental Epidemiology **5**(4): 449-472.

Özkaynak, H. (1999). Exposure Assessment, in Air Pollution and Health. (Holgate S, Koren H, Samet J, Maynard R, eds). London: Academic Press, 149–162.

Tang, W., A. Huber, B. Bell, W. Schwarz, and K. Kuehlert (2006). Application of CFD Simulations for Short-Range Dispersion over the Open Fields of Project Prairie Grass: Neutral Atmospheric Boundary Layer (in review)

Appendix 30

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Modeling Near-Road Air Quality Using a Computational Fluid Dynamics Model, CFD-VIT-RIT

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Received May 27, 2009. Revised manuscript received August 19, 2009. Accepted August 22, 2009.

It is well recognized that dilution is an important mechanism governing the near-road air pollutant concentrations. In this paper, we aim to advance our understanding of turbulent mixing mechanisms on and near roadways using computation fluid dynamics. Turbulent mixing mechanisms can be classified into three categories according to their origins: vehicle-induced turbulence (VIT), road-induced turbulence (RIT), and atmospheric boundary layer turbulence. RIT includes the turbulence generated by road embankment, road surface thermal effects, and roadside structures. Both VIT and RIT are affected by the roadway designs. We incorporate the detailed treatment of VIT and RIT into the CFD (namely CFD-VIT-RIT) and apply the model in simulating the spatial gradients of carbon monoxide near two major highways with different traffic mix and roadway configurations. The modeling results are compared to the field measurements and those from CALINE4 and CFD without considering VIT and RIT. We demonstrate that the incorporation of VIT and RIT considerably improves the modeling predictions, especially on vertical gradients and seasonal variations of carbon monoxide. Our study implies that roadway design can significantly influence the near-road air pollution. Thus we recommend that mitigating near-road air pollution through roadway designs be considered in the air quality and transportation management. In addition, thanks to the rigorous representation of turbulent mixing mechanisms, CFD-VIT-RIT can become valuable tools in the roadway designs process.

Introduction

Elevated air pollutants concentrations have been measured in congested urban areas and near roadways (*1, 2*), which have been associated with adverse human health effects (*3*). These effects vary with levels of human exposure to traffic-related air pollutants through different activities (e.g., driving on the road, living/working near or away from the road) (*4, 5*). Therefore, it is important to understand the spatial gradient of pollutants near roadways, which requires measurements and simulations addressing complex road configurations and meteorological conditions (*6, 7*).

Dilution is the dominant mechanism for changing the near-road concentrations. Pollutant dispersion near roadways usually experiences two distinct stages -- 'tailpipe-to-road' and 'road-to-ambient' (*8*). The dilution ratio of the first stage usually reaches up to about 1000:1 in around 1−3 s; for the second stage, the dilution ratio is usually about 10:1, and the process usually lasts around 3−10 min (*8*). The aerosol processes such as nucleation, condensation, and coagulation are strongly coupled with dilution (*8*). For nitrogen oxides (NO_x), the concentrations change results from the coupling of dilution and chemical reactions (*9*). For carbon monoxide (CO), an inert species under typical atmospheric conditions, dilution is the only governing mechanism. Therefore CO is usually used as a dilution indicator since it comes mostly from vehicle exhaust and can be easily measured (*10*).

Dilution is caused by on-road and near-road turbulent mixing. Given the importance of dilution on near-road air quality, it is imperative to gain a better understanding of the mechanisms contributing to the turbulent mixing. Several mechanisms affect the generation of turbulence near roadways besides atmospheric boundary layer turbulence (ABLT) (*11*). First, the movement of vehicles on the road results in a significant increase in turbulence, which is known as vehicle-induced turbulence (VIT) (*11−13*). Second, turbulence can be generated by the embankment on which a roadway is located when wind flows over it (*15*). Third, thermal effects caused by solar radiation generate turbulence during hot season and cannot be ignored for pollutant dispersion (*16−18*). Fourthly, road structures (i.e., noise barrier, tree planting) can also produce turbulence that influences the flow field (*6, 19, 20*). Since these three effects can be attributed to roadway design, we refer to them as RIT in this paper.

Gaussian plume-based dispersion models such as CALINE4 and AERMOD have been widely used to assess the pollutant concentrations of urban road environments (*21−24*). These models typically treat the region directly above the roadway and at prescribed distances on each side of the roadway as a zone of uniform emissions and turbulence called a "mixing zone" (*21*). The introduction of the "mixing zone" concept is equivalent to a fixed VIT, i.e., not adjustable to the specific roadway conditions (e.g., the different vehicles speeds and types). Their dispersion parametrizations are based in part on roadway geometry and wind direction, but they face the challenge of how to incorporate the effect of road configurations exactly (*14, 25−27*). In recent years, computation fluid dynamics (CFD) has been applied in modeling the dynamical and mechanical processes taking place in complicated urban street canyons and road tunnels (*16, 28, 29*). However, it has been rarely applied to simulate near-road air quality, and the comprehensive representation of VIT and RIT is scarce (*27, 30*).

In this paper, we aim to investigate the effects of different turbulent mixing mechanisms on dilution near roadways. An improved CFD with detailed treatment of VIT and RIT, namely CFD-VIT-RIT, is used to simulate the horizontal and vertical dispersions of CO in the vicinity of two highways during two seasons. The modeling results are compared with field measurements, CALINE4, and a CFD model without considering VIT and RIT. The implications of our findings on future road design and the advantages and disadvantages of applying different dispersion models are also discussed.

Mechanisms for on-Road and near-Road Turbulence Generation

In this section, we provide a brief summary of the mechanisms that generate VIT and RIT in on-road and near-road environments.

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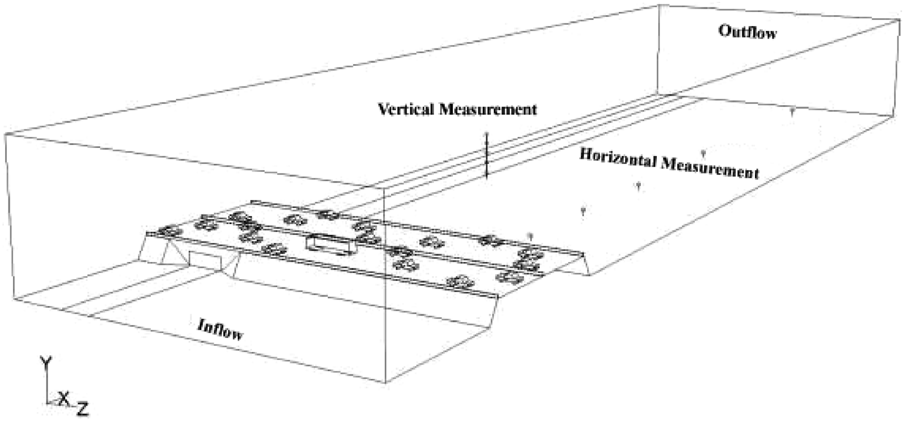

FIGURE 1. Geometric features of the computational domain for I-405.

Turbulence Induced by Vehicles. Traffic has a dominant effect in the immediate vicinity of the roadway (*14*). Moving vehicles enhance mixing processes by inducing turbulence, which originates from the interaction between moving vehicles and ambient air. It is known that up to 50% of kinetic energy is converted into additional turbulence when a fluid hits an obstacle (*28*). The wakes behind moving vehicles are characterized as momentum wakes and contain organized trailing vortices which play a key role in determining the flux of kinetic energy and rapidly mix the pollutants released in the turbulent wake (*14, 31, 32*). VIT, which is strongly related to vehicle type and speed (*27, 33, 34*), can be expected to significantly influence the diffusion of roadway emissions, especially in the microenvironment near roadways (*13, 14, 33*). VIT increases with vehicle speed, indicating increased wake production of turbulence (*14*). Experiments also showed that compared with gasoline cars, heavy-duty diesel trucks induce more turbulence due to its size and structure (*34*).

Turbulence Induced by an Embankment. An embankment acts as a topographic obstacle which causes a form drag and produces turbulence to compensate for the deformation of the flow field when wind flows over it (*35*). A recirculation cavity is created downwind of the embankment, containing a well-mixed, and often lower, zone of pollution concentrations (*36*). The induced turbulence depends on the wind velocity, wind direction, the height, and the shape of the embankment (*15, 33*).

Turbulence Induced by Thermal Effects on Road Surface. The available solar radiation on a surface, Q_0, can be divided into turbulent fluxes of sensible heat, H_0, latent heat, V_0, and the soil heat flux, B_0 (*34*). With high absorptivity and low heat capacity, the asphalted surface of roadway receives much net energy. Compared to the grassy or concrete surroundings, it provides a very small latent heat flux and leads to an increased sensible heat flux, which generates turbulence (*33*). The thermally induced flow is combined with mechanically induced flows and affects the transport of pollutants. It should be noted that due to the large solar zenith angle in the winter, the road surface receives much less direct solar radiation, so the temperature difference between road surface and air can be neglected.

Turbulence Induced by Roadside Structures. Roadside structures affect pollutant concentrations around the structure by blocking initial dispersion and increasing turbulence and initial mixing of the emitted pollutants (*6, 19, 20*). A noise barrier disturbs the wind field as a still obstacle while a tree planting consisting of branches and leaves can be considered as a porous body (*6, 19*). It has been shown that the plume behind noise barrier and vegetation is relatively uniform and vertically well-mixed, and pollutant concentrations are reduced under certain meteorological conditions. With winds directionally from the road, concentrations of CO and particle concentrations generally decrease between 15 and 50% behind the noise barrier (*6*).

Field Measurements

The experimental data utilized in this paper are collected from previous measurements near Interstate 405 (I-405) and Interstate 710 (I-710) in Los Angeles in the summer and winter (*10, 37–40*). I-405 is 30 m wide, with an embankment of 4.5 m-height, while I-710 is 26 m wide at ground level. The horizontal sampling points are taken within 300 m downwind and upwind from the center of the highways at height 1.6 m. Meanwhile, the vertical CO concentrations at different heights are measured at 50 m downwind of I-405 in the summer. There are relatively large differences in temperature, but small differences in wind speed and vehicle volume for each highway between different seasons. For I-405, gasoline cars dominate the vehicle mix, while for I-710, more than 25% of the vehicles are heavy-duty diesel trucks. All related conditions are considered in our simulation. More meteorological and road data are listed in the Supporting Information.

CFD-VIT-RIT

The $k - \varepsilon$ turbulence model available in the CFD code, FLUENT (*41*), is used for modeling flow and dispersion in the vicinity of roadways and is described in the Supporting Information.

Figure 1 shows the computational domain of I-405 and the sketch of measurement locations. The number of computational cells used for the simulation is 2,305,712, with a size of 380 m by 80 m in the horizontal and 30 m in the vertical direction. The computational domain for I-710 is similar, except that the highway is not located on an embankment. The spatial domain has a size of 380 m by 40 m in the horizontal and 30 m in the vertical direction and is divided into 1,063,541 unstructured cells.

Test zones above road surface are created to obtain average turbulent kinetic energy (TKE). Different heights of the domain are set according to the heavy-duty truck percentage. Since most of the vehicles are cars and vans for I-405, the height of the zone is 2.5 m, while for I-710, the height is 3.5 m since it is a major truck route.

We model the vehicles as real-shaped rather than block-shaped to keep the conditions similar to the streamlined shape of real vehicles (*27*), since the turbulence for the block-shaped vehicle is estimated to be 25% higher than for the true vehicle models (*42*). Different types of vehicles are built approximately following their actual sizes. Since the average vehicle speed, 24 m s^{-1}, is measured during the experiments (*37*), the same moving speed for all vehicles is adopted in the simulation (*43*). For the vehicle surface, an equivalent roughness height of 0.0015 m is chosen to match the

TABLE 1. Summary of TKE in the Test Zone

	I-405				I-710			
	summer	percentage	winter	percentage	summer	percentage	winter	percentage
VIT[a]	0.36	41.4%	0.35	53.9%	0.63	76.8%	0.63	95.5%
RIT - embankment[a]	0.30	34.5%	0.27	41.5%	N/A	N/A	N/A	N/A
RIT - thermal effects[a]	0.17	19.5%	N/A	N/A	0.15	18.3%	N/A	N/A
ABLT[a]	0.04	4.6%	0.03	4.6%	0.04	4.9%	0.03	4.5%
total TKE[a]	0.87	100.0%	0.65	100.0%	0.82	100.0%	0.66	100.0%

[a] Unit is m^2 s^{-2a}.

simulated drag force of vehicles with the value based on drag coefficient (*44*). The exhaust pipe is modeled as a small area on the back of the light-duty vehicle or on the top of the heavy-duty diesel vehicles. Since traffic volumes change little between seasons, just one set of vehicles is built for each highway. The embankment for I-405 is built corresponding to its real size (in Figure 1). All the solid boundaries, including ground surfaces and vehicle surfaces, are specified as nonslip boundary conditions in the flow module and are prescribed at a fixed temperature in the heat transfer module. Symmetric boundary conditions (zero gradient normal to boundary) are applied to the top and side faces of the domain. More description of model set up and the figure of meshed vehicles are illustrated in the Supporting Information.

Based on a meteorological study in Los Angeles (*45*), the temperature difference between air and roadway surface is estimated to be 20 °C for the summer season under strong solar radiation. Considering the atmospheric wind in two seasons, fully developed in-flow vertical profiles for ABLT are incorporated through User-Defined Function (UDF) and described in the Supporting Information.

In summary, we incorporate the turbulence induced by moving traffic, embankment, thermal effects, and atmospheric wind into our model. Since there are no noise barriers and few trees in the surrounding of I-405 and I-710, turbulence generated by the road barriers and trees is not simulated here and will be investigated in future studies.

Results

TKE Results. Induced TKE within the test zone is summarized in Table 1. From Table 1, it is clear that total TKE changes with seasons and highways and the largest TKE is obtained from I-405 with the embankment in the summer. The produced VIT, especially for I-710, is dominated over ABLT, as suggested by previous wind tunnel studies (*46*). Due to the large percentage of heavy-duty trucks, VIT of I-710 is much larger than that of I-405. Excellent agreements are found for VIT between our model (0.36 m^2 s^{-2} for I-405 and 0.63 m^2 s^{-2} for I-710) and the empirical formula (0.37 m^2 s^{-2} for I-405 and 0.64 m^2 s^{-2} for I-710) reported by Baumer et al. (*33*). TKE produced by embankment, $\sim$0.30 m^2 s^{-2}, or 34.5% of the total TKE in the test zone, is also in good agreement with the value, 0.34 m^2 s^{-2}, calculated from the empirical formula in Baumer et al. (*33*). The large contribution of embankment-induced TKE implies that elevated highways enhance turbulent mixing downwind, potentially reducing human exposure to traffic-generated air pollutants. Furthermore, TKE caused by the thermal effects due to road surface properties accounts for about 20% of total TKE in the test zone and therefore cannot be ignored.

It should be noted that the main advantage of our model over the empirical formula is its capability to resolve the effects of VIT and RIT over the near-road region beyond the test zone. Our simulations show that TKE reaches the maximum value on road and decays with the increasing distance from the highway, until at 300 m it is negligibly small. Due to a large turbulence dissipation rate, VIT, averaged from the ground to the height of the test zone, drops to below 50% at about 20 m downwind of highway. When wind velocity increases, VIT dissipates faster but is also transported to a greater horizontal distance. When wind velocity is small, VIT can spread to higher elevation. RIT decreases slower than VIT, due to the big size of the embankment which results in a larger influence range. For I-405, the ratio of VIT to RIT decreases with the increasing distance.

Spatial Gradients of Carbon Monoxide Concentrations. In this section, we compare the simulated CO concentrations in both horizontal and vertical directions against the field measurement data. In addition to the CFD-VIT-RIT model, we also present the results from CALINE4 and a standard CFD model. In the standard CFD model, referred to as “CFD” in the text, the highways are treated as elevated line sources without explicit treatment of VIT and RIT. We use 405S, 405W, 710S, and 710W to refer to the studies of two different highways (i.e., I-405 and I-710) at two seasons with “S” and “W” representing summer and winter, respectively.

While the spatial gradients of near-road concentrations of inert species such as CO are determined by turbulent mixing, the absolute concentrations are determined by both vehicle emission factors and turbulent mixing. Since the emission factors derived by models such as MOBILE6 and EMFAC have known discrepancies in representing real-world emission factors (*47, 48*), our comparisons focus on the relative concentrations of CO, thus avoiding the additional uncertainties introduced by the emission factor models. The CO concentrations at downwind distances are normalized by their values at the closest distances to the roadways, i.e., 30 m for I-405 and 17 m for I-710, respectively. For instance, the relative CO concentrations at 30 m from I-405 are unity for both measurements and modeling results. However, the concentrations at 60 m, 90 m, 150 m, and 300 m vary depending on measurements and selected models.

Horizontal Gradients and Seasonal Variations. Figure 2(a) compares the simulation results obtained from the CFD-VIT-RIT, CALINE4, and CFD models to the measurement data for I-405 in the summer. Relative CO concentration decays exponentially when moving away from the traffic source. The dilution between 30 and 60 m varies with different models: CALINE4 and CFD underpredict more than 33% compared to measurement data, while CFD-VIT-RIT reduces the error to less than 15%. In Figure 2(b), since turbulence induced by the road surface thermal effects can be ignored in the winter, the differences in CALINE4 and CFD-VIT-RIT predictions are relatively small. However, CFD still shows big error due to no-consideration of VIT and RIT. The simulation results for I-710 in the summer and winter are shown in Figure 2(c) and Figure 2(d). The improvement of predictions by CFD-VIT-RIT over CFD and CALINE4 on I-710 can be attributed to the detailed treatment of VIT and RIT.

The horizontal dispersion of CO is determined mainly by wind velocity and turbulence (*38*). To compare near-road dispersions for both I-405 and I-710 in different seasons, we introduce a parameter called the dilution ratio, which is the

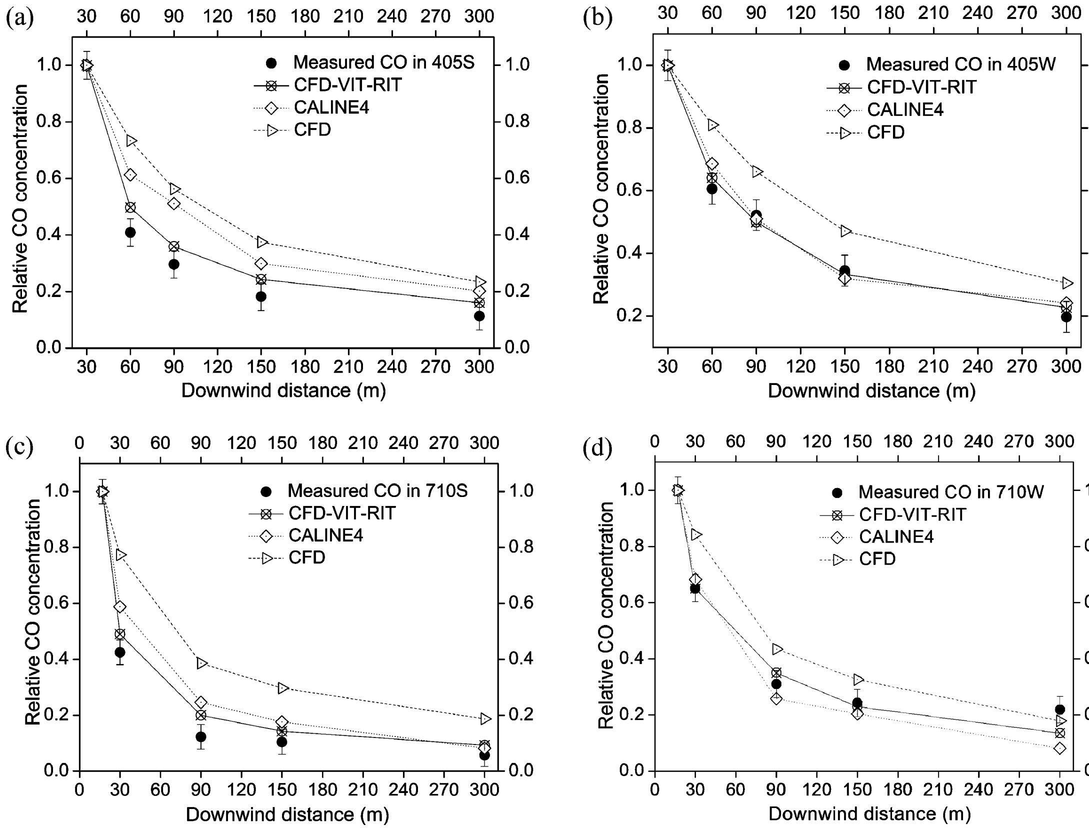

FIGURE 2. Comparison of relative CO concentrations between models and field experiment for I-405 in summer (a) and winter (b) and for I-710 in summer (c) and winter (d).

TABLE 2. RMS of Relative CO Concentration and Dilution Ratio between 30 and 150 m

		measurement	CFD-VIT-RIT	CALINE4	CFD
405S horizontal	30 m/150 m	5.5	4.11	3.34	2.67
	rms	N/A	0.065	0.186	0.270
405W horizontal	30 m/150 m	2.89	3.00	3.13	2.12
	rms	N/A	0.031	0.052	0.162
710S horizontal	30 m/150 m	4.12	3.43	3.32	2.61
	rms	N/A	0.064	0.124	0.277
710W horizontal	30 m/150 m	2.78	2.83	3.37	2.58
	rms	N/A	0.024	0.042	0.131
405S vertical	rms	N/A	0.059	0.246	0.213

ratio of background-subtracted CO concentrations at 30 and 150 m, listed in Table 2. The root-mean-square (rms) of measured and simulated relative CO concentrations at 60 m, 90 m, and 150 m for I-405 and 30 m, 90 m, and 150 m for I-710, respectively, is also shown in Table 2. More details can be found in ref *10*. From Table 2, it is clear that due to the thermal effects, dilution ratios between 30 and 150 m in the summer are much larger than those of winter for both highways. Seasonal effects are significant with winters generally less dynamic than summers; therefore, thermal effects cannot be neglected during the summer, especially under low wind conditions and wind perpendicular to the street (*10, 16, 29, 49*). Mainly due to the existence of the embankment, dilution ratios of I-405 are higher than that of I-710 for both seasons with similar total TKE values. The dilution ratios obtained from CFD-VIT-RIT show the same trend as the measurement data, while CFD and CALINE4 show little change between different seasons. rms of CFD-VIT-RIT is consistently smaller than those of CALINE4 and CFD, which shows a more precise prediction of dilution ratio for CO horizontal dispersion and seasonal variations. CFD-VIT-RIT's capability in capturing the seasonal variations is particular useful in long-term human exposure assessment of near-road exposure.

Vertical Gradients. We first compare the simulated wind velocity vertical profile with the field measurement. As illustrated in Figure S2 in the Supporting Information, the measured wind velocities are approximately constant with vertical height and have relatively small and similar standard deviations (*38*). CFD-VIT-RIT shows good consistence, except at height 0.6 m, where the simulated velocity is not within the standard deviation of the measured data. A possible reason is that since the sampling point is close to the surface, it is probably disturbed by the unconsidered structure on the ground.

Next, we compare the measured and simulated vertical profile of relative CO concentrations at eight sampling locations above the ground at 50 m downwind of I-405 horizontally in the summer, depicted in Figure 3(a). The vertical CO concentration is observed to reach a maximum at a height around 5 m above the ground and decreases by 30% at 18 m above the ground. There is a dimple observed at 10 m, which is likely due to secondary mixing above the central line of emission (*38*). CFD-VIT-RIT demonstrates great

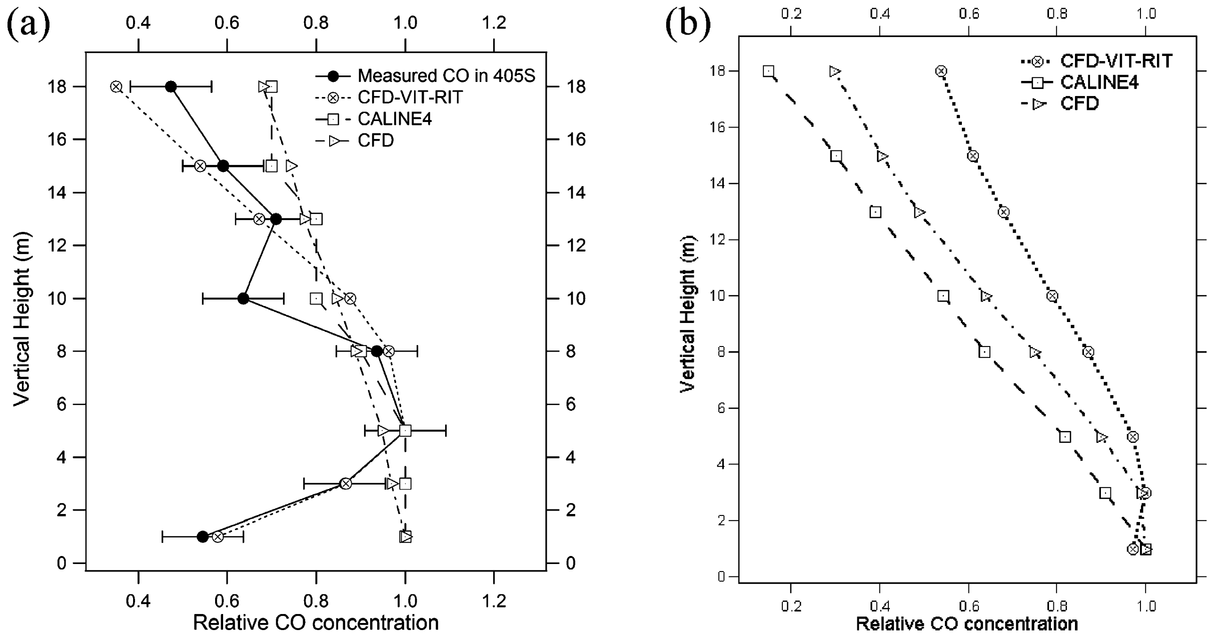

FIGURE 3. Comparison of vertical relative CO concentration for I-405 in the summer (a), and for I-710 in the summer (b).

superiority in predicting CO vertical profile compared to CALINE4 and CFD. The rms of CFD-VIT-RIT shown in Table 2 is nearly one-quarter of those of CALINE4 and CFD. VIT and RIT play more significant roles in the vertical dispersion, where turbulence dominates the mixing process, than in the horizontal dispersion, where both turbulence and axial wind transport govern the mixing process. CFD-VIT-RIT yields good predictions at almost all sampling points. Its maximum concentration is obtained at 6.4 m, about 1.9 m above the highway. The small rise of the plume from the highway is mainly due to the buoyancy of the exhaust induced by a higher temperature on surface of asphalted road. However, because of the strong mechanical mixing due to moving vehicles on road, the plume rise is small (*14*). Simulated CO concentration at the height of 0.6 m is in good agreement with the measurement data, though simulated wind velocity shows an error. This is mainly because vertical dispersion is mostly controlled by turbulence rather than wind velocity. The capability of CFD-VIT-RIT to accurately predict the vertical profiles of air pollutants is important in studying human exposure to near-road air pollution for people living at different elevations.

Figure 3(b) compares the simulated CO vertical profiles at 50 m from I-710 in the summer by CFD-VIT-RIT, CALINE4, and CFD models. CFD-VIT-RIT predicts maximum concentration around 2 m above the highway (at the ground level) due to the thermal effects. In contrast, the maximum concentrations predicted by CALINE4 and CFD are both at the ground level due to lack of representation of the thermal effects.

On-Road Emission Factors of Carbon Monoxide. As the capability of CFD-VIT-RIT has been validated by the horizontal and vertical gradients of CO, we apply the inverse modeling method to derive the on-road CO emission factors using CFD-VIT-RIT, following the methodology reported earlier (*37*). The derived CO emissions factors are, in g mile^{-1} vehicle^{-1}, 6.1 for 405S, 7.2 for 405W, 7.0 for 710S, and 6.0 for 710W, which are similar to the values reported in the earlier study (*37*).

Implications

We have demonstrated that the significant improvement in predicting the spatial gradients of air pollutants near roadways can be achieved by incorporating detailed treatment of VIT and RIT into dispersion modeling. RIT is determined by the roadway design characteristics such as roadway configurations (e.g., elevated or depressed), road surface properties (e.g., asphalt or concrete), and roadside structures (e.g., noise and vegetation barriers). VIT is governed by the traffic mix on the roadways, which is, to a large extent, affected by roadway designs such as road width, slope and speed limits. Given the large effects of VIT and RIT on pollutant dispersion, we argue that roadway designs affect near-road air quality and that future roadway designs could serve as an effective strategy to mitigating near-road air pollution. Nevertheless, further understanding of the effects of the roadway designs on pollution dispersion is needed before making scientifically sound policies. We hope that our study can initiate future investigations into this subject.

CFD-VIT-RIT is still more computationally expensive than Gaussian plume models such as CALINE4, but it is able to provide much more physical insights thanks to its rigorous treatment of turbulence mixing mechanisms on- and near-road, evinced by the excellent prediction of vertical gradients of air pollutants near roadways. Thus CFD-VIT-RIT, or a combination of CFD-VIT-RIT and CALINE4, can become a valuable tool in roadway design process and near-roadway air quality research. The caveat is that a CFD model without detailed treatment of VIT and RIT adds no more benefits than CALINE4 besides high computational cost.

Acknowledgments

The authors would like to acknowledge New York State Energy Research and Development Authority (NYSERDA) and University Transportation Research Center (UTRC) for the funding support.

Supporting Information Available

Meteorological and road data, governing equations for $k-\varepsilon$ turbulence model, meshed vehicle model for I-710, and wall function for the fully developed vertical profile of inlet wind flow. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Hagler, G. S. W.; Baldauf, R. W.; Thoma, E. D.; Long, T. R.; Snow, R. F.; Kinsey, J. S.; Oudejans, L.; Gullett, B. K. Ultrafine particles

near a major roadway in Raleigh, North Carolina: Downwind attenuation and correlation with traffic-related pollutants. *Atmos. Environ.* **2009**, *43* (6), 1229–1234.

(2) Westerdahl, D.; Wang, X.; Pan, X. C.; Zhang, K. M. Characterization of on-road vehicle emission factors and microenvironmental air quality in Beijing, China. *Atmos. Environ.* **2009**, *43* (3), 697–705.

(3) Samet, J. M. Traffic, air pollution, and health. *Inhalation Toxicol.* **2007**, *19* (12), 1021–1027.

(4) Peters, A.; von Klot, S.; Heier, M.; Trentinaglia, I.; Hormann, A.; Wichmann, H. E.; Lowel, H. Exposure to traffic and the onset of myocardial infarction. *New Engl. J. Med.* **2004**, *351* (17), 1721–1730.

(5) McConnell, R.; Berhane, K.; Yao, L.; Jerrett, M.; Lurmann, F.; Gilliland, F.; Kunzli, N.; Gauderman, J.; Avol, E.; Thomas, D.; Peters, J. Traffic, susceptibility, and childhood asthma. *Environ. Health Perspect.* **2006**, *114* (5), 766–772.

(6) Baldauf, R.; Thoma, E.; Khlystov, A.; Isakov, V.; Bowker, G.; Long, T.; Snow, R. Impacts of noise barriers on near-road air quality. *Atmos. Environ.* **2008**, *42* (32), 7502–7507.

(7) Riddle, A.; Carruthers, D.; Sharpe, A.; McHugh, C.; Stocker, J. Comparisons between FLUENT and ADMS for atmospheric dispersion modelling. *Atmos. Environ.* **2004**, *38* (7), 1029–1038.

(8) Zhang, K. M.; Wexler, A. S. Evolution of particle number distribution near roadways--Part I: analysis of aerosol dynamics and its implications for engine emission measurement. *Atmos. Environ.* **2004**, *38* (38), 6643–6653.

(9) Fraigneau, Y. C.; Gonzalez, M.; Coppalle, A. Dispersion and chemical-reaction of a pollutant near a motorway. *Sci. Total Environ.* **1995**, *169* (1−3), 83–91.

(10) Zhang, K. M.; Wexler, A. S.; Zhu, Y. F.; Hinds, W. C.; Sioutas, C. Evolution of particle number distribution near roadways. Part II: the 'road-to-ambient' process. *Atmos. Environ.* **2004**, *38* (38), 6655–6665.

(11) Rao, S. T.; Sedefian, L. Characteristics of turbulence and dispersion of pollutants near major highways. *J. of Appl. Meteorol.* **1979**, *18* (3), 283–293.

(12) Singh, N.; Joshi, R. R.; Chun, H. Y.; Pant, G. B.; Damle, S. H.; Vashishtha, R. D. Seasonal, annual and inter-annual features of turbulence parameters over the tropical station Pune (18 degrees 32 ' N, 73 degrees 51 ' E) observed with UHF wind profiler. *Ann. Geophys.* **2008**, *26* (12), 3677–3692.

(13) Chock, D. P. General-Motors sulfate dispersion experiment - An analysis of the wind-field near a road. *Boundary-Layer Meteorol.* **1980**, *18* (4), 431–451.

(14) Rao, K. S.; Gunter, R. L.; White, J. R.; Hosker, R. P. Turbulence and dispersion modeling near highways. *Atmos. Environ.* **2002**, *36* (27), 4337–4346.

(15) Hauf, T.; Neumannhauf, G. The turbulent wind flow over an embankment. *Boundary-Layer Meteorol.* **1982**, *24* (3), 357–369.

(16) Kim, J.-J.; Baik, J.-J. Urban street-canyon flows with bottom heating. *Atmos. Environ.* **2001**, *35* (20), 3395–3404.

(17) Sini, J. F.; Anquetin, S.; Mestayer, P. G. Pollutant dispersion and thermal effects in urban street canyons. *Atmos. Environ.* **1996**, *30* (15), 2659–2677.

(18) Xie, X. M.; Huang, Z.; Wang, J. S.; Xie, Z. The impact of solar radiation and street layout on pollutant dispersion in street canyon. *Build. Environ.* **2005**, *40* (2), 201–212.

(19) Gromke, C.; Buccolieri, R.; Di Sabatino, S.; Ruck, B. Dispersion study in a street canyon with tree planting by means of wind tunnel and numerical investigations - Evaluation of CFD data with experimental data. *Atmos. Environ.* **2008**, *42* (37), 8640–8650.

(20) Lidman, J. K. Effect of a noise wall on snow accumulation and air quality. *Transp. Res. Rec.* **1985**, *1033*, 79–88.

(21) Benson, P. E. A Review of the Development and Application of the Caline3 and Caline4 Models. *Atmos. Environ. Part B-Urban Atmos.* **1992**, *26* (3), 379–390.

(22) Cimorelli, A. J.; Perry, S. G.; Venkatram, A.; Weil, J. C.; Paine, R. J.; Wilson, R. B.; Lee, R. F.; Peters, W. D.; Brode, R. W. AERMOD: A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization. *J. Appl. Meteorol.* **2005**, *44* (5), 682–693.

(23) Cook, R.; Isakov, V.; Touma, J. S.; Benjey, W.; Thurman, J.; Kinnee, E.; Ensley, D. Resolving local-scale emissions for modeling air quality near roadways. *J Air Waste Manage. Assoc.* **2008**, *58* (3), 451–461.

(24) Venkatram, A.; Isakov, V.; Yuan, J.; Pankratz, D. Modeling dispersion at distances of meters from urban sources. *Atmos. Environ.* **2004**, *38* (28), 4633–4641.

(25) Coe, D. L.; Eisinger, D. S.; Prouty, J. D.; Kear, T. *User's Guide for CL4: A User Friendly Interface for the CALINE4 Model for Transportation Project Impact Assessments*; Caltrans-U.C. Davis Air Quality Project, Sacramento, 1998.

(26) Benson, P. E. A review of the development and application of the CALINE3 and CALINE4 models. *Atmos. Environ. Part B-Urban Atmos.* **1992**, *26* (3), 379–390.

(27) Sahlodin, A. M.; Sotudeh-Gharebagh, R.; Zhu, Y. F. Modeling of dispersion near roadways based on the vehicle-induced turbulence concept. *Atmos. Environ.* **2007**, *41* (1), 92–102.

(28) Katolicky, J.; Jicha, M. Eulerian-Lagrangian model for traffic dynamics and its impact on operational ventilation of road tunnels. *J. Wind Eng. Ind. Aerodynamics* **2005**, *93* (1), 61–77.

(29) Xie, X.; Liu, C.-H.; Leung, D. Y. C. Impact of building facades and ground heating on wind flow and pollutant transport in street canyons. *Atmos. Environ.* **2007**, *41* (39), 9030–9049.

(30) Liu, C. S.; Ahmadi, G. Computer simulation of pollutant transport and deposition near Peace Bridge. *Part. Sci. Technol.* **2005**, *23* (2), 109–127.

(31) Ozdemir, E.; Ozdemir, I. B. Turbulent structure of three-dimensional flow behind a model car: 2. Exposed to crosswind. *J. Turbul.* **2004**, *5*, 18.

(32) Kozaka, E. O.; Ozkan, G.; Ozdemir, I. B. Turbulent structure of three-dimensional flow behind a model car: 1. Exposed to uniform approach flow. *J. Turbul.* **2004**, *5*, 22.

(33) Baumer, D.; Vogel, B.; Fiedler, F. A new parameterisation of motorway-induced turbulence and its application in a numerical model. *Atmos. Environ.* **2005**, *39* (31), 5750–5759.

(34) Kalthoff, N.; Baumer, D.; Corsmeier, U.; Kohler, M.; Vogel, B. Vehicle-induced turbulence near a motorway. *Atmos. Environ.* **2005**, *39* (31), 5737–5749.

(35) Garbrecht, T.; Lupkes, C.; Augstein, E.; Wamser, C. Influence of a sea ice ridge on low-level airflow. *J. Geophys. Res., [Atmos.]* **1999**, *104* (D20), 24499–24507.

(36) Kim, H. G.; Patel, V. C. Test of turbulence models for wind flow over terrain with separation and recirculation. *Boundary-Layer Meteorol.* **2000**, *94* (1), 5–21.

(37) Zhang, K. M.; Wexler, A. S.; Niemeier, D. A.; Zhu, Y. F.; Hinds, W. C.; Sioutas, C. Evolution of particle number distribution near roadways. Part III: Traffic analysis and on-road size resolved particulate emission factors. *Atmos. Environ.* **2005**, *39* (22), 4155–4166.

(38) Zhu, Y. F.; Hinds, W. C. Predicting particle number concentrations near a highway based on vertical concentration profile. *Atmos. Environ.* **2005**, *39* (8), 1557–1566.

(39) Zhu, Y. F.; Hinds, W. C.; Kim, S.; Shen, S.; Sioutas, C. Study of ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmos. Environ.* **2002**, *36* (27), 4323–4335.

(40) Zhu, Y. F.; Hinds, W. C.; Shen, S.; Sioutas, C. Seasonal trends of concentration and size distribution of ultrafine particles near major highways in Los Angeles. *Aerosol Sci. Technol.* **2004**, *38*, 5–13.

(41) *Fluent 6.3.26 -User's Guide*; Fluent Inc.: 2006.

(42) Thompson, R. S.; Eskridge, R. E. Turbulent diffusion behind vehicles: Experimentally determined influence of vortex pair in vehicle wake. *Atmos. Environ.* **1987**, *21* (10), 2091–2097.

(43) Gidhagen, L.; Johansson, C.; Omstedt, G.; Langner, J.; Olivares, G. Model simulations of NOx and ultrafine particles close to a Swedish highway. *Environ. Sci. Technol.* **2004**, *38* (24), 6730–6740.

(44) White, F. M. *Fluid Mechanics*; McGraw-Hill Science Engineering: 2002.

(45) Terjung, W. H.; Orourke, P. A. The effects of changing solar angles, cloud regimes, and air temperatures on the temperatures of contrasting surfaces. *Boundary-Layer Meteorol.* **1982**, *24* (3), 269–279.

(46) Khare, M.; Chaudhry, K. K.; Gowda, R. M. M.; Ahmad, K. Effects of the homogeneous traffic on vertical dispersion parameter in the near field of roadways - A wind tunnel study. *Environ. Model. Assess.* **2005**, *10* (1), 55–62.

(47) Cook, R.; Touma, J. S.; Fernandez, A.; Brzezinski, D.; Bailey, C.; Scarbro, C.; Thurman, J.; Strum, M.; Ensley, D.; Baldauf, R. Impact of underestimating the effects of cold temperature on motor vehicle start emissions of air toxics in the United States. *J. Air Waste Manage. Assoc.* **2007**, *57* (12), 1469–1479.

(48) Ban-Weiss, G. A.; McLaughlin, J. P.; Harley, R. A.; Lunden, M. M.; Kirchstetter, T. W.; Kean, A. J.; Strawa, A. W.; Stevenson, E. D.; Kendall, G. R. Long-term changes in emissions of nitrogen oxides and particulate matter from on-road gasoline and diesel vehicles. *Atmos. Environ.* **2008**, *42* (2), 220–232.

(49) Xie, X. M.; Liu, C. H.; Leung, D. Y. C.; Leung, M. K. H. Characteristics of air exchange in a street canyon with ground heating. *Atmos. Environ.* **2006**, *40* (33), 6396–6409.

ES9014844

Appendix 31

McAlpine J. D. and Ruby M. (2004) *Using CFD to Study Air Quality in Urban Microenvironments.* Chapter 1 of *Environmental Sciences and Environmental Computing. Vol. II* (P. Zannetti, Editor). Published by The EnviroComp Institute (http://www.envirocomp.org)

Chapter 1

Using CFD to Study Air Quality in Urban Microenvironments

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Abstract

The study of building effects on air quality has grown beyond stack plume downwash. The relative placement of air intakes and exhausts and cooling tower exhausts on buildings can significantly affect the indoor air quality. Earlier studies of effects on building air intakes have been limited to relatively simple situations, unable to treat the complex envelope of most buildings and building groups. Computational Fluid Dynamics (CFD) is becoming available as a tool to assist with modeling the airflow and dispersion of pollutants among complex urban geometries on the scale of a section of a building exterior up to several city blocks. This tool allows more accurate predictions of impacts over a range of meteorological scenarios and alternative building designs and placements relative to roadways and other pollutant sources. Recent projects are discussed to illustrate the capabilities of CFD in modeling urban microenvironments. The steps in a CFD application are presented including geometry and mesh creation, simulation of meteorological conditions, handling of pollutant sources, and post-processing visualization. The benefits and shortcomings of this approach are also discussed.

Introduction

Recent studies have found that urban Americans spend about 90% of their time indoors (USEPA, 1995). Most of today's commercial and institutional buildings have mechanical air handling systems that are designed to provide proper ventilation, to ensure indoor sources of pollutants are quickly vented to the outside. It is equally necessary to design the systems so the source outdoor air is free of odors or contamination. If the source air is contaminated, the effects can range from odor complaints to serious illnesses such as Legionnaire's disease. The positioning of air handling units and exhaust stacks on buildings should be carefully analyzed to ensure that building inhabitants are not exposed to irritants, carcinogens, and odors that originate from outdoor sources or the building's own exhausts.

Studies of airflow around buildings generally involve the positioning of cooling towers, exhausts and air-handling units. These projects have ranged from assisting architects with the placement of large cooling towers and air-handling units to addressing odor complaints due to exhaust sources near to air intakes.

Until recently, analytical methods were most often used to model the airflow in these types of projects. The ASHRAE static model is commonly used to determine roof recirculation and turbulence zones (Wilson, 1979) and downwind building recirculation zones (Fackrell, 1984). A simple picture of the descriptive ”zones” which can be calculated by this method is included in Figure 1. Consultants have also utilized theatrical smoke releases in existing situations to illustrate the flow of sources to intakes. Wind tunnels have also been popular tools in the industry to model airflow and pollutant dispersion in scale models of urban environments, especially for proposed buildings.

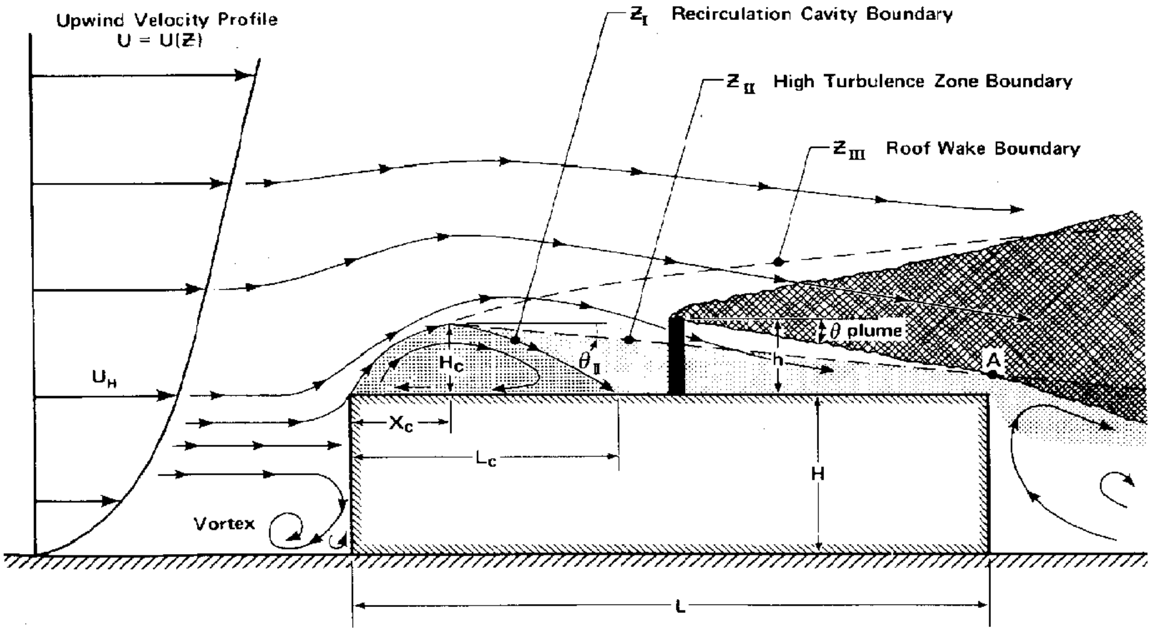

Figure 1: Illustration of building wake boundary, recirculation zones, turbulence zones, and streamlines calculated by static analytical methods. (Wilson, 1979)

Each of these traditional methods has shortcomings that call for a better approach. Simple mathematical methods can not account for complex urban spatial relationships or meteorological conditions. Theatrical smoke release can achieve this, but can require an extended effort to capture more than one or two conditions and can not yield quantitative results without intricate instrumentation. Theatrical smoke is also limited to examination of nearby existing conditions. Wind tunnels offer more control, but are quite costly. Meteorological conditions are difficult to imitate in the wind tunnel environment because arrangements of upstream obstacles must be placed strategically to simulate incoming turbulence.

Recently, a new tool has become more widely available that overcomes many of the shortcomings of traditional methods. Computational Fluid Dynamics (CFD) has a long history of use in computing fluid flow around obstacles (Anderson, 1995). As it has become more available in the desktop-computing environment CFD has been applied to a wider range of problems, most recently urban microclimates. With CFD the urban spatial geometry can be represented in computer simulation with reasonable accuracy, including more than just the building surfaces. Topography, vegetation, and mechanical features such as stacks and air intakes are easily described. CFD also offers the ability to experiment with solutions by making it easy to alter site geometry and features or stack and inlet parameters. A host of meteorological conditions including wind directions and magnitudes, temperatures, and atmospheric stabilities can be simulated in a CFD project in a reasonable time.

Using CFD as the main tool in addressing these problems has been successful in recent projects. These projects have involved using the tool to assist with stack and cooling tower positioning, air intake positioning and odor source diagnosis. Details of several of these projects are discussed in this paper.

As with all computer simulations that are used to model real world phenomena, validation of the results is always crucial. However, this may be difficult for CFD because of the complexity of flows in the atmospheric surface layer and wide varieties of problems that may be addressed with CFD. The results of a few simple methods to attempt some qualitative validation of the modeling results are presented at the conclusion of this paper.

CFD Availability

With the advent of fast powerful desktop computing, the ability to model complex computational fluid dynamic problems in economical timeframes has increasingly become a reality. In the past, large mainframe computers were required to compute CFD problems. Now, using an efficient commercial CFD package, a problem can be solved in a matter of hours on a desktop computer. We have found that a computer with 1Gbyte of memory and operating at 1800 MHz on a single processor is adequate to provide runs in a reasonable time. For example, a model in rectangular Cartesian coordinates with approximately one million cells solving only the wind fields took about 6 hours to run for 4 minutes of model time.

Many commercial CFD packages are now available that offer a variety of features, but the main aspects of the CFD approach is rather similar for all packages. First, a package has a geometry creation and visualization program where the CFD problem is set up. The project geometry and mesh including buildings, topography, vegetation, and boundary conditions such as air inlets, outlets, and exhaust stack parameters are all established in this program. When the model parameters are all defined, the CFD project is sent to a second program, the solver. In the solver, the equations of fluid motion are solved for the given geometry using a time-marching technique. Since the steady state solutions to the equations of motion are parametric, a time-marching technique, given adequate initial conditions, can solve for a steady state solution. Finally, the solution is loaded into a visualization program, where streamlines, vectors, scalers, and a variety of other features can be graphed to observe the results.

The commercial CFD package we are using is CFD2000 by Adaptive Research, which is equipped with its fast, efficient STORM solver (http://www.adaptive-research.com). This program provides the classical first-order closure scheme, the k-ε turbulence model to account for steady state turbulence and advanced numerical schemes to solve CFD problems efficiently. Several types of k-ε turbulence models are available to use with the solver including a Re-normalized Group (RNG) model. The most recent version of CFD2000 also offers a Large Scale Eddy model, but we have not yet tested it.

The Equations of Motion

The basic equations of motion are known as the Navier-Stokes equations. They are a set of equations that relate the conservation of mass, momentum, and energy. Initially we have five equations (the continuity equation, the conservation of momentum equation in each of three dimensions, and the energy equation) and seven unknowns (pressure [P], density [ρ], temperature [T], x-component velocity [u_1], y-component velocity [u_2], z-component velocity [u_3], and internal energy [expressed in terms of the enthalpy H]). The continuity equation for an open Newtonian system with possible sources or sinks S_{mp} for mass at a point within the system can be written:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = S_{mp} \tag{1}$$

where the subscript i identifies the directions through the faces of each sub-volume of the system. Similarly, the three, separable equations for the conservation of momentum can each be written:

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_i} = \frac{\partial \tau_{ij}}{\partial x_i} - \frac{\partial P}{\partial x_i} + \rho B_i + S_{uip} \tag{2}$$

where B includes body forces on the sub-volume (e.g., gravity), S is again source or sink terms and τ_{ij} is a collection of cross product terms of velocity differential components identified as the viscous stress tensor. Finally, the conservation of energy equation can be written for a fixed sub-volume as:

$$\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\frac{\kappa}{C_p}\frac{\partial H}{x_i}\right] + \frac{\partial P}{\partial t} + u_i \frac{\partial P}{\partial x_i} + \Phi + Q_p + S_{Hp} \tag{3}$$

where Φ is another collection of cross product terms, identified as the Stokes molecular dissipation function, Q is the rate of energy added as heat to the sub-volume and S is a source or sink term for enthalpy. The additional terms κ, the thermal conductivity, and

C_p, the specific heat, which are measured data for a specific problem, are necessitated by our use of H instead of the internal energy.

Such a system of equations is not solvable without additional assumptions. We can assume a relationship between the fluid density and the other thermodynamic variables. In our case we use the perfect gas law, $T = P/\rho R$, where R is the gas constant, which is reasonable for air at the surface of the earth. In addition, we can assume that we are able to express the conservation of turbulent kinetic energy k and the dissipation rate ε of turbulent kinetic energy with similar transport equations (usually expressed in a more complex form than would be useful to reproduce here) that relate back to the other equations through the stress tensor τ and the molecular dissipation function Φ and do not include any more unknowns because we are able to assume values for k and ε that are constant across the system.

With the five initial equations, the assumption of the perfect gas law and the k-ε assumption we now have a system of equations that can be solved. Any number of scalar transport equations as well as chemical reaction equations that couple to this set of equations can also be used in the solution.

The interesting problems for CFD involve moving air and obstacles to flow which require the flow to have zero velocity at the object wall. This results in a gradient in the velocity across the flow field even with no changes in the air direction or velocity. Similarly the real atmosphere under gravitational force yields a pressure gradient that must be considered even at the small scale of urban buildings. The perfect gas law assumption is then valid only locally, which limits the size of the solution space to the microscale.

The most useful, steady state solutions will be in dynamic equilibrium averaged over both space and time. The model does not provide information about the range of fluctuations about this equilibrium solution. Reynolds (or “ensemble”) averaging is applied to the equations to derive the steady state solutions. With Reynolds averaging the instantaneous value of a variable is assumed to be the sum of the mean value and a perturbation from that value. For example, if $u(t) = \bar{u} + u'(t)$ then the steady state solution is the mean of this quantity, or $\bar{u}(t) = \text{mean}(\bar{u} + u'(t))$. Replacing each velocity variable with the Reynolds averaged variable results in the Reynolds averaged Navier-Stokes equations, which can be solved for the steady state flow. The vector cross products generated when the mean value is taken of the velocity perturbations are known as the Reynold’s stresses. It is these cross product terms that allow information, for example about the location of a wall, to be disseminated throughout the model space. Turbulence modeling is concerned with accounting for these terms and the viscous dissipation term. The k-ε equations assume isotropic eddy-viscosity, which simplifies the viscous dissipation term.

The method of parameterized Reynold’s stresses and viscous dissipation by turbulent kinetic energy transport is a popular one that has been used rigorously, mostly due to the comparatively lower computational burden of the method. The two turbulent kinetic energy and dissipation equations replace a complex numerical representation of the flow, which would be difficult to model. Further, isotropic eddy-viscosity is a good assumption in lower velocity atmospheric boundary layer flow. Though this method is not perfect, and inaccurate in certain situations, it has proven to be sufficiently accurate in representing the steady state flow of situations where the length scales of velocity and obstacles are much greater than the length scales of turbulence.

The Focus of a Local Scale Analysis

On the local scale, in the urban microclimates around buildings and sets of buildings, we can identify six pollutant sources that are of the highest concern. The majority of CFD projects performed to address HVAC positioning, health or odor complaints, or exposure analyses will focus on one, several, or all of these. They are, in no particular order: lab hood exhaust, cooling tower exhaust, automobile exhaust, odor sources (from kitchen stacks, garbage storage, industrial exhausts, etc.), allergens such as grass clippings or cigarette smoke, and general building exhaust. Little regulation beyond the common law of nuisance exists for these pollutants or the conditions that make them a problem. Vague guidelines for exhaust stack heights, filtering, and safety are incorporated in different standards documents but no one standard can be applied for the world of circumstances that can occur at the local scale. Also, these types of exhausts effect different people in different ways. For example, an allergen source near an air intake may have a dramatic impact on sensitive individuals while non-allergic persons have no notice. An odor from a kitchen stack may be quite pleasing to one passing on the street, but may be highly objectionable to the nearby office worker exposed to the exhaust for hours on end. Some details of the handling of these exhausts in the CFD modeling follows.

Lab hood exhaust stacks

Exhaust from lab hood stacks can potentially be harmful depending on the agents used in the lab. Various chemicals with toxic or acidic properties may be ejected from these stacks. In some cases, biological hazards may be emitted from similar stacks. In any case, this exhaust may be the most dangerous exhaust element of this scale and being so, it is very important to keep this exhaust away from air intakes or any place where the public may encounter it.

The volumes of these stacks are often quite small (ranging from 1,000 – 10,000 cfm). They are often small in diameter, ranging from 6 inches to 2 feet and are often placed in groups or in lines along building roofs. The relatively low volume of flow means that the effective stack heights (physical height plus momentum and buoyant plume rise) of these exhausts may be quite low during stronger winds. Thus, the heights of these stacks often need to be quite high to avoid entrainment into recirculation zones which may bring the exhaust to the surface or concentrate it in regions near intakes, etc. CFD can assist with the analysis to determine placement and height of these stacks.

Odorous sources

Odourous sources are highly variable in their make-up. The most common of these are often stacks similar to lab hood exhausts that emit kitchen odors, lab odors, locker room odors, or industrial odors. Airflow volumes from these stacks can be quite large (>30,000 acfm) such as those from larger kitchens or industrial sources. Other sources of odor may be from street level garbage bins or diesel exhaust from idling vehicles.

The impact of each odor source is highly dependent on the amount of dilution of the exhaust that is needed before the odor is not offensive. However, this is a highly subjective area, considering that odor sensitivity varies considerably throughout the population. Standard descriptions of odors are based on the number of dilutions of the original source odor that are needed to render the sample gas odorless (that is, below the threshold of detection) to a majority of a panel of seven to thirteen average individuals. Thus, an odor strength may be cited as “1000 dilutions to threshold” (d/t). Typical odor strengths for an industrial source might be 2,000 to 5,000 d/t. while a kitchen exhaust might be 5,000 to 10,000 d/t. Because this represents the odor strength evaluated by 50% of the population it may be necessary to go to more than twice the dilutions of the measured detection threshold to avoid notice by all but a very few in the general population.

The best way to handle these types of odors in CFD modeling is by examining the dilution of the exhaust at locations throughout the CFD domain from the concentration at the initial source. Exhaust dilutions can then be compared to the d/t measured in odor studies to estimate impacts. For visualization purposes, different outlines of the plume can be illustrated at various dilution levels of the exhaust to assess areas of impact.

Motor vehicle exhaust

Emissions from motor vehicles are one of the main sources of pollutants in the atmosphere, contributing to emissions of nitrogen oxides, carbon monoxide, benzene, and many other chemicals. Therefore, it is ideal to place intakes away from busy intersections or roads where exhaust may buildup in adverse traffic or wind conditions. Street canyons can concentrate motor vehicle exhaust under certain wind conditions or funnel high levels of exhaust to sensitive regions. CFD can simulate street canyons and other recirculation zones to assist in the placement of the air intakes of a building on the street.

Simulating motor vehicle exhaust in the CFD environment is difficult. Tailpipes from vehicles are placed at different heights depending on the type of vehicle and diesel engines have different kinds and amounts of emissions from gasoline engines. Also, vehicle movement creates its own airflow that disperses the pollution itself. This poses a challenge in CFD modeling. Perhaps the best way to account for this is by using a volume source in the CFD domain, with emissions calculated from the EPA vehicle emissions models (e.g., MOBILE 6). If only plume path needs to be analyzed, an array of plume streamlines released from the traffic exhaust volume region may be adequate.

Cooling tower exhaust

At first thought, cooling tower exhaust seems a harmless aerosol, consisting of water mist. However, the possibility of bacterial growth in the cooling tower water stream makes it a possible source of contamination. The infection of a cooling tower by bacteria makes it a biohazardous source. Steps taken to reduce the chance of bacteria infection may make the tower a chemically hazardous source depending on the antibacterial agents used in the stream. Ammonia, bromine, and chlorine are common chemicals used to treat cooling tower water which make the exhaust potentially hazardous to nearby receptors.

Mist drift from cooling towers has been implicated as a source of the infectious proteobacteria *legionella pneumophila.* The conditions in cooling towers can be ideal for the growth of *legionella*, which is present in low concentrations in most water supply systems. The conditions which promote growth of the bacteria are

- water temperatures between 95 and 115 degrees F
- sediment and food sources in the water which support the growth of algae, protozoa, etc.
- the presence of l-cysteine-HCl and iron salt

Legionella belongs to an unusual group of bacteria with special properties that can defeat the respiratory disease response system, a group which includes tuberculosis and salmonella. *Legionella* is widely distributed and occurs in five different varieties. Infections commonly appear with only two of the forms, one occurring relatively infrequently but manifesting as a mild respiratory disease in approximately 95% of those exposed and the other a more troublesome form that only matures in 2 to 5% of those exposed. The milder form causes flu-like symptoms that pass in less than a week. The other results in severe symptoms, often requires hospitalization and is fatal in about 10% of the cases.

In the best known cases of disease outbreak (an American Legion convention in Philadelphia and the Oakland County Health Department in Pontiac, Michigan) the building air intakes were close to the infected cooling tower. However even with significant separation it is judicious to determine the likelihood of cross-contamination in order chose relative locations that will minimize the opportunity for infection.

Because a cooling tower uses sprays of water to cool the working liquid, the exhaust air from a cooling tower contains fine droplets of water, called mist, that can drift with the exhaust air away from the cooling tower in a plume. If the cooling tower water has developed a *legionella* growth, the mist will contain the bacteria. The mist will evaporate quickly in warm dry conditions, but may remain as droplets for quite a distance in humid conditions. Even when dried, *legionella* can retain its infective capability.

Concentration Guidance and Visualizing CFD Results

There are several effective ways to visualize the results of your CFD modeling either for analysis, verification, or demonstration. Perhaps the most effective way to visualize dispersion in the CFD environment is by examining dilutions of the exhaust from a source.

In most cases, actual concentrations of harmful entities in the exhaust, such as acid in a lab hood exhaust stack plume or bacteria per cubic meter of cooling tower exhaust, will not be known. Stack test data from similar sources is usually not available as the exhaust makeup is often unique.

If the concentration of, for example, a release of sulfur dioxide in a lab fume hood exhaust is approximately 0.5%, a high but not unreasonable concentration for short period discharges during certain procedures, a dilution of only 1,000 times would reduce it to 5 ppm, at approximately the industrial hygiene limits for an eight-hour exposure and 10 times the recommended short-term exposure for sensitive members of the public. Thus a dilution of only 1,000 averaged across an entire air intake (assuming 100% outside air circulation) or in an area of public exposure would be considered unacceptable and a dilution of more than 10,000 times would be marginally acceptable.

For a kitchen exhaust stack, an adequate dilution is somewhat debatable, being highly dependent on the type of food being cooked and the nature and sensitivity of the receptor. Kitchen exhaust itself is not harmful and often even has a desirable odor, especially as advertising at lunchtime. However, a sensitive individual working at his or her desk may find an odor to be unbearable after repeated exposures. Even mild coffee odors from roasters lead to vigorous complaints to air quality agencies. As a general rule, a stack from a kitchen using garlic, soy sauce or high in grease, such as an Asian or a hamburger grill would require about 5,000 dilutions to prevent significant complaints and 10,000 dilutions to avoid detection by most of the population. A more standard kitchen exhaust from well maintained systems would require 1,000 dilutions to avoid significant complaints.

The necessary dilution of cooling tower exhausts to avoid exposure to *Legionell*a bacteria from an infected cooling tower has not been established. Obviously at a higher level of contamination, a greater dilution would be needed to minimize the possibility of exposure. The U.S. Centers for Disease Control have recommended treating cooling tower exhaust as potentially infective even at dilutions greater than 100,000. It is not known how conservative this is. Clearly proper maintenance of cooling towers must be the first line of defense but proper siting can minimize the problems that might occur if an infection arises in spite of ongoing maintenance.

In some CFD cases, the volume of gas from a source is too small or the resolution of the CFD model domain is too great to incorporate the plume from a stack. In these cases, it is necessary to model the plume centerline using the visualization of a streamline originating from the effective release point of a stack. The “effective” stack height accounts for rise due to mechanical lift and thermal buoyancy of the plume after release. Simple analytical plume Gaussian dispersion models can be sources of guidance for the plume dilution at certain points if properly handled. The stack parameters and average wind speed of the plume throughout the CFD modeling domain can be used to assess a dilution at downwind points.

Successful Projects Using CFD

CFD can be used to examine the movement and dispersion of pollutants around buildings for length scales of tens of meters up to hundreds of meters. So far, CFD has been used successfully to analyze the flow around buildings and building clusters in urban microenvironments. From our experience, the more common types of projects can be divided into two classes. The first type of project involves cases where the client is dealing with current odor or contamination complaints inside or in sensitive areas outside an existing building. The second type involves projects where the client seeks consultation on the placement of air intakes or exhaust stacks to avoid future odor or contamination problems. Several of both types of projects that we have conducted are discussed in this section.

Though model geometry is simple in several of these cases, the possible complexity of the geometry in a CFD case is unbounded. More complex geometry, including minute details, takes more time to construct and thus must only be included in the model when necessary. The most critical region in the model domain is often the source or receptors and the region surrounding each. The shape and dimensions of a stack or other source must be established correctly to ensure the parameters of the stack gas flows are as near to reality as possible. Building surfaces or topography far away from the regions of interest in the model can have less detail as long as the necessary dimensions and surface roughness are accounted for to properly simulate wind flow in that region of the model.

Chemical analysis lab exhaust near building air intake.

In this project, building occupants were complaining of odors in their offices, which were located in a building housing several chemical analysis labs. Most of these labs contain fume hoods, which were vented out short stacks to the building roof. Several of these stacks were very near to the two air intakes for the office areas, in an area of complex building geometry, as can be seen in Figure 2.

When the odor complaint log was compared to meteorological conditions, it was observed that many of the chemical odors occurred during the periods of southwest and northwest winds. Complaints in rooms served by the south air intake corresponded to periods of northwest winds, which are rare winds for the region. Complaints in rooms served by the north air intake corresponded to periods of southwest winds, which are common winds for the region.

For CFD modeling, the exhaust stacks, the air intakes, and the three most prevalent wind directions during complaint periods were modeled in a simple geometry domain. All positions of exhaust stacks were noted and visualized using unit emissions and/or plume centerlines. Considering the light color of the building roof, building roof heat was not considered to have a large impact on the flow, so was not included in the model. For each wind case, neutral atmospheric conditions were assumed.

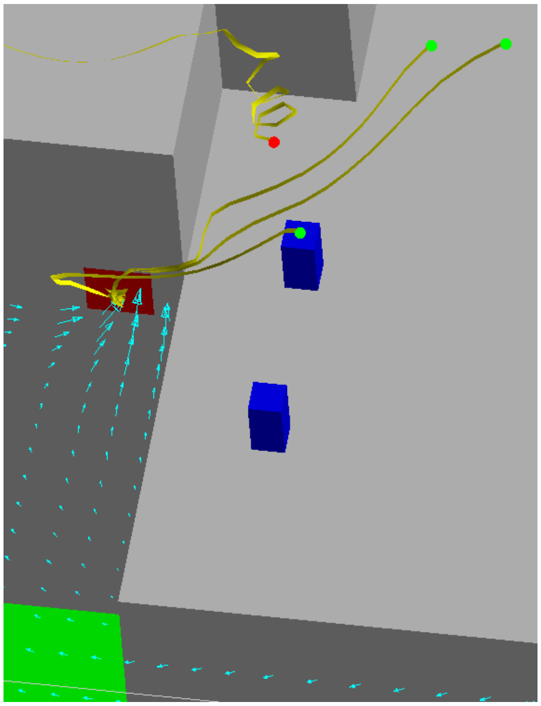

Figure 2: Plume centerline streamlines under light southwest wind. Several of these plumes travel across the building roof, and down into the air intake (the red square on the side of the building).

The modeling results showed that several of the exhaust plumes directly entered the air intake. Plume-centerline visualization showed that the plumes from several exhaust stacks were completely taken up by the air intake, as seen in Figure 2.

To alleviate this problem, several alternatives were suggested. The best alternative was to move the air intake out of a re-circulation "well" that forms in the area where it is currently located. Another alternative was to raise the height of the exhaust stacks above the building top roof. Both these alternatives are illustrated in Figure 3. (The stacks are shown with a square cross-section because the model was created as all rectangular solids to speed execution time.)

The green dot on the top of the exhaust stack represents the existing arrangement, with a streamline originating there which enters the air intake. The red dot, positioned directly above the green dot, represents the elevation of a raised stack which will allow the exhaust to avoid the re-circulation zone and travel over the top of the adjoining roof.

Positioning of lab exhausts and cooling towers for a new building.

In this project, two new buildings, including a medical research facility, were proposed to be constructed together on a sloping hillside. These buildings required air intakes, cooling towers, and vivarium (i.e., housing for laboratory animals) and lab hood exhausts as part of their HVAC design. CFD modeling was used to assist with the proper positioning of the HVAC elements to lower the risk of exhaust entering the air intakes.

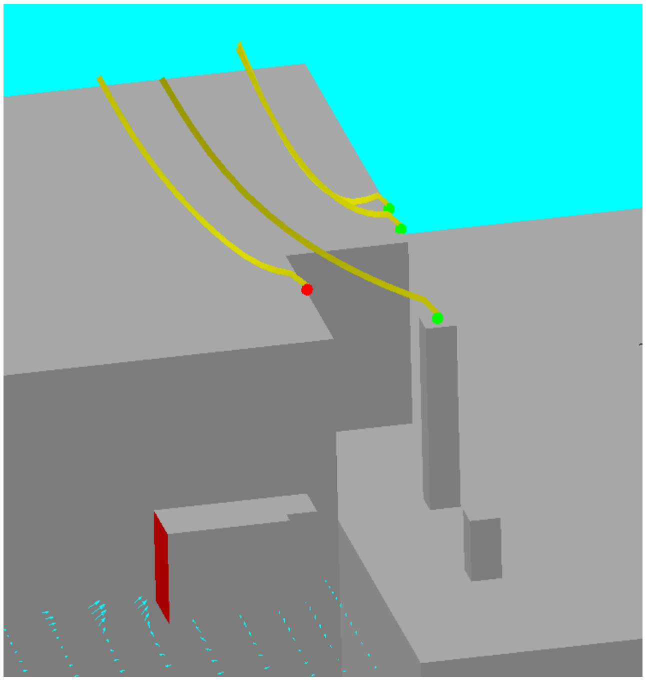

Figure 3: CFD modeling with alternatives included. The air intake (in red on the near side of the building on the left) is shifted to the left, and the most important exhaust stacks are raised to adequate heights to avoid the building re-circulation zone. In this figure a northwest wind is shown.

CFD modeling confirmed that the initial stack height was adequate for the lab hood stacks. Exhaust from the hoods remained well above the ground, avoiding sensitive receptors such as pedestrian walkways and air intakes. However, the initial configuration of the vivarium exhausts and cooling towers allowed the exhaust to reach the air intakes.

The vivarium exhaust points, potentially carrying significant levels of odor, reached the air intakes at around 300 dilutions, as illustrated in Figure 4 on the following page. The CFD model found that the initial design, which vented the exhaust from roof-level louvers, would not lift the exhaust out of the roof and lee re-circulation zones of the building. CFD was used to test different alternatives, leading to a final solution of venting the exhaust out taller stacks, which allowed the plume to avoid the air intakes.

Air intakes near busy road and truck/bus-idling location

In another project, odors from outside had become a nuisance indoors. The building was completely climate controlled, with the high capacity air intake near to a busy intersection with a high volume of diesel traffic. In addition, a bus stop was located directly adjacent to the intake and the far lane of the street was a sharp uphill ramp for traffic. Building occupants throughout the buildings were complaining about diesel exhaust odor in their offices. Site visits and building occupant observations confirmed that the truck traffic required increased power on the uphill ramp, emitting large amounts of diesel exhaust. Also, delivery and other trucks used the bus stop and adjacent sidewalk as a parking and idling spot.

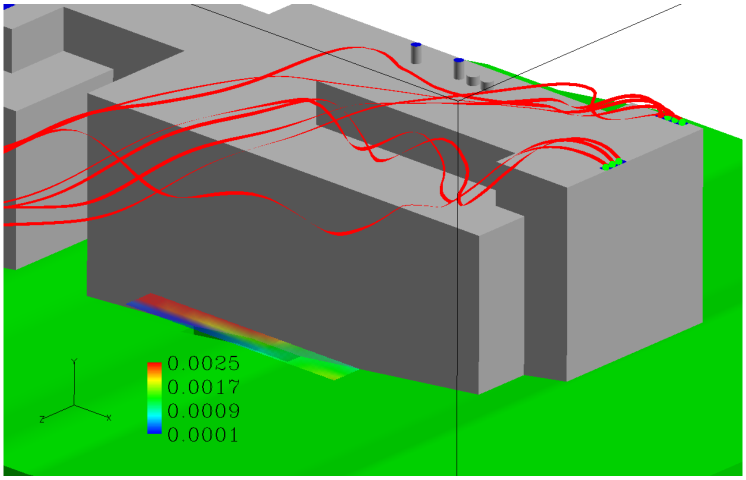

Figure 4. Plume centerline streamlines (red streamers) originating from vivarium exhaust louvers, flow freely at roof level and do appear to stay at that elevation. However a portion of the dispersing edge of the plume is entrained in the lee recirculation zone and travels down the wall. A measurement plane is placed directly above the surface air intake of the building (the red and yellow streak at ground level on the near side of the building) to measure the concentration of exhaust entering the intake. Exhaust enters the building at a dilution of around 300, a potentially high odorous concentration. (The measurement plane only reports in concentration units, the inverse of dilution. So the 0.0025 on the red end scale is 400 dilutions while the 0.0017 in the yellow is 588 dilutions.)

CFD was used to analyze the significance of the various exhaust source areas and to analyze alternatives that might relieve the impacts. Air movements around the building and from the potential source areas were modeled for several wind directions. The complaint record indicated that rare easterly winds were very common when complaint were made, so careful attention was directed to the easterly winds. For all winds, neutral atmospheric conditions were assumed. A standard sharp wind profile for neutral conditions and high ground turbulence due to the presence of many obstacles was assumed.

Visualization was performed of plume centerlines released from a typical truck exhaust height at these source areas. The source areas examined included a nearby loading dock, idling locations on the adjacent access road, a stop sign/ acceleration zone near the intake, the uphill ramp, the bus stop idling zone, and several locations along the main road.

The CFD modeling demonstrated that only in certain of these locations did the exhaust plumes reach the air intake under a variety of wind conditions, and most especially during periods of winds common when complaints were recorded. An example visualization of the results is provided in Figure 5.

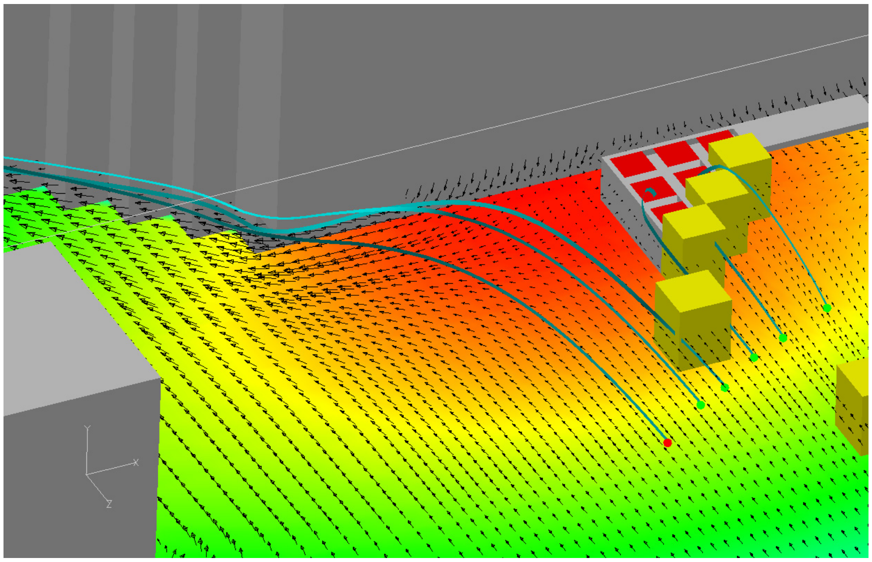

Figure 5. An illustration of results visualization showing flow vectors, pressure anomalies, and plume centerlines. The plume centerlines travel directly from nearby acceleration zones (marked by the red and green dots at the end of the ribbons) into the air intake (represented by the red squares on top of the structure adjacent to the main building). The yellow blocks included in the modeling were porous objects representing trees along side the air intake. The coloration along the ground represents surface atmospheric pressure, with the red area at higher pressure than the yellow and green. The vectors on the ground illustrate the direction of air flow at each cell along the ground surface.

Several alternatives were proposed for the existing design. Modeling was required to test some of these options. For one alternative, raising the height of the air intake structure to lift it away from the exhaust plumes was examined. CFD modeling showed that this alternative was would not solve the problem as the air flow would simply rise up the side of the intake carrying the plumes with it, as demonstrated in Figure 6 on the next page. In order to prevent the extra lift created from a single mass intake extension, several design modifications are modeled. The modeling identified a design which utilizes an “organ-pipe” configuration by extending the intake opening to the region of clean air well above the street as potentially beneficial. The space between the pipes allows for the flow of air through the obstruction, limiting the lift that was seen with the total extension alternative. An illustration of this design is shown in Figure 7 on the next page.

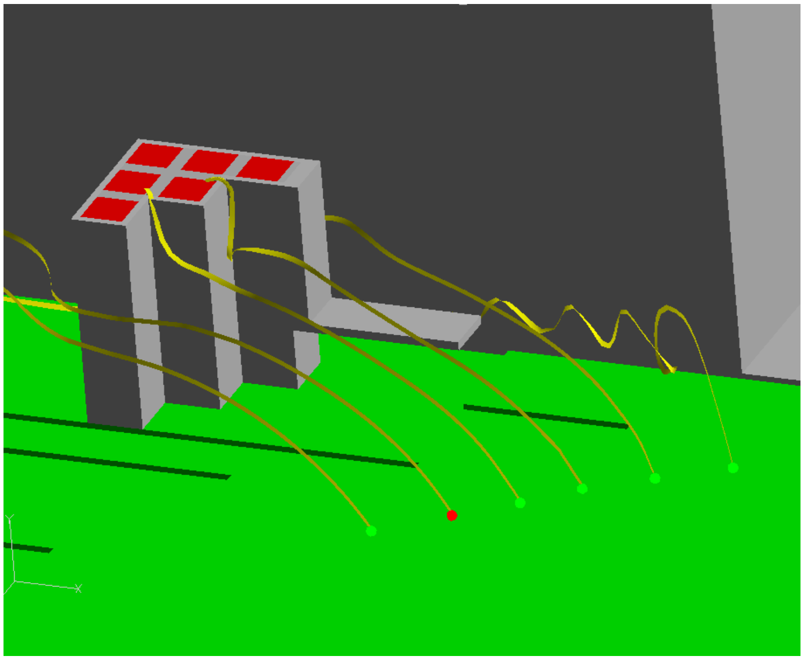

Figure 6: Plume centerlines, released on the road, enter the alternative raised air intake.

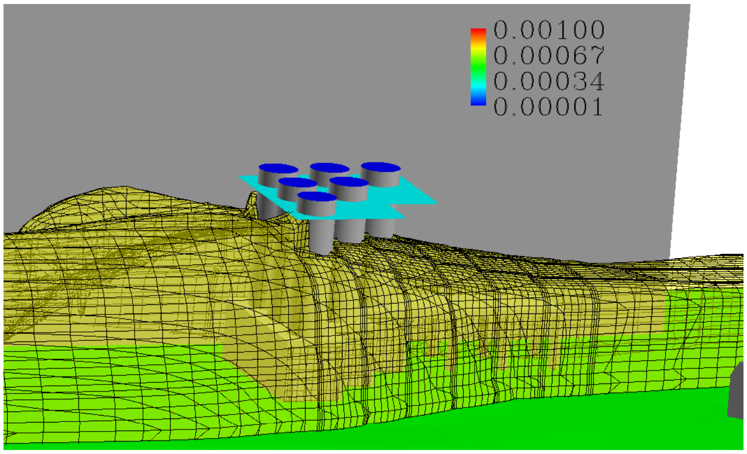

Figure 7. Alternative design of air intake in CFD modeling. Illustrated is the flow of a plume around and through the intake structure, avoiding lift into the intake opening. Measurement planes were placed on top of the air intakes. The blue in the scale shows 0.00001, which means the pollution was at 100,000 dilutions.

Assisting architects with the placement of air intakes and cooling towers on new buildings in a building complex.

In this case, several new buildings are being added to an existing building complex. CFD gives us the ability to examine future conditions and also to easily analyze different arrangements of building air intakes and exhausts. This project is about as large as can be modeled using a desktop computer. An illustration of the modeling domain can be seen in Figure 8.

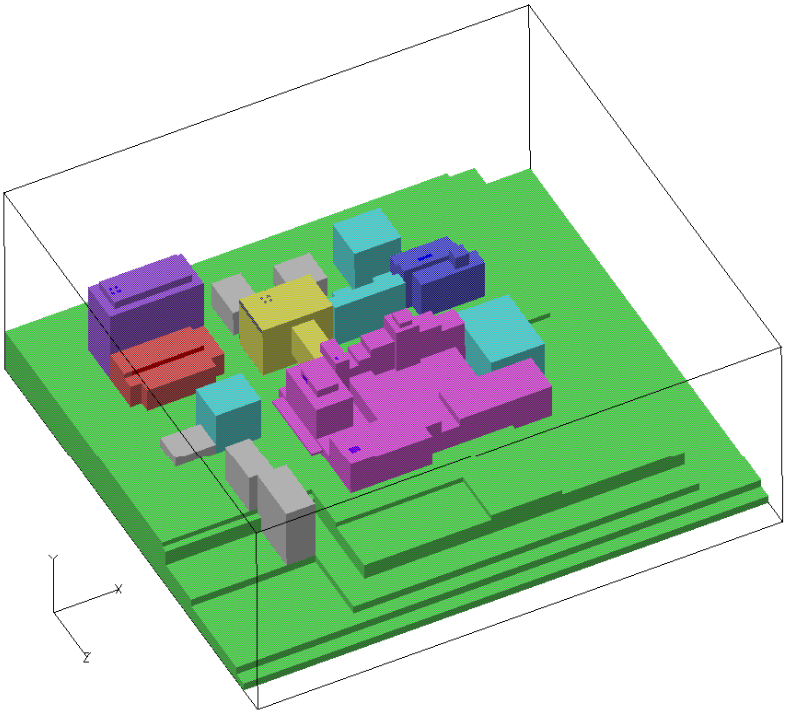

Figure 8: Modeling domain of a building complex.

Many exhaust points and sensitive receptors had to be addressed due to the number of buildings in the domain. Cooling tower exhaust points, kitchen, and a diesel emergency generator had to be carefully modeled to address any impacts and avoid cross-over from exhausts to air intakes.

A number of meteorological conditions needed to be examined to cover the range of possibilities. Exhaust from nearby roads and freeways were also examined. Though not related to air quality, pressure forces and air velocities in critical areas were also examined to ensure that the building configuration did not create any dangerous conditions for pedestrians and to determine the types of hangers needed for wall ornamentation. These are some of the many features of CFD that can be applied to assist architects and city planners.

Figure 9 illustrates the impacts from a set of cooling towers on one of the complex buildings on its own air intake. Impacts were significantly low for treatment chemicals, but of some concern for bacterial agents. CFD was used to assess the impacts of certain alternatives such as raising the cooling towers to eject the exhaust above the recirculation zones.

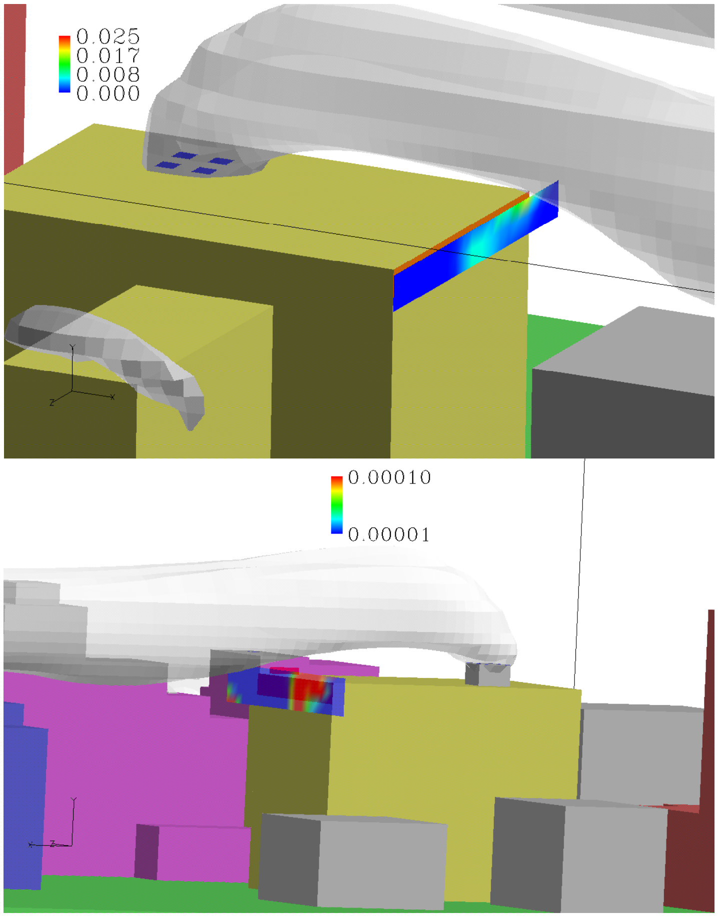

Figure 9. Two views of cooling tower impact at a building air intake. The blue and blue-green screen in the top view shows the roof-level exhaust readily entering the air intake. The bottom view shows the raised cooling towers, which reduced the impact of the cooling tower exhaust. Note the change in the scale of the measurement plane between the two views. For the upper view the blue-green portion represents only 125 dilutions while in the lower view even the red portion of the measurement plane represents 10,000 dilutions.

Odor from a kitchen stack impacting air intakes

In another project, remodeling of a building included the construction of an Asian grill, which was expected to exhaust at a source odor of 7,500 to 10,000 dilutions-to-threshold. The exhaust stack from the restaurant is located on the roof of the building. An adjacent building is home to offices and is served by air intakes in the roof penthouse. It was necessary to place the stack properly to prevent constant uptake of restaurant exhaust into the office building.

In this project, dilution levels of the exhaust were examined at the air intakes on the office building and an adjacent residential building. In Figure 10, the plume is visualized with the various surfaces represented at isopleths of dilutions from initial stack concentration. The interior yellow surface represent the 2,000 dilutions isopleth and the red exterior surface represents the 10,000 dilutions isopleth. The modeling helped demonstrate the height of stack needed to avoid impacts at air intakes on both buildings.

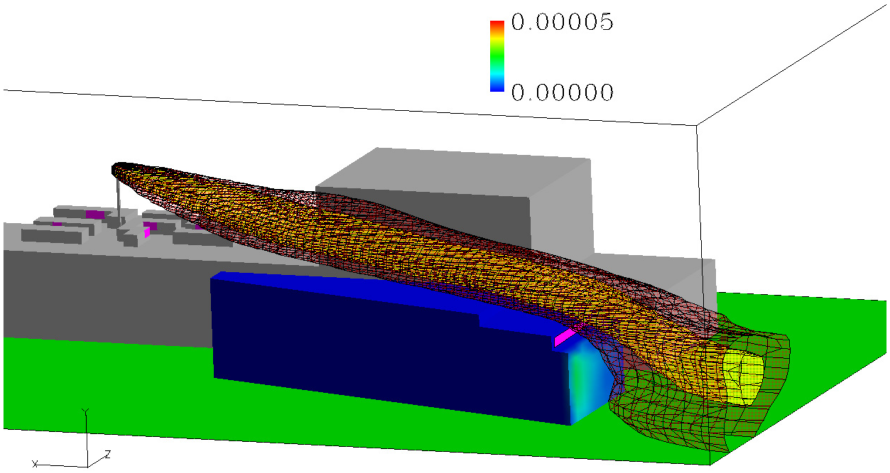

Figure 10. Exhaust plume from kitchen stack showing size of plume. The inner 2,000 dilution isopleth is represented in yellow and the10,000 dilution outer isopleth is represented in red. The entire office building surface is treated as a measurement plane to determine odor levels at critical points along the building surface such as air intakes and operable windows.

A Comparison of CFD to the Standard EPA Model ISCST3-Prime.

The most widely used air quality model is the U.S. Environmental Protection Agency's Industrial Source Complex Short Term Model 3 (ISCST3). This model is used to address the air quality impacts from stationary sources to demonstrate compliance to permitting regulations. While the model is useful for estimating pollutant concentrations beyond the zone of building wakes it is not intended for analysis within a recirculation zone nor can it account for air movement affecting the path of a plume caused by obstructions downwind from the source complex.

In a recent project, where CFD was used to address the level of odor from a building exhaust at the air intake of a neighboring building, the regulatory agency requested ISCST3 modeling to compare to the CFD modeling. The results of this modeling demonstrated how much more effective CFD was at determining the impacts due to its advanced handling of airflow around structures. The ISCST3 modeling could not account for the upward jet at the face of the receptor building caused by the high-speed wind directly hitting the face of the building. CFD handled this feature nicely, as illustrated in Figure 11. The result was a substantial over-estimate of concentration at the air intake with the ISCST3 model. CFD modeling demonstrated that odorous exhaust was entering the intake at nearly 43,000 dilutions, where the ISCST3 modeling indicated odor entering the intake at 950 dilutions. This particular model, along with a comparison of both the

CFD and ISCST3 results to the EPA model AERMOD, has been described in detail by Ruby and McAlpine (2004).

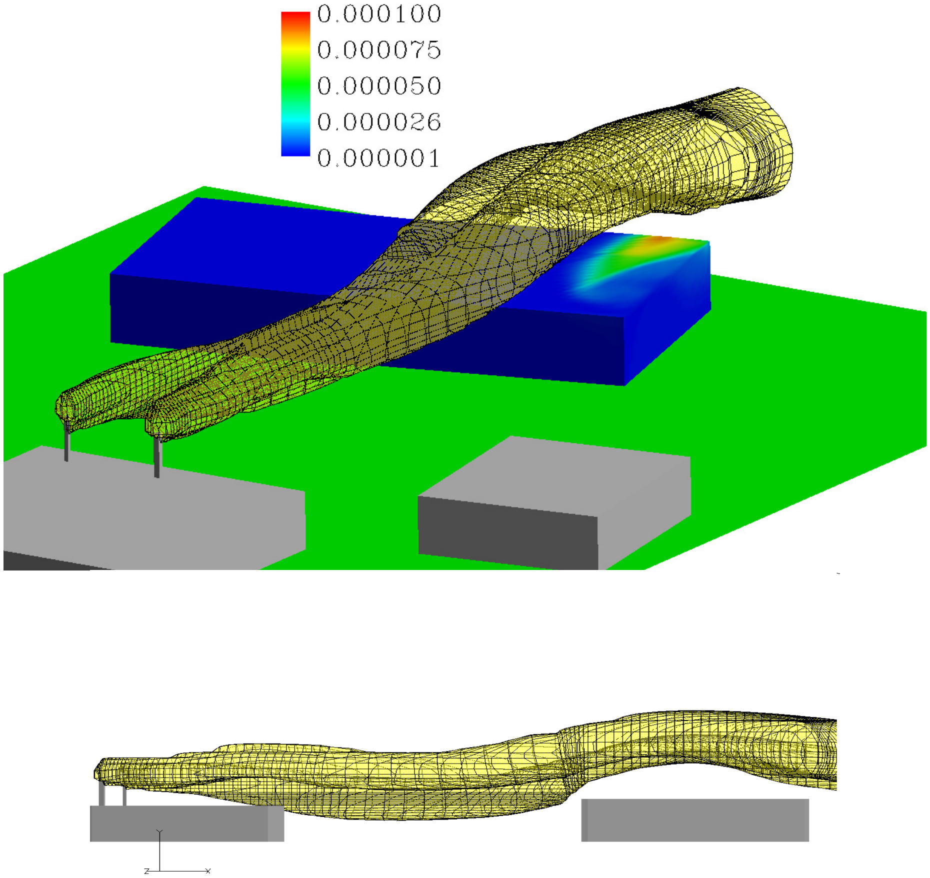

Figure 11. An aerial view (top) and cross-sectional view (bottom) of plume movement over a building with roof air intakes (right building). The upward jet at the leading edge of the second building that pushes the plume up and over the building is not accounted for in ISCST3.

Design of Exhaust Systems

Another application of CFD in the air quality field is in the design of exhaust systems. In one project, concern was raised over the accuracy of assuming two plumes merged quickly into one effective plume. Two exhausts from a process were oriented at right angles, one horizontal, with the other directly under it and vertical. It was proposed to model a single vertical plume. CFD demonstrated that the plumes did merge quickly and could be considered a single plume for dispersion modeling. An illustration of the results is provided in Figure 12 on the next page.

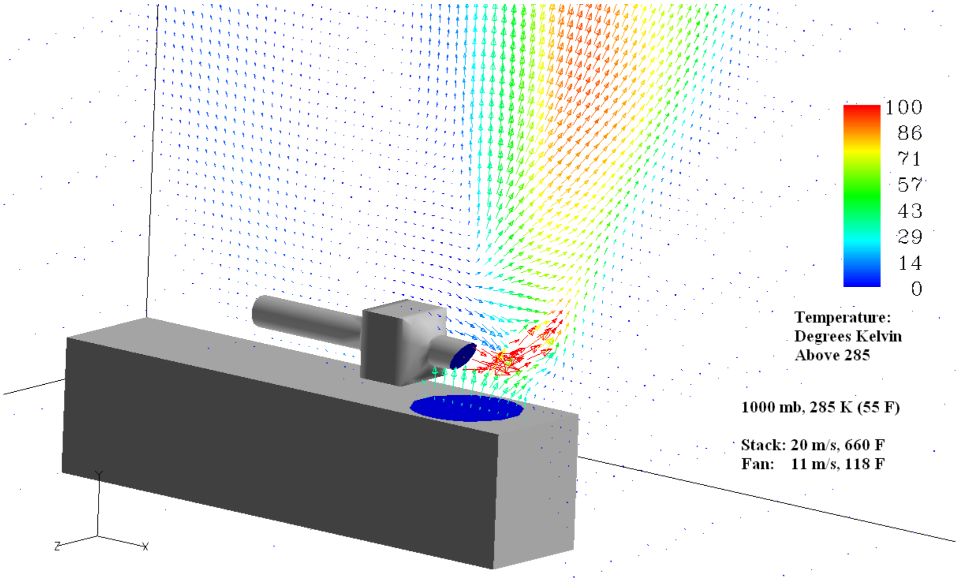

Figure 12. CFD modeling of exhaust stack configurations to demonstrate plume merger for dispersion modeling.

An Example CFD Project

Setting up and executing a CFD project consists of several steps: creating the model geometry and mesh, model setup and execution, and visualization. An example CFD case is analyzed here to sample the CFD process. Some of the basic "rules of thumb" of CFD modeling are also discussed.

In this simple sample case, an office building is proposed to be constructed adjacent to a busy family restaurant. The high volume kitchen exhaust stack is located on the roof of the restaurant. HVAC planners proposed two alternative locations for the office building air intake, off a mechanical room on the second floor or on a mechanical penthouse on the building roof. A CFD air quality analysis is to help choose between the alternatives.

The first step in CFD model creation is the establishment of the modeling domain. Careful attention must be paid to the project site to ensure that all possible receptors are included in the domain. Air intakes and open windows are the most critical receptors for all types of exhaust. Occupants of offices or apartments are likely to be at the most risk to long term exposure. Less critical, but important to include nevertheless are pedestrian walkways.

When all of the potential receptors have been chosen, the next step is to include all of the buildings in the area that will have influence on the airflow at your subject sources. The behavior of air pressure and windflow is not always intuitive so all adjacent obstacles should be included. Adjacent buildings are very important to include, even if the building is upwind of the subject source only during infrequent winds. More distant buildings and obstacles should be included that are upwind during stronger wind conditions. Generally it is not feasible to include every building, tree, or obstacle in the area in the model; one must use judgement in each case to ensure that the modeled airflow is as realistic as possible within the time and computer resources available.

After all of the receptors, sources, and buildings have been selected for inclusion in the model, the size of the domain can be established. The edges of the domain must be placed at a distance adequate enough to allow the full development of airflow features around the structures. A rule similar to the “5L” rule used as a guide in air quality modeling to account for the building wake zone has been found to be a useful in setting the domain size. Each edge of the domain must be at least L_b+ $4w_m$ the distance from the nearest building edge where where w_m is the maximum wind speed modeled and L_b is the smaller of building height or projected building width (in consistent units). The domain roof must be tall enough that no signature of turbulence from lower layers effects the roof layers of airflow. A general rule of thumb for the height of the domain is at least three times the height of the tallest building in the domain. However, this can vary depending on the case. For example, if a tall buoyant plume is being modeled in light winds, it will be necessary to have a height that can account for the high plume rise. If the plume is significantly buoyant, it may still reach the domain roof. This does not create problems at the surface as long as any reentrainment of the plume to sensitive receptors is fully accommodated.

Since the modeling domain size guideline depends on the maximum wind speed modeled, a full analysis of the site meteorology must be conducted before model construction. Each CFD model run will only use one wind condition, so a discrete amount of wind conditions must be selected for modeling based on the climatological record for the site. The modeler must be selective and develop a modeling scheme that includes the more important of the possible wind directions and wind speeds. First, the modeler must choose wind directions that correspond with the worst case re-circulation zones that may form around the buildings. These generally occur at the roof and in the lee wake of the building when the wind direction is perpendicular to a building face. For wind speeds, one generally wants to select the likely worst case wind to perform a conservative estimate. However, the client will be interested in the frequency and severity of impacts. Therefore, modeling must account for the distribution of wind speeds at each direction modeled. As a general guideline, it is advantageous to model three wind speeds per direction. This limits the number of modeling runs that must be conducted, while accounting for the distribution in wind speeds. Generally we have had success modeling the 98th percentile, 90th percentile, and median wind speed in frequency of occurrence per direction. These magnitudes generally will account for the worst case wind speed, the most common high wind, and the average wind.

Now, for the simple kitchen stack case we apply these guidelines to establish the model domain. We find that the sensitive receptors are our proposed air intake alternative positions and pedestrian sidewalks at the surface. The only buildings required in the modeling are the subject restaurant and the proposed office building. An illustration of the site and dimensions are included in Figure 13.

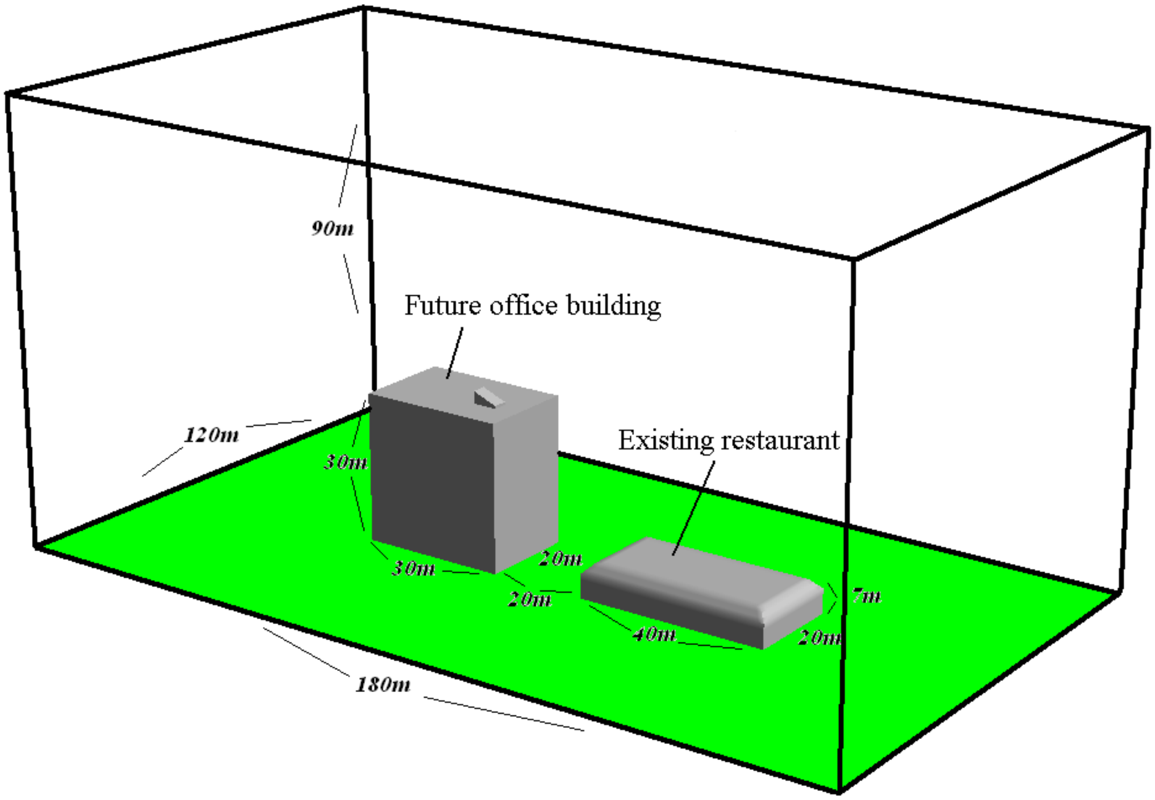

Figure 13. Illustration of the sample project site domain. The structure on the left is the proposed office building and the building on the right is the restaurant. Site dimensions are labeled with the domain edges determined by the rule of thumb described above.

To determine the distance from the sides of the domain to the closest building surfaces we apply the general guideline of L_b+ $4w_m$. To determine this, we need to examine the building dimensions and site meteorology. For sake of an example, we will presume that the wind blows from one direction, where the restaurant is directly upwind of the office building. Examination of the meteorology of the region reveals that the 98th percentile wind is 8 m/s, 90th percentile wind is 5 m/s, and the mean wind is 3 m/s. Therefore, our w_m is 8. The office building is 30 meters tall, 30 meters long, and 20 meters wide, so the office building L_b is 20. With L_b+ $4w_m$=52, our corresponding domain sides will be located at 50 meters (rounded to simplify the model creation process) from the office building. The top of the domain will be 90 meters above the surface. The restaurant is 7 meters tall, 40 meters long, and 20 meters wide. Then L_b+ $4w_m$=39 gives us a guideline distance of 40 meters to place the domain walls from the faces of the restaurant.

After completion of the domain walls, the building geometry itself is placed in the domain. Small details of the building can be left out to simplify the modeling process. Details near sources or other regions important to specific airflows near receptors or sources should be included to make the modeling runs as realistic as possible. In this case, there are no roof obstacles near to the stack on the restaurant. On the roof of the adjacent office building, the roof access stairway door is upwind of the air intake, so we must include this detail in the modeling. Both the surfaces of the restaurant and office building are smooth brick with little detail. The street surface is fairly flat and distant from the source and receptors, so no details such as sidewalks and planter boxes are necessary. To simplify the example, the site is level so there is no topography to include. Topographical variation is critical to include in modeling cases where buildings are located on slopes, to account for the impact of the topography on vertical airflow.

The next step is to initialize the gas flow of the source kitchen stack and the office building air intake. For sake of demonstration, the atmosphere is assumed stable at an annual average temperature. The HVAC elements are shown in Figure 14.

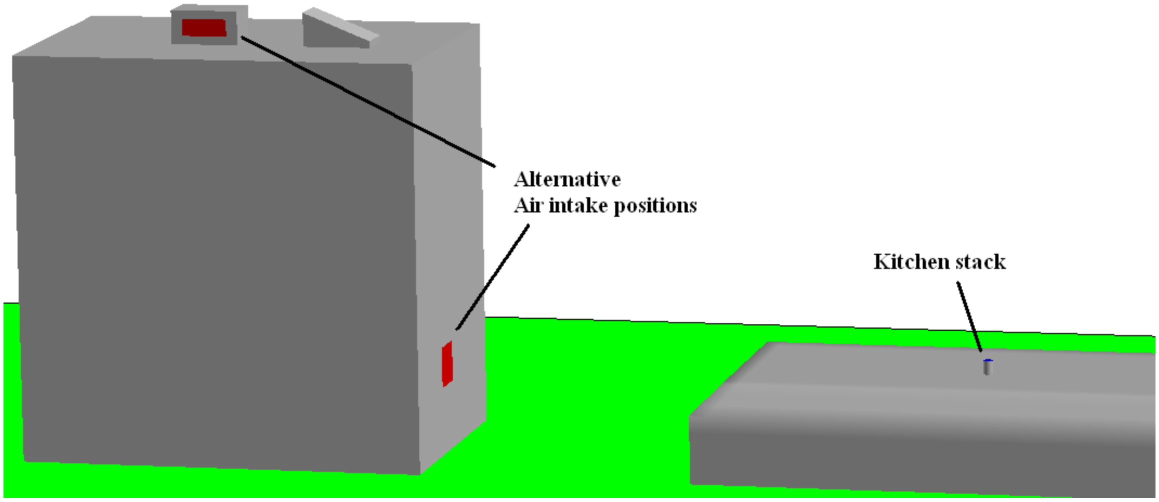

Figure 14. Illustration labeling the positions of the alternative air intake positions on the project office building and the kitchen stack on the existing restaurant.

After all features have been placed in the modeling, the domain must be cut into individual discrete volumes or “cells” where the actual computations for solving the Navier-Stokes equations take place. Enough cells must be initiated in the domain to accurately simulate the interaction of the gas flow with the domain features. However, one also wants to minimize the number of cells in the domain in order to shorten the length of time the computer has to run to solve the problem. This can be most easily accomplished by placing a high concentration of cells around the subject obstacles such as the stack, air intakes and building edges. The domain edges can have a lower concentration of cells because there is little change in the flow field gradient away from obstacles. As a general rule of thumb it is necessary to divide the smallest side of an object in the domain into at least 3 cells if it is to be resolved. In our example project, this would mean that each side of kitchen exhaust stack (the smallest obstacle in the domain) would have at least 3 cells per side if the stack were square. If more accuracy is needed, then more cells are required. However, one must take care that the gradient of cell size is even and smooth to ensure the solution is as accurate as possible. For a large domain, too many cells on the smallest object side may require too great a number of cells overall as you gradually step down from wider to finer mesh near small objects. Excessive computational time per case is undesirable. Figure 15 illustrates the mesh generated for our project domain. The lines in each coordinate plane are projected into the domain space to create individual cells. They can be easily seen on the surface of the obstacles but they also exist in the free space of the model. Each small cell represents a separate set of calculations during each time step.

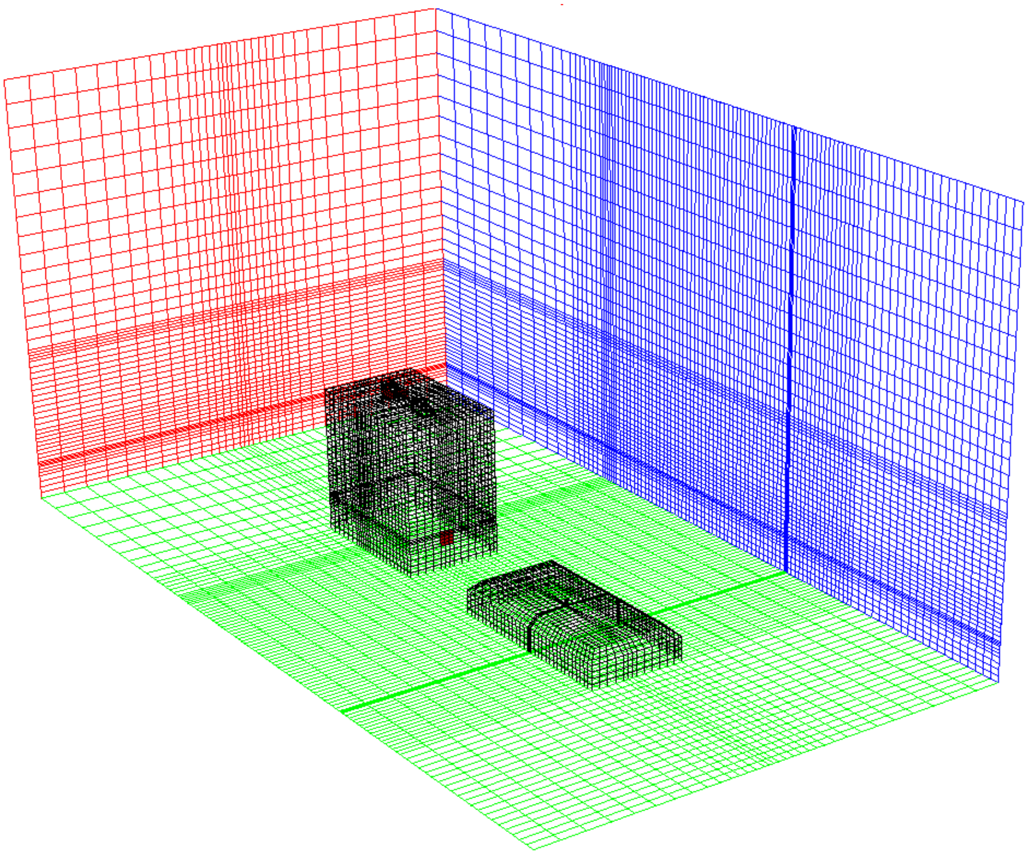

Figure 15. Illustration of "meshing," the partitioning of the domain into discrete volumes or "cells." Cell sizes must be smaller near areas of significant variation in the wind vector so all features of the flow are properly computed.

When our domain has been properly "meshed" with good cell coverage, the domain walls must be initialized as proper boundaries. The domain floor will be initialized as a "wall" to simulate the impermeable ground surface. The domain roof, and sides can be initialized as "equal pressure" barriers, to ensure that air can flow evenly in or out of the domain depending on the wind field, or for the two walls at the appropriate sides, as "inlets" for air flowing into the domain at the defined wind speed and direction.

Each cell is initialized with a horizontal wind direction and speed, an initial atmospheric pressure and temperature and local turbulent intensity. The wind speed can be varied with height according to known conditions for an urban or rural surrounding and mean wind speed, as appropriate. The choice of the horizontal wind speed at an elevation is determined by the median, 90th and 98th percentile test wind velocities described above and the height of the meteorological tower providing the historic data. As mentioned above, neutral stability is assumed. No vertical velocity is provided in the initialization but is allowed to develop as the model evolves just as some of the cells close to walls will evolve lower horizontal velocities.

Now we have finished model construction and the problem can be solved. We must first initialize the amount of real-time that we wish the model to simulate. There are two factors that must be considered when considering the modeled length of time. First, enough time must be allotted for transport of all pollutants to the domain edge. This ensures that all the features of the plume behavior are evident in the final result. You can easily find this amount of time by considering the distance of the sources to their respective downwind domain boundaries and the windspeed being modeled. The other factor one must consider in determining the amount of time to run in the model is the amount of time that the model takes to “spin-up”, that is, to approach the nearest solution to steady state. This time must be determined from the experience of the modeler with a particular program and choice of closure model. This can be determined initially for a project with a run which is visualized at several intervals, looking for fully developed turbulence that finally does not change significantly with additional run time. In our sample project, the model time needed for the plume to reach the downwind wall should be about 50 seconds at most and the time needed to acquire full turbulence is about 8 seconds. Once the turbulence is fully developed, the solution of the full equation set can be halted and the plume allowed to disperse in a frozen wind field.

The k-ε turbulence model is selected and the solver is initiated. The solver uses its time-marching technique to solve the steady state solution from the initial conditions we prescribed.

After the solution has been reached, and it is seen to be physically reasonable, the results can be displayed graphically. In Figure 16, the visualization at the 98th percentile wind of 8 m/s includes mean wind vectors, exhaust concentrations, and the plume centerline.

We can see from these results that a 2nd floor mechanical room location of the air intake may pose problems during strong wind events in the vicinity. The plume is trapped in the re-circulation zone between the restaurant and the office building, and a significant amount of exhaust reaches the air intake. For a standard steak-house kitchen grill, we would probably consider a dilution threshold of about 2,000 as a target measurement. As illustrated, exhaust enters at the intake are at 100 dilutions, significantly above the threshold.

At slower, more common wind speeds (3 m/s), the plume does not entrain into a recirculation zone, but rises significantly as illustrated in Figure 17. Unfortunately, the plume reaches an air intake located on the roof. Exhaust enters the intake in this case at around 2,500 dilutions. This is marginally below our nuisance threshold value, but will not be below detection level for many other kitchen plumes.

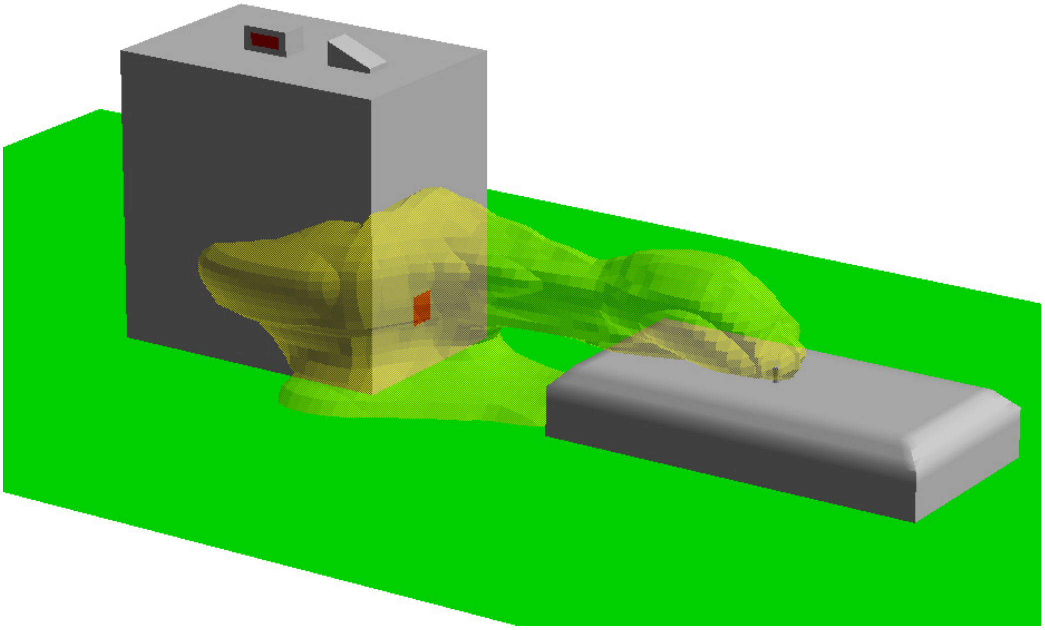

Figure 16. Illustration of model results with the 8 m/s wind. Impacts at the mechanical room alternative air intake are high, at around 200 dilutions.

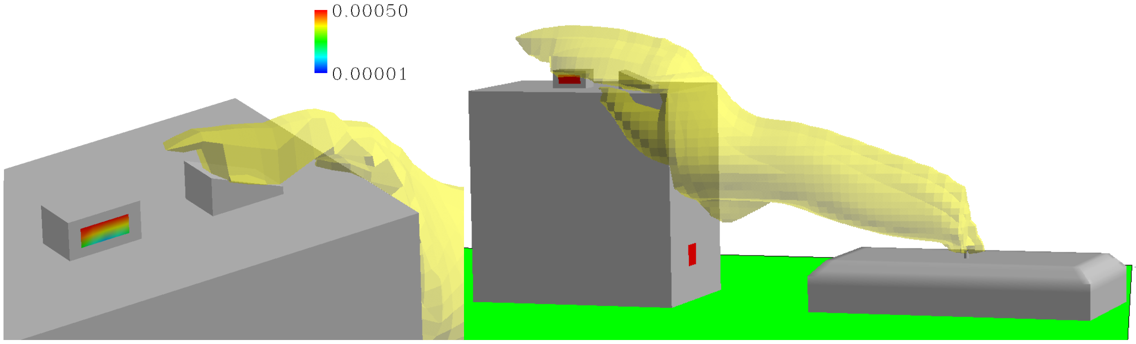

Figure 17. Illustration of the plume behavior during two winds at 3 m/s and slight variations in direction. The plume boundary is illustrated at 1,000 dilutions. The plume avoids a lower intake position but rises to roof level where it impacts an air intake at around 2,500 dilutions. The red end of the scale is at 2,000 dilutions.

The next step demonstrates the primary usefulness of CFD; the ability to modify existing conditions to examine alternatives. If the roof position of the air-handling unit is chosen, then odor of the plume may be evident in the building from time to time. Raising the kitchen stack may lower the frequency of odor if the plume does not reach the intake during lower wind speeds. Modeling conducted with the stack raised 2 meters to a 3-meter stack demonstrates that the plume will be more dispersed when it reaches the air intake, as illustrated in Figure 18. The plume reaches the air intake at around 8,000 dilutions in this case, which is significantly more dilutions than with the initial stack height. However, this doesn't mean that the plume will no longer be a problem. Considering that we chose only several of the possible wind magnitudes that occur, impacts just as high as observed with the lower stack are likely during stronger winds, which will knock down the plume rise. However, since the stronger winds occur less frequently, raising the stack will lower the amount of time of higher impacts. The modeler must work closely with the site meteorology to develop an idea of the frequency of impacts to determine the best alternative.

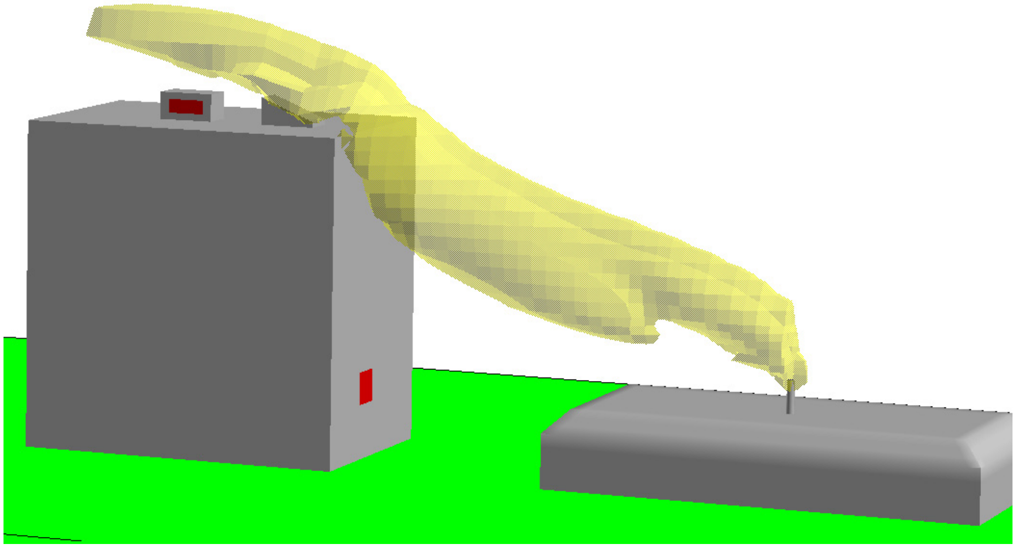

Figure 18. Model run with the kitchen stack raised 2 meters to a 3-meter stack. During the lighter 3 m/s winds, the plume impacts the air intake at about 8,000 dilutions.

CFD: a Valid Approach to Studying the Surface Layer of the Atmosphere?

Though CFD shows much promise for the future of air quality analysis in urban environments, it should be used cautiously. Examining the steady state flow alone may not always be the best method when dealing with dispersion of exhaust plumes. It is very difficult to accurately model the surface layer of the atmosphere. It is a highly-variable chaotic entity which rarely resembles a steady state flow. Additionally, CFD turbulence modeling should be treated with care. Parameterizing turbulence may not result in realistic solutions when flows are highly turbulent.

Steady state flow

When dealing with air quality, some pollutants are a concern for exposures as brief as a few minutes (particularly odors) while for others long term exposure is the main concern. CFD steady state solutions can be a useful tool to analyze the long-term risks of outdoor pollutant impacts. However, the atmosphere itself is not steady, so analyzing air quality in the surface layer for shorter term exposures requires additional evaluation. In these cases it is useful to analyze a spectrum of wind directions and velocities for each climatological mode of wind that records indicate are common, or for the suspect wind in a odor/pollutant complaint study. Standard deviations of wind angle can be estimated if one knows the stability properties of the atmosphere. For example, during neutral stability the standard deviation of an hourly wind direction is 7.5 to 12.5 degrees around the mean wind direction (EPA, 1987).

Wind speed variance can not be estimated so easily, being greatly dependent on the nature of upwind obstacles. The surface layer itself is in a constant rolling turbulence, even without upwind obstacles, due to its viscous nature and the mixing of higher momentum wind down towards the surface. Therefore, for each wind direction, a range of wind speeds should be modeled. The modeler should note that each climatological or suspect wind case can only be investigated by examining the output of several CFD runs which encompass the range of variability that wind case may endure. Even so, this technique does not fully result in modeling of true atmospheric phenomena, but in a screening type analysis it can be used to estimate impacts.

Domain turbulence initialization

Even with a rigorous method to account for wind variability, the nature of the incoming flow may not be represented adequately. Upstream objects such as buildings, hills, or vegetation may create large eddies and other flow variations which will have an impact on the incoming flow of our domain. Therefore, a CFD analysis would not be recommended for a building located among many other buildings of similar or larger size without special care. To account for incoming turbulence, every building which has a moderate to large impact on the incoming flow would have to be included. In a dense urban environment such as a downtown district with many skyscrapers, a CFD analysis might require modeling the entire city skyline to accurately predict flow at one building! Therefore, each CFD case has to be examined carefully to determine what factors need to be included to initialize realistic flow.

Model properties

Another factor in CFD is the mathematics of the model itself. As mentioned before, there are many different approaches to handling the turbulence terms in CFD modeling. The k-ε model, or first order closure model, is an efficient and often used model that returns adequate results in modeling air flow at the surface layer of the atmosphere. Several other more accurate methods are becoming more popular as desktop computers become more powerful. Reynolds Stess Transport Models (RSTMs), or second order closure models, and Large Eddy Simulation (LES) are two methods that are being used more frequently. However, these models can be computationally demanding. A model run which may only take a few hours on a fast desktop computer using the k-ε model may take a one or two orders of magnitude longer using many implementations of the LES model. In validation tests, LES and RSTMs generally have performed better than the k-ε model, that is, generating results that more closely match wind tunnel streamlines. Nevertheless, the k-ε model results are sufficiently accurate in tests involving airflow in the scales of concern with air quality modeling.

One popular method in validation of CFD models is the “block” test, where CFD steady state flow results are compared to the mean flow streamlines around blocks in wind tunnels. Air quality analyses often are concerned with the lengths of re-circulation zones, so these are often compared in validation tests, as seen in Figure 19.

Most validation tests have found that the k-ε model often over-predicts the length of the lee re-circulation zone and under-predicts the length of the windward re-circulation zone. The roof re-circulation zone tends to be comparable, but may not be seen if the project is not initialized correctly or the mesh is not small enough to properly characterize the leading edge (a common failing). Even with these problems CFD for stack placement purposes is useful and even conservative in respect to re-entrainment. Since the re-circulation zones often grow with increasing wind speed, an over-predicted re-circulation zone analysis would then represent the zone of the high range of wind speed variability.

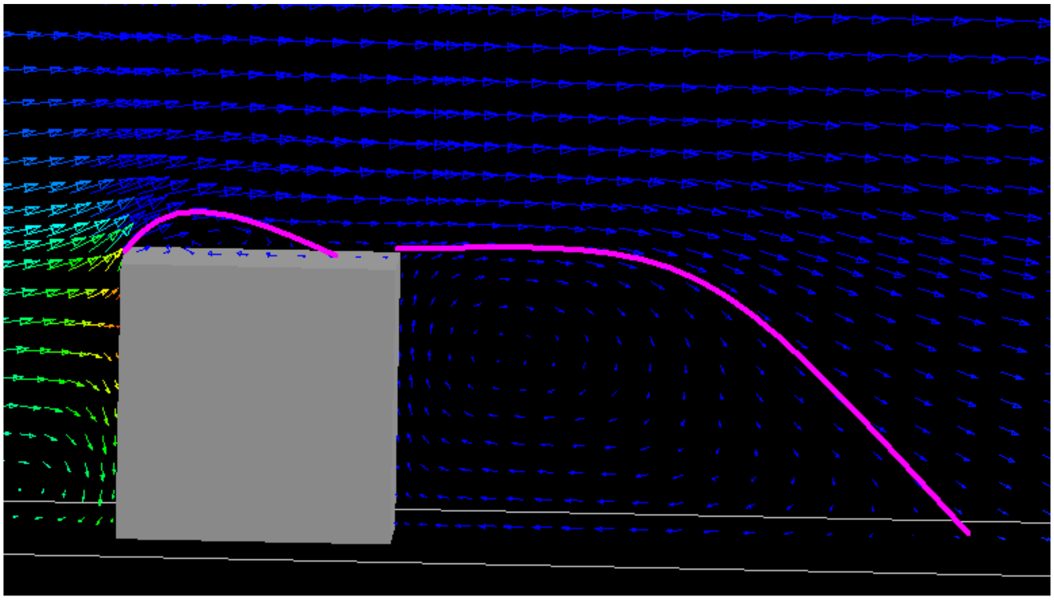

Figure 20: Airflow around a block for a validation test. Re-circulation zone lengths are compared to wind-tunnel and water-channel tests.

Another factor involving model accuracy in CFD is plume modeling. So much attention is given to dispersion and plume centerline streamlines in air quality analysis, it is important to make sure that the model is accurately modeling plume rise and dispersion. Some qualitative comparisons of CFD plume dispersion to the U.S. Environmental Protection Agency’s basic dispersion model, SCREEN3, were carried out. These comparisons found that the CFD plume rise and dispersion is quite comparable to the SCREEN3 output for lower wind speeds. At higher wind speeds, the CFD model predicted a buoyant plume rise greater than the initial plume rise modeled by SCREEN3.

Conclusion

Air quality analysts can successfully use CFD using the k-ε turbulence closure approach included in the commercial model CFD2000 for evaluation of plume movement in urban microenvironments. CFD offers a cost-effective new tool for analyzing pollutant dispersion around buildings and sets of buildings. It is a useful tool to help guide the placement of exhaust stacks and air handling units on buildings and in investigating sources of odor which impact building air intakes. Better initialization schemes for the atmospheric conditions and improved turbulence closure models will improve CFD results.

References

Anderson, J.D., 1995: *Computational Fluid Dynamics: The Basics with Applications*, McGraw-Hill (ISBN: 0070016852)

Fackrell, J.E., 1984: Parameters characterizing dispersion in the near wake of buildings, *Journal of Wind Engineering and Industrial Aerodynamics* **16**, 97-118.

Ruby, M. and McAlpine, J.D., 2004: Estimating Odor Impact with Computational Fluid Dynamics, *Proceedings WEF/A&WMA Odors and Air Emissions 2004*, Water Environment Federation, Alexandria VA

Wilson, D.J., 1979: Flow patterns over flat-roofed buildings and application to exhaust stack design, *ASHRAE Transactions*, **85**, 284-295.

United States Environmental Protection Agency, June 1987: On-site meteorological program guidance for regulatory modeling applications, EPA 450/4-87-013

United States Environmental Protection Agency, April 1995: The Inside Story: A guide to indoor air quality, EPA 402-K-93-007.

Appendix 32

Risk Analysis, Vol. 15, No. 3, 1995

Five-Hundred Life-Saving Interventions and Their Cost-Effectiveness

Tammy O. Tengs,[1] Miriam E. Adams,[2] Joseph S. Pliskin,[3,6] Dana Gelb Safran,[4] Joanna E. Siegel,[5,7] Milton C. Weinstein,[6,7] and John D. Graham[6,7]

Received July 26, 1994

We gathered information on the cost-effectiveness of life-saving interventions in the United States from publicly available economic analyses. "Life-saving interventions" were defined as any behavioral and/or technological strategy that reduces the probability of premature death among a specified target population. We defined cost-effectiveness as the net resource costs of an intervention per year of life saved. To improve the comparability of cost-effectiveness ratios arrived at with diverse methods, we established fixed definitional goals and revised published estimates, when necessary and feasible, to meet these goals. The 587 interventions identified ranged from those that save more resources than they cost, to those costing more than 10 billion dollars per year of life saved. Overall, the median intervention costs $42,000 per life-year saved. The median medical intervention costs $19,000/life-year; injury reduction $48,000/life-year; and toxin control $2,800,000/life-year. Cost/life-year ratios and bibliographic references for more than 500 life-saving interventions are provided.

KEY WORDS: Cost-effectiveness; economic evaluation; life-saving; resource allocation.

1. INTRODUCTION

Risk analysts have long been interested in strategies that can reduce mortality risks at reasonable cost to the public. Based on anecdotal and selective comparisons, analysts have noted that the cost-effectiveness of risk-reduction opportunities varies enormously, often over several orders of magnitude.(1–5) This kind of variation is unnerving because economic efficiency in promoting survival requires that the marginal benefit per dollar spent be equal across investments.

Despite continuing interest in cost-effectiveness, we could find no comprehensive and accessible data set on the estimated costs and effectiveness of risk management options. Such a dataset could provide useful comparative information for risk analysts as well as practical information for decision makers who must allocate scarce resources. To this end, we report cost-effectiveness ratios for more than 500 life-saving interventions across all sectors of American society.

2. METHODS

2.1. Literature Review

We performed a comprehensive search for publicly available economic analyses of life-saving interventions.

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[7] Center for Risk Analysis, Harvard School of Public Health, Boston, Massachusetts.

"Life-saving interventions" were defined as any behavioral and/or technological strategy that reduces the probability of premature death among a specified target population. To identify analyses we used several on-line databases, examined the bibliographies of textbooks and review articles, and obtained full manuscripts of conference abstracts. Analyses retained for review met the following three criteria: (1) written in the English language, (2) contained information on interventions relevant to the United States, and (3) reported cost per year of life saved, or contained sufficient information to calculate this ratio. Most analyses were scientific journal articles or government regulatory impact analyses, but some were internal government memos, reports issued by research organizations, or unpublished manuscripts.

Two trained reviewers (from a total of 11 reviewers) read each document. Each reviewer recorded 52 items, including detailed descriptions of the nature of the life-saving intervention, the baseline intervention to which it was compared, the target population at risk, and cost per year of life saved. The two reviewers worked independently, then met and came to consensus on the content of the document.

Approximately 1200 documents were identified for retrieval. Of these 1200 documents, 229 met our selection criteria. The 229 documents contained sufficient information for reviewers to calculate cost/life-year saved for 587 interventions.

2.2. Definitional Goals

To increase the comparability of cost-effectiveness estimates drawn from different economic analyses, we established seven definitional goals. When an estimate failed to comply with a goal, reviewers attempted to revise the estimate to improve compliance.[8] In general, reviewers used only the information provided in the document to revise estimates. The seven definitional goals were:

1. Cost-effectiveness estimates should be in the form of "cost per year of life saved." Cost/life saved estimates should be transformed to cost/life-year by considering the average number of years of life saved when a premature death is averted.
2. Costs and effectiveness should be evaluated from the societal perspective.
3. Costs should be "direct." Indirect costs, such as foregone earnings, should be excluded.
4. Costs and effectiveness should be "net." Any resource savings or mortality risks induced by the intervention should be subtracted out.[9]
5. Future costs and life-years saved should all be discounted to their present value at a rate of 5%.
6. Cost-effectiveness ratios should be marginal or "incremental." Both costs and effectiveness should be evaluated with respect to a well-defined baseline alternative.
7. Costs should be expressed in 1993 dollars using the general consumer price index.

2.3. Categorization

Interventions were classified according to a four-way typology. (1) Intervention Type (Fatal Injury Reduction, Medicine, or Toxin Control), (2) Sector of Society (Environmental, Health Care, Occupational, Residential, or Transportation), (3) Regulatory Agency (CPSC, EPA, FAA, NHTSA, OSHA, or None), and (4) Prevention Stage (Primary, Secondary, or Tertiary).

Interventions we classified as primary prevention are designed to completely avert the occurrence of disease or injury; those classified as secondary prevention are intended to slow, halt, or reverse the progression of disease or injury through early detection and intervention; and interventions classified as tertiary prevention include all medical or surgical treatments designed to limit disability after harm has occurred, and to promote the highest attainable level of functioning among individuals with irreversible or chronic disease.(6)

3. RESULTS

Cost-effectiveness estimates for more than 500 life-saving interventions appear in Appendix A. This table is separated into three sections according to the type of intervention: Fatal Injury Reduction, Toxin Control, and Medicine. The first column of Appendix A contains the reference number assigned to the document from which the cost-effectiveness estimate was drawn (references are in Appendix B.) The second column contains a very brief description of the life-saving intervention. The

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[8] Appendices describing the cost-effectiveness formulas used to operationalize these definitional goals, along with some examples of the calculations made by reviewers of the economic analyses, are available from Dr. Tengs.

[9] If savings exceed costs, the result could be negative, so that the cost-effectiveness ratio might be ≤$0.

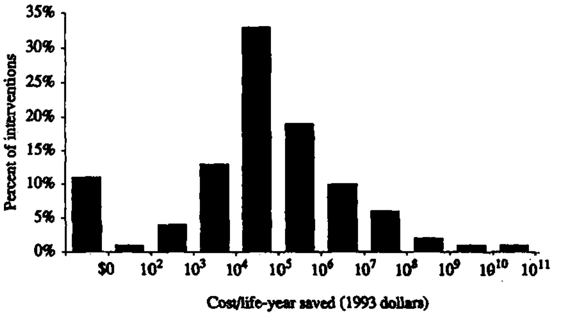

Fig. 1. Distribution of cost/life-year saved estimates (n = 587).

baseline intervention to which the life-saving intervention was compared appears parenthetically as "(vs. ___)" when the author described it. The last column of Appendix A contains the cost per year of life saved in 1993 dollars.

As shown in Fig. 1, these interventions range from those that save more resources than they consume, to those costing more than 10 billion dollars per year of life saved. Furthermore, variation over 11 orders of magnitude exists in almost every category.

In addition to the large variation within categories, variation in cost-effectiveness also exists between categories. As summarized in Table I, while the median intervention described in the literature costs $42,000 per life-year saved (n = 587), the median medical intervention costs $19,000/life-year ($n$ = 310); the median injury reduction intervention costs $48,000/life-year ($n$ = 133); and the median toxin control intervention costs $2,800,000/life-year ($n$ = 144).

Cost-effectiveness also varies as a function of the sector of society in which the intervention is found. For example, as shown in Table I, the median intervention in the transportation sector costs $56,000/life-year saved ($n$ = 87), while the median intervention in the occupational sector costs $350,000/life-year ($n$ = 36). Further dividing occupational interventions into those that avert fatal injuries and those that involve the control of toxins, reveals medians of $68,000/life-year ($n$ = 16) and $1,400,000/life-year ($n$ = 20), respectively.

As noted in Table II, the median cost-effectiveness estimate among those interventions classified as primary prevention is $79,000/life-year saved ($n$ = 373), exceeding secondary prevention at $23,000/life-year ($n$ = 111) and tertiary prevention at $22,000/life-year ($n$ = 103). However, if medicine is considered in isolation, we find that primary prevention is more cost-effective that secondary or tertiary prevention at $5,000/life-year ($n$ = 96).

Table I. Median of Cost/Life-Year Saved Estimates as a Function of Sector of Society and Type of Intervention

	Type of intervention			
Sector of society	Medicine	Fatal injury reduction	Toxin control	All
Health care	$19,000 ($n$=310)	N/A[a]	N/A	$19,000 ($n$=310)
Residential	N/A	$36,000 ($n$=30)	N/A	$36,000 ($n$=30)
Transportation	N/A	$56,000 ($n$=87)	N/A	$56,000 ($n$=87)
Occupational	N/A	$68,000 ($n$=16)	$1,400,000 ($n$=20)	$350,000 ($n$=36)
Environmental	N/A	N/A	$4,200,000 ($n$=124)	$4,200,000 ($n$=124)
All	$19,000 ($n$=310)	$48,000 ($n$=133)	$2,800,000 ($n$=144)	$42,000 ($n$=587)

[a] Not applicable by definition.

Table II. Median of Cost/Life-Year Saved Estimates as a Function of Prevention Stage and Type of Intervention

	Type of intervetion			
Prevention stage	Medicine	Fatal injury reduction	Toxin control	All
Primary	$5,000 ($n$=96)	$48,000 ($n$=133)	$2,800,000 ($n$=144)	$79,000 ($n$=373)
Secondary	$23,000 ($n$=111)	N/A	N/A	$23,000 ($n$=111)
Tertiary	$22,000 ($n$=103)	N/A	N/A	$22,000 ($n$=103)
All	$19,000 ($n$=310)	$48,000 ($n$=133)	$2,800,000 ($n$=144)	$42,000 ($n$=587)

The median cost-effectiveness of proposed government regulations for which we have data also varies considerably. Medians for each agency are as follows: Federal Aviation Administration, $23,000/life-year ($n$ = 4); Consumer Product Safety Commission, $68,000/life-year ($n$ = 11); National Highway Traffic Safety Administration, $78,000/life-year ($n$ = 31); Occupational Safety and Health Administration, $88,000/life-year ($n$ = 16); and Environmental Protection Agency, $7,600,000/life-year ($n$ = 89).

4. LIMITATIONS

This compilation of existing data represents the most ambitious effort ever undertaken to amass cost-effectiveness information across all sectors of society. In addition, our work to bring diverse estimates into compliance with a set of definitional goals has improved the comparability of cost-effectiveness estimates that were originally derived by different authors using a variety of methods. Nevertheless, several caveats are warranted to aid the reader in interpreting these results.

First, the accuracy of the results presented herein is limited by the accuracy of the data and assumptions upon which the original analyses were based. There remains considerable uncertainty and controversy about the cost consequences and survival benefits of some interventions. This is particularly true for toxin control interventions where authors often extrapolate from animal data. In addition, due to insufficient information in some economic analyses, reviewers were not always successful in bringing estimates into conformity with definitional goals. For example, if the original author did not report the monetary savings due to the reduction in nonfatal injuries requiring treatment, we were unable to "net out" savings, and so the costs used to calculate cost-effectiveness ratios remain gross. While some of these omissions are important, others are largely inconsequential given the relative size of cost and effectiveness estimates.

Second, the life-saving interventions described in this report include those that are fully implemented, those that are only partially implemented, and those that are not implemented at all. These interventions are best thought of as opportunities for investment. While they may offer insight into actual investments in life-saving, the cost-effectiveness of possible and actual investments are not equivalent. Work on the economic efficiency of actual expenditures is in progress.(7)

Third, this dataset may not represent a random sample of all life-saving interventions, so the generalizability of any descriptive statistics may be limited. This is because interventions that have been subjected to economic analysis may not represent a random sample of all life-saving interventions due, for example, to publication bias. That is, those economic analyses that researchers have chosen to perform and journal editors have chosen to publish may be disproportionately expensive or inexpensive. However, the statistics presented herein are certainly applicable to the 587 life-saving interventions in our dataset which by themselves comprise a vast and varied set, worthy of interest even without generalization.

Finally, we recognize that many of these interventions have benefits other than survival, as well as adverse consequences other than costs. For example, interventions that reduce fatal injuries in some people may also reduce nonfatal injuries in others; interventions designed to control toxins in the environment may have short-term effects on survival, but also long-term cumulative effects on the ecosystem; medicine and surgery may increase quantity of life, while simultaneously increasing (or even decreasing) quality of life.

5. CONCLUSIONS

This compilation of available cost-effectiveness data reveals that there is enormous variation in the cost of saving one year of life and these differences exist both within and between categories. Such a result is important because efficiency in promoting survival requires that the marginal benefit per dollar spent be the same across programs. Where there are investment inequalities, more lives could be saved by shifting resources. It is our hope that this information will expand the perspective of risk analysts while aiding future resource allocation decisions.

APPENDIX A. FIVE-HUNDRED LIFE-SAVING INTERVENTIONS AND THEIR COST-EFFECTIVENESS

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
	Fatal injury reduction	
	Airplane safety	
174	Automatic fire extinguishers in airplane lavatory trash receptacles	$16,000
173	Fiberglass fire-blocking airplane seat cushions	$17,000
174	Smoke detectors in airplane lavatories	$30,000
172	Emergency signs, floor lighting etc. (vs. upper lighting only) in airplanes	$54,000
	Automobile design improvements	
190	Install windshields with adhesive bonding (vs. rubber gaskets) in cars	≤ $0
52	Dual master cylinder braking system in cars	$13,000
1128	Automobile dummy acceleration (vs. side door strength) tests	$63,000
299	Collapsible (vs. traditional) steering columns in cars	$67,000
189	Side structure improvements in cars to reduce door intrusion upon crash	$110,000
52	Front disk (vs. drum) brakes in cars	$240,000
299	Dual master cylinder braking system in cars	$450,000
	Automobile occupant restraint systems	
1129	Driver automatic (vs. manual) belts in cars	≤ $0
59	Mandatory seat belt use law	$69
175	Mandatory seat belt use and child restraint law	$98
67	Driver and passenger automatic shoulder belt/knee pads (vs. manual belts) in cars	$1,300
59	Driver and passenger automatic shoulder/manual lap (vs. manual lap) belts in cars	$5,400
67	Airbag/manual lap belts (vs. manual lap belts only) in cars	$6,700
2	Airbag/lap belts (vs. lap/shoulder belts)	$17,000
56	Driver and passenger automatic (vs. manual) belts in cars	$32,000
1129	Driver airbag/manual lap belt (vs. manual lap/shoulder belt) in cars	$42,000
1129	Driver and passenger airbags/manual lap belts (vs. airbag for driver only and belts)	$61,000
59	Driver and passenger airbags/manual lap belts (vs. manual lap belts only) in cars	$62,000
68	Child restraint systems in cars	$73,000
1127	Rear outboard lap/shoulder belts in all (vs. 96%) cars	$74,000
56	Airbags (vs. manual lap belts) in cars	$120,000
1127	Rear outboard and center (vs. outboard only) lap/shoulder belts in all cars	$360,000
	Construction safety	
1137	Full (vs. partial) compliance with 1971 safety standard for concrete construction	≤ $0
1137	1988 (vs. 1971) safety standard for concrete construction	≤ $0
909	1989 (vs. no) safety standard for underground construction	$30,000
909	1989 (vs. 1972) safety standard for underground construction	$30,000
1132	1989 safety standard for underground gassy construction	$30,000
1132	Revised safety standard for underground non-gassy construction	$46,000
106	Install canopies on underground equipment in coal mines	$170,000
910	Safety standard to prevent cave-ins during excavations at construction sites	$190,000
1165	Full compliance with 1989 (vs. partial with 1971) safety standard for trenches	$350,000
1165	Full (vs. partial) compliance with 1971 safety standard for trenches	$400,000
	Fire, heat, and smoke detectors	
193	Federal law requiring smoke detectors in homes	≤ $0
13	Fire detectors in homes	≤ $0
306	Federal law requiring smoke detectors in homes	$920
19	Smoke and heat detectors in homes	$8,100
19	Smoke and heat detectors in bedroom area and basement stairwell	$150,000
303	Smoke detectors in homes	$210,000
	Fire prevention and protection, other	
122	Child-resistant cigarette lighters	$42,000
	Flammability standards	
292	Flammability standard for children's sleepwear size 0–6X	≤ $0
306	Flammability standard for upholstered furniture	$300
292	Flammability standard for children's sleepwear size 7–14	$45,000

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
372	Flammability standard for upholstered furniture	$68,000
12	Flammability standard for children's sleepwear size 7–14	$160,000
292	Flammability standard for children's clothing size 0–6X	$220,000
292	Flammability standard for children's clothing size 7–14	$15,000,000
Helmet promotion		
31	Mandatory motorcycle helmet laws	≤ $0
186	Federal mandatory motorcycle helmet laws (vs. state determined policies)	$2,000
175	Mandatory motorcycle helmet laws	$2,000
1006	Promote voluntary helmet use while riding All-Terrain Vehicles	$44,000
Highway improvement		
747	Grooved pavement on highways	$29,000
1105	Decrease utility pole density to 20 (vs 40) poles per mile on rural roads	$31,000
747	Channelized turning lanes at highway intersections	$39,000
747	Flashing lights at rail-highway crossings	$42,000
747	Flashing lights and gates at rail-highway crossings	$45,000
747	Widen existing bridges on highways	$82,000
1107	Widen shoulders on rural two-lane roads to 5 (vs. 2) feet	$120,000
1105	Breakaway (vs. existing) utility poles on rural highways	$150,000
1107	Widen lanes on rural roads to 11 (vs. 9) feet	$150,000
1105	Relocate utility poles to 15 (vs. 8) feet from edge of highway	$420,000
Light truck design improvements		
1091	Ceilings of 0–6000 lb light trucks withstand forces of 1.5 × vehicle's weight	$13,000
1091	Ceilings of 0–10,000 lb light trucks withstand forces of 1.5 × vehicle's weight	$14,000
1091	Ceilings of 0–8500 lb light trucks withstand forces of 1.5 × vehicle's weight	$78,000
1091	Ceilings of 0–10,000 lb light trucks withstand 5000 lb of force	$170,000
1126	Side door strength standard in light trucks to minimize front seat intrusion	$190,000
1091	Ceilings of 0–6000 lb light trucks withstand 5000 lb of force	$1,100,000
1126	Side door strength standard in light trucks to minimize back seat intrusion	$10,000,000
Light truck occupant restraint systems		
1089	Driver and passenger nonmotorized automatic (vs. manual) belts in light trucks	$14,000
834	Push-button release and emergency locking retractors on truck and bus seat belts	$14,000
1089	Driver and passenger motorized automatic (vs. manual) belts in light trucks	$50,000
1089	Driver airbag (vs. manual lap/shoulder belt) in light trucks	$56,000
1089	Driver and passenger airbags (vs. manual lap/shoulder belts) in light trucks	$67,000
Natural disaster preparedness		
1221	Soils testing and improved site-grading in landslide-prone areas	≤ $0
1221	Ban residential growth in tsunami-prone areas	≤ $0
710	Strengthen unreinforced masonry San Francisco bldgs to LA standards	$21,000
710	Strengthen unreinforced masonry San Francisco bldgs to beyond LA standards	$1,000,000
1221	Triple the wind resistance capabilities of new buildings	$2,600,000
1221	Construct sea walls to protect against 100-year storm surge heights	$5,500,000
1221	Strengthen buildings in earthquake-prone areas	$18,000,000
School bus safety		
1124	Seat back height of 24" (vs. 20") in school buses	$150,000
1124	Crossing control arms for school buses	$410,000
1124	Signal arms on school buses	$430,000
1124	External loud speakers on school buses	$590,000
1124	Mechanical sensors for school buses	$1,200,000
1124	Electronic sensors for school buses	$1,500,000
1124	Seat belts for passengers in school buses	$2,800,000
1124	Staff school buses with adult monitors	$4,900,000
Speed limit		
9	National (vs. state and local) 55 mph speed limit on highways and interstates	$6,600
175	Full (vs. 50%) enforcement of national 55 mph speed limit	$16,000

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
353	National (vs. state and local) 55 mph speed limit on highways and interstates	$30,000
185	National (vs. state and local) 55 mph speed limit on highways	$59,000
2	National (vs. state and local) 55 mph speed limit	$89,000
185	National (vs. state and local) 55 mph speed limit on rural interstates	$510,000
Traffic safety education		
175	Driver improvement schools (vs. suspending/revoking license) for bad drivers	≤ $0
175	Media campaign to increase voluntary use of seat belts	$310
175	Public pedestrian safety information campaign	$500
175	Improve traffic safety information for children grades K–12	$710
175	Motorcycle rider education program	$5,700
175	Improve motorcycle testing and licensing system	$8,700
157	Improve basic driver training	$20,000
175	Alcohol safety programs for drunk drivers	$21,000
175	Multimedia retraining courses for injury-prone drivers	$23,000
175	Improve educational curriculum for beginning drivers	$84,000
175	First aid training for drivers	$180,000
1124	Improve pedestrian education programs for school bus passengers grades K-6	$280,000
175	Warning letters sent to problem drivers	$720,000
Vehicle inspection		
864	Random motor vehicle inspection	$1,500
1172	Compulsory annual motor vehicle inspection	$20,000
864	Periodic motor vehicle inspection	$21,000
64	Periodic motor vehicle inspection	$57,000
175	Periodic inspection of motor vehicle sample focusing on critical components	$390,000
175	Periodic motor vehicle inspection	$1,300,000
Injury reduction interventions, miscellaneous		
192	Terminate sale of three-wheeled All-Terrain Vehicles	≤ $0
175	Require front and rear lights to be on when motorcycle is in motion	$1,100
175	Selective traffic enforcement programs at high-risk times and locations	$5,200
217	Insulate omnidirectional CB antennae to avert electrocution	$8,500
311	Oxygen depletion sensor systems for gas space heaters	$13,000
863	Require employers to ensure employees' motor vehicle safety	$25,000
372	"American" oxygen depletion sensor system for gas space heaters	$51,000
1160	Workplace practice standard for electric power generation operation	$59,000
175	Pedestrian and bicycle visibility enhancement programs	$73,000
315	Lock out or tag out of machinery in repair	$99,000
372	"French" oxygen depletion sensor system for gas space heaters	$130,000
1005	Redesign chain saws to reduce rotational kickback injuries	$230,000
101	Ground fault circuit interrupters	$1,100,000
468	Ejection system for the Air Force B-58 bomber	$1,200,000
1161	Equipment, work practices, and training standard for hazardous waste cleanup	$2,000,000
	Toxin control	
Arsenic control		
497	Arsenic emission standard (vs. capture and control) at high-emit copper smelters	$36,000
1216	Arsenic emission control at high-emitting copper smelters	$74,000
497	Arsenic emission standard (vs. capture and control) at glass plants	$2,300,000
1183	Arsenic emission control at low-emitting ASARCO/El Paso copper smelter	$2,600,000
1216	Arsenic emission control at glass plants	$2,900,000
497	Arsenic emission standard (vs. capture and control) at low-emit copper smelters	$3,900,000
881	Arsenic emission control at secondary lead plants	$7,600,000
1216	Arsenic emission control at low-emitting copper smelters	$16,000,000
1183	Arsenic emission control at low-emitting copper smelters	$29,000,000
881	Arsenic emission control at primary copper smelters	$30,000,000
881	Arsenic emission control at glass manufacturing plants	$51,000,000

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
1183	Arsenic emission control at low-emitting Copper Range/White Pine copper smelter	$890,000,000
	Asbestos control	
881	Ban asbestos in brake blocks	$29,000
819	Asbestos exposure standard of 1.0 (vs. 2.0) fibers/cc in asbestos cement industry	$55,000
881	Ban asbestos in pipeline wrap	$65,000
881	Ban asbestos in specialty paper	$80,000
651	Ban products containing asbestos (vs. 0.2 fibers/cc standard)	$220,000
651	Phase in ban of products containing asbestos (vs. 0.2 fibers/cc standard)	$240,000
819	Asbestos exposure standard of 1.0 (vs. 2.0) fibers/cc in textile industry	$400,000
387	Asbestos exposure standard of 0.2 (vs. 2.0) fibers/cc in ship repair industry	$410,000
881	Ban asbestos in roofing felt	$550,000
881	Ban asbestos in friction materials	$580,000
881	Ban asbestos in non-roofing coatings	$790,000
881	Ban asbestos in millboard	$920,000
819	Asbestos exposure standard of 0.2 (vs. 0.5) fibers/cc in friction products industry	$1,200,000
819	Asbestos exposure standard of 0.2 (vs. 0.5) fibers/cc in cement industry	$1,900,000
881	Ban asbestos in beater-add gaskets	$2,000,000
881	Ban asbestos in clutch facings	$2,700,000
881	Ban asbestos in roof coatings	$5,200,000
881	Ban asbestos in sheet gaskets	$5,700,000
881	Ban asbestos in packing	$5,700,000
819	Ban products containing asbestos (vs. 0.5 fibers/cc) in textile industry	$6,800,000
881	Ban asbestos in reinforced plastics	$8,200,000
881	Ban asbestos in high grade electrical paper	$15,000,000
387	Asbestos exposure standard of 0.2 (vs. 2.0) fibers/cc in construction industry	$29,000,000
881	Ban asbestos in thread, yarn, etc.	$34,000,000
819	Asbestos exposure standard of 1.0 (vs. 2.0) fibers/cc in friction products industry	$41,000,000
881	Ban asbestos in sealant tape	$49,000,000
881	Ban asbestos in automatic transmission components	$66,000,000
881	Ban asbestos in acetylene cylinders	$350,000,000
881	Ban asbestos in missile liner	$420,000,000
881	Ban asbestos in diaphragms	$1,400,0000,000
	Benzene control	
1139	Benzene exposure standard of 1 (vs. 10) ppm in rubber and tire industry	$76,000
881	Control of new benzene fugative emissions	$230,000
881	Control of existing benzene fugative emissions	$240,000
721	Benzene exposure standard of 1 (vs. 10) ppm	$240,000
881	Benzene emission control at pharmaceutical manufacturing plants	$460,000
881	Benzene emission control at coke by-product recovery plants	$1,400,000
1139	Benzene exposure standard of 1 (vs. 10) ppm in coke and coal chemicals industry	$3,000,000
881	Benzene emission control during transfer operations	$4,100,000
881	Control of benzene storage vessels	$14,000,000
881	Benzene emission control at ethylbenzene/styrene process vents	$14,000,000
881	Benzene emission control during waste operations	$19,000,000
881	Benzene emission control at maleic anhydride plants	$20,000,000
881	Benzene emission control at service stations storage vessels	$91,000,000
881	Control of benzene equipment leaks	$98,000,000
881	Benzene emission control at chemical manufacturing process vents	$180,000,000
881	Benzene emission control at bulk gasoline plants	$230,000,000
881	Benzene emission control at chemical manufacturing process vents	$530,000,000
881	Benzene emission control at rubber tire manufacturing plants	$20,000,000,000
	Chlorination	
42	Chlorination of drinking water	$3,100
42	Chlorination, filtration and sedimentation of drinking water	$4,200
	Coal and coke oven emissions control	
38	Coal-fired power plants emission control through high stacks etc.	≤ $0

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
38	Coal-fired power plants emission control through coal beneficiation etc.	$37,000
745	Coke oven emission standard for iron- or steel-producing plants	$130,000
745	Acrylonitrile emission control via best available technology	$9,000,000
Formaldehyde control		
716	Ban urea-formaldehyde foam insulation in homes	$11,000
311	Ban urea-formaldehyde foam insulation in homes	$220,000
1164	Formaldehyde exposure standard of 1 (vs. 3) ppm in wood industry	$6,700,000
Lead control		
1217	Reduced lead content of gasoline from 1.1 to 0.1 grams per leaded gallon	≤ $0
1,3 Butadiene control		
1138	1,3 Butadiene exposure standard of 10 (vs. 1000) ppm PEL in polymer plants	$340,000
1138	1,3 Butadiene exposure standard of 2 (vs. 1000) ppm PEL in polymer plants	$770,000
Pesticide control		
713	Ban chlorobenzilate pesticide on noncitrus	≤ $0
403	Ban amitraz pesticide on apples	≤ $0
403	Ban amitraz pesticide on pears	$350,000
713	Ban chlorobenzilate pesticide on citrus	$1,200,000
Pollution control at paper mills		
844	Chloroform emission standard at 17 low cost pulp mills	≤ $0
844	Chloroform private well emission standard at 7 papergrade sulfite mills	$25,000
844	Chloroform private well emission standard at 7 pulp mills	$620,000
844	Chloroform reduction by replacing hypochlorite with chlorine dioxide at 1 mill	$990,000
844	Dioxin emission standard of 5 lbs/air dried ton at pulp mills	$4,500,000
844	Dioxin emission standard of 3 (vs. 5) lbs/air dried ton at pulp mills	$7,500,000
844	Chloroform emission standard of 0.001 (vs. 0.01) risk level at pulp mills	$7,700,000
844	Chloroform reduction by replace hypochlorite with chlorine dioxide at 70 mills	$8,700,000
844	Chloroform reduction at 70 (vs. 33 worst) pulp and paper mills	$15,000,000
844	Chloroform reduction at 33 worst pulp and paper mills	$57,000,000
844	Chloroform private well emission standard at 48 pulp mills	$99,000,000,000
Radiation control		
468	Automatic collimators on X-ray equipment to reduce radiation exposure	$23,000
881	Radionuclide emission control at underground uranium mines	$79,000
881	Radionuclide emission control at Department of Energy facilities	$730,000
1216	Radionuclide control via best available technology in uranium mines	$850,000
44	Radiation standard "as low as reasonably achievable" for nuclear power plants	$1,100,000
468	Radiation levels of 0.3 (vs. 1.0) WL at uranium mines	$1,600,000
1215	Radiation standard "as low as reasonably achievable" for nuclear power plants	$2,500,000
881	Radionuclide emission control at surface uranium mines	$3,900,000
881	Radionuclide emission control at elemental phosphorous plants	$9,200,000
881	Radionuclide emission control at operating uranium mill tailings	$11,000,000
1216	Radionuclide control via best available technology in phosphorous mines	$16,000,000
881	Radionuclide emission control at phosphogypsum stacks	$29,000,000
881	Radionuclide emission control during disposal of uranium mill tailings piles	$40,000,000
1216	Rdiation emission standard for nuclear power plants	$100,000,000
468	Radiation emission standard for nuclear power plants	$180,000,000
926	Thin, flexible, protective leaded gloves for radiologists	$190,000,000
881	Radionuclide emission control at coal-fired industrial boilers	$260,000,000
881	Radionuclide emission control at coal-fired utility boilers	$2,400,000,000
881	Radionuclide emission control at NRC-licensed and non-DOE facilities	$2,600,000,000
881	Radionuclide emission control at uranium fuel cycle facilities	$34,000,000,000

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
	Radon control	
1266	Radon remediation in homes with levels ≥ 21.6 pCi/L	$6,100
1267	Radon remediation in homes with levels ≥ 8.11 pCi/L	$35,000
1030	Radon limit after disposal of uranium mill tailings of 20 (vs. 60) p(i/m2s)	$49,000
1265	Radon remediation in homes with levels ≥ 4 pCi/L	$140,000
1030	Radon limit after disposal of uranium mill tailings of 2 (vs. 6) p(i/m2s)	$260,000
881	Radon emission control at Department of Energy facilities	$5,100,000
	SO2 control	
923	SO2 controls by installation of capacity to desulphurize residual fuel oil	≤ $0
	Trichloroethylene control	
1215	Trichloroethylene standard of 2.7 (vs. 11) microgram/L in drinking water	$34,000,000
	Vinyl chloride control	
881	Vinyl chloride emission control at EDC/VC and PVC plants	$1,600,000
718	Vinyl chloride emission standard	$1,700,000
	VOC control	
1122	South Coast of California ozone control program	$610,000
	Toxin control, miscellaneous	
725	Process safety standard for management of hazardous chemicals	$77,000

Medicine

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
	Alpha antitrypsin replacement therapy	
1004	Alpha antitrypsin replacement (vs. med) therapy for smoking men age 70	$31,000
1004	Alpha antitrypsin replacement (vs. med) therapy for smoking women age 40	$36,000
1004	Alpha antitrypsin replacement (vs. med) therapy for nonsmoking women age 30	$56,000
1004	Alpha antitrypsin replacement (vs. med) therapy for nonsmoking men age 60	$80,000
	Beta-blocker treatment following myocardial infarction	
952	Beta blockers for myocardial infarction survivors with no angina or hypertension	$360
952	Beta-blockers for myocardial infarction survivors	$850
176	Beta-blockers for high-risk myocardial infarction survivors	$3,000
176	Beta-blockers for low-risk myocardial infarction survivors	$17,000
	Breast cancer screening	
142	Mammography for women age 50	$810
283	Mammography every 3 years for women age 50–65	$2,700
658	Annual mammography and breast exam for women age 35–49	$10,000
658	Annual physical breast cancer exam for womena age 35–49	$12,000
611	Annual mammography and breast exam (vs. just exam) for women age 40–64	$17,000
1230	Annual mammography and breast exam for women age 40–49	$62,000
1230	Annual mammography and breast exam (vs. just exam) for women age 40–49	$95,000
86	Annual mammography for women age 55–64	$110,000
1230	Annual mammography (vs. current screening practices) for women age 40–49	$190,000
	Breast cancer treatment	
1238	Postsurgical chemotherapy for premenopausal women with breast cancer	$18,000
1238	Postsurgical chemotherapy for women with breast cancer age 60	$22,000
1269	Bone marrow transplant and high (vs. standard) chemotherapy for breast cancer	$130,000
	Cervical cancer screening	
1316	Cervical cancer screening every 3 years for women age 65+	≤ $0
120	Cervical cancer screening every 9 (vs. 10) years for women age 30–39	$410
618	One time mass screening for cervical cancer for women age 38	$1,200
1316	Cervical cancer screening every 5 years for women age 65+	$1,900
1316	One time cervical cancer screening for women age 65+	$2,100

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
120	Cervical cancer screening every 2 (vs. 3) years for women age 30–39	$2,300
1316	Cervical cancer screening every 3 years for women age 65+	$2,800
120	Annual (vs. every 2 years) cervical cancer screening for women age 30–39	$4,100
783	One time cervical cancer screening for never-screened poor women age 65	$5,000
707	Annual cervical cancer screening for women beginning at age 60	$11,000
81	Cervical cancer screening every 4 years (vs. never) for women age 20	$12,000
88	One time mass screening for cervical cancer	$13,000
258	Cervical cancer screening every 5 years for women age 35+ with 3+ kids	$32,000
1316	Cervical cancer screening every 3 years for regularly-screened women age 65+	$41,000
1316	Annual (vs. every 3 years) cervical cancer screening for women age 65+	$49,000
707	Annual cervical cancer screening for women beginning at age 21	$50,000
603	Annual cervical cancer screening for women beginning at age 20	$82,000
81	Cervical cancer screening every 3 (vs. 4) years for women age 20	$220,000
456	Annual cervical cancer screening for women beginning at age 20	$220,000
81	Cervical cancer screening every 2 (vs. 3) years for women age 20	$310,000
81	Annual (vs. every 2 years) cervical cancer screening for women age 20	$1,500,000
Childhood immunization		
65	Immunization for all infants and pre-school children (vs. scattered efforts)	≤ $0
143	Pertussis, diphtheria, and tetanus (vs. just diphtheria and tetanus) immunization	≤ $0
349	Measles, mumps, and rubella immunization for children	≤ $0
812	Polio immunization for children age 0–4	≤ $0
812	Rubella vaccination for children age 2	≤ $0
1178	National measles eradication program for children	≤ $0
Cholesterol screening		
605	Cholesterol screening for boys age 10 and their first-degree relatives	$4,600
605	Cholesterol screening for boys age 10	$6,500
Cholesterol treatment		
1071	Lovastatin for men age 35–54 with heart disease and ≥ 250 mg/dL	≤ $0
785	Low-cholesterol diet for men age 60 and 180 mg/dL	$12,000
2	Low-cholesterol diet for men age 30	$19,000
1071	Lovastatin for men age 55–64 with heart disease and < 250 mg/dL	$20,000
791	Oat bran cholesterol reduction for men age 48 and > 265 mg/dL	$24,000
785	Lovastatin/low cholesterol diet (vs. diet) for men age 60 and 300 mg/dL	$26,000
785	Cholestyramine/low cholesterol diet (vs. diet) for men age 60 and 300 mg/dL	$31,000
1071	Lovastatin for men age 45–54 with no heart disease and ≥ 300 mg/dL	$34,000
768	Cholestyramine/low cholesterol diet (vs. diet) for age 35–39 and 290 mg/dL	$100,000
768	Cholestyramine/low cholesterol diet (vs. diet) for men age 50–54 and 290 mg/dL	$150,000
791	Cholestyramine for men age 48 and > 265 mg/dL	$160,000
768	Cholestyramine/low cholesterol diet (vs. cholestyramine) age 35–39 290 mg/dL	$200,000
1191	Cholestyramine for men with cholesterol levels above the 95th percentile	$230,000
785	Low-cholesterol diet for men age 20 and 180 mg/dL	$360,000
1071	Lovastatin 40 (vs. 20) mg for women age 35–44 with heart disease < 250 mg/dL	$360,000
768	Cholestyramine/low cholesterol diet (vs. diet) for men age 65–69 and 290 mg/dL	$920,000
1071	Lovastatin for women age 35–44 with no heart disease and ≥ 300 mg/dL	$1,200,000
785	Cholestyramine/low cholesterol diet (vs. diet) for men age 20 and 240 mg/dL	$1,300,000
785	Cholestyramine/low cholesterol diet (vs. diet) for men age 20 and 240 mg/dL	$1,800,000
Clinical trials		
1134	Women's Health Trial to evaluate low-fat diet in reducing breast cancer	$18,000
1004	Clinical trial to evaluate alpha antitrypsin replacement therapy	$53,000
Colorectal screening		
86	Annual stool guaiac colon cancer screening for people age 55+	≤ $0
96	One stool guaiac colon cancer screening for people age 40+	$660
528	One hemoccult screening for colorectal cancer for asymptomatic people age 55	$1,300
1135	Colorectal cancer screening for people age 40+	$4,500
1135	Colonoscopy for colorectal cancer screening for people age 40+	$90,000
96	Six (vs. five) stool guaiacs colon cancer screening for people age 40+	$26,000,000

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
	Coronary artery bypass graft surgery (CABG)	
358	Left main coronary artery bypass graft surgery (vs. medical management)	$2,300
99	Left main coronary artery bypass graft surgery (vs. medical management)	$5,600
99	3-vessel coronary artery bypass graft surgery (vs. medical management)	$12,000
1200	3-vessel coronary artery bypass graft surgery (vs. PTCA) for severe angina	$23,000
358	2-vessel coronary artery bypass graft surgery (vs. medical management)	$28,000
99	2-vessel coronary artery bypass graft surgery (vs. medical management)	$75,000
1200	3-vessel coronary artery bypass graft surgery (vs. PTCA) for mild angina	$100,000
1200	2-vessel coronary artery bypass graft surgery (vs. PTCA) for severe angina	$430,000
	Drug and alcohol treatment	
86	Occupational assistance programs for working problem-drinkers	≤ $0
650	Detoxification for heroin addicts	≤ $0
650	Methadone maintenance for heroin addicts	≤ $0
650	Narcotic antagonists for heroin addicts	≤ $0
	Emergency vehicle response	
987	Defibrillators in emergency vehicles for resuscitation after cardiac arrest	$39
987	Defibrillators in emergency vehicles staffed with paramedics (vs. EMTs)	$390
986	Defibrillators in ambulances for resuscitation after cardiac arrest	$460
987	Emergency vehicle response for cardiac arrest	$820
2	Advanced life support paramedical equipped vehicle	$5,400
237	Advanced resuscitative care (vs. basic emergency services) for cardiac arrest	$27,000
175	Combined emergency medical services for coordinated rapid response	$120,000
	Gastrointestinal screening and treatment	
578	Sclerotherapy (vs. medical therapy) for esophageal bleeding in alcoholics	≤ $0
148	Truss (vs. elective inguinal herniorrhaphy) for inguinal hernia in elderly patients	≤ $0
352	Expectant management of silent gallstones in men age 30	≤ $0
797	Home (vs. hospital) parenteral nutrition for patients with acute loss of bowels	≤ $0
797	Home parenteral nutrition for patients with acute loss of bowels	≤ $0
584	Pre-operative total parenteral nutrition in gastrointestinal cancer patients	≤ $0
235	Ulcer therapy (vs. surgery) for duodenal ulcers	$6,600
577	Medical or surgical treatment for advanced esophageal cancer	$12,000
587	Surgery for liver cirrhosis patients with acute variceal bleeding	$17,000
1046	Ulcer (vs. symptomatic) therapy for episodic upper abdomen discomfort	$41,000
1067	Misoprostol to prevent drug-induced gastrointestinal bleed in at-risk patients	$47,000
587	Medical management for liver cirrhosis patients with acute variceal bleeding	$61,000
1067	Misoprostol to prevent drug-induced gastrointestinal bleed	$210,000
1046	Upper gastrointestinal X-ray and endoscopy (vs. ulcer therapy) for gastric cancer	$300,000
1046	Upper gastrointetinal X-ray and endoscopy (vs. antacids) for gastric cancer	$420,000
	Heart disease screening and treatment, miscellaneous	
518	Exercise stress test for asymptomatic men age 60	$40
358	Pacemaker implant (vs. medical management) for atrioventricular heart block	$1,600
251	Reconstruct mitral valve for symptomatic mitral valve disease	$6,700
350	Exercise stress test for age 60 with mild pain and no left ventricular dysfunction	$13,000
990	Implantable cardioverter-defibrillator (vs. medical therapy) for cardiac arrest	$23,000
1066	Coronary angiogaphy (vs. medical therapy) in men age 45–64 with angina	$28,000
346	Regular leisure time physical activity, such as jogging, in men age 35	$38,000
251	Replace (vs. reconstruct) mitral valve for symptomatic mitral valve disease	$150,000
	Heart transplantation	
544	Heart transplantation for patients age 55 or younger and favorable prognosis	$3,600
835	Heart transplantation for patients age 50 with terminal heart disease	$100,000
	HIV/AIDS screening and prevention	
6	Voluntary (vs. limited) screening for HIV in female drug users and sex partners	≤ $0
1097	Screen blood donors for HIV	$14,000
1100	Screen donated blood for HIV with an additional FDA-licensed test	$880,000

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
1102	Universal (vs. category-specific) precautions to prevent HIV transmission	$890,000
	HIV/AIDS treatment	
1199	Zidovudine for asymptomatic HIV+ people	≤ $0
1121	Oral dapsone for prophylaxis of PCP in HIV+ people	$16,000
1121	Aerosolized pentamidine for prophylaxis of PCP in HIV+ people	$20,000
1096	AZT for people with AIDS	$26,000
1264	Prophylactic AZT following needlestick injury in health care workers	$41,000
1117	Zidovudine for asymptomatic HIV+ people	$45,000
	Hormone replacement therapy	
227	Estrogen for menopausal women age 50	≤ $0
748	Estrogen-progestin for symptomatic monopausal women age 50	$15,000
748	Estrogen for symptomatic menopausal women age 50	$26,000
748	Estrogen-progestin for 15 years in asymptomatic menopausal women age 50	$30,000
748	Estrogen-progestin for 5 years in asymptomatic menopausal women age 50	$32,000
90	Estrogen for post-menopausal women age 55–70	$36,000
227	Estrogen for menopausal women age 50	$42,000
90	Estrogen for asymptomatic post-menopausal women age 50–65	$77,000
90	Estrogen for symptomatic post-menopausal women age 50–65	$81,000
748	Estrogen for asymptomatic menopausal women age 50	$89,000
244	Hormone replacement for asymptomatic perimenopausal white women age 50	$120,000
227	Estrogen-progestin for post-menopausal women age 60	$130,000
90	Estrogen for asymptomatic post-menopausal women age 55–70	$250,000
	Hypertension drugs	
225	Antihypertensive drugs for men age 25+ and 125 mmHg	$3,800
225	Antihypertensive drugs for men age 25+ and 85 mmHg	$4,700
1068	Beta-blockers for hypertensive patients age 35–64 no heart disease and ≥ 95 mmHg	$14,000
91	Antihypertensive drugs for patients age 40 and ≥ 105 mmHg	$16,000
91	Antihypertensive drugs for patients age 40 and 95–104 mmHg	$32,000
1068	Captopril for people age 35–64 with no heart disease and ≥ 95 mmHg	$93,000
	Hypertension screening	
111	Hypertension screening for Black men age 55–64 and ≥ 90 mmHg	$5,000
761	Hypertension screening for men age 45–54	$5,200
111	Hypertension screening for White men age 45–54 and ≥ 90 mmHg	$6,500
111	Hypertension screening for Black women age 45–54 and ≥ 90 mmHg	$8,400
1202	Hypertension screening for asymptomatic men age 60	$11,000
1202	Hypertension screening for asymptomatic women age 60	$17,000
1202	Hypertension screening for asymptomatic men age 40	$23,000
761	Hypertension screening every 5 years for men age 55–64	$31,000
1202	Hypertension screening for asymptomatic women age 40	$36,000
111	Hypertension screening for White women age 18–24 and ≥ 90 mmHg	$37,000
1202	Hypertension screening for asymptomatic men age 20	$48,000
1202	Hypertension screening for asymptomatic women age 20	$87,000
	Hysterectomy to prevent uterine cancer	
750	Hysterectomy without oopherectomy for asymptomatic women age 35	≤ $0
750	Hysterectomy with oopherectomy for asymptomatic women age 40	$51,000
758	Hysterectomy for asymptomatic women age 35	$230,000
	Influenza vaccination	
455	Influenza vaccination for all citizens	$140
156	Influenza vaccination for high risk people	$570
156	Influenza vaccination for people age 5+	$1,300
	Intensive care	
422	Coronary care unit for patients under age 65 with cardiac arrest	$390
125	Intensive care for young patients with barbiturate overdose	$490
1208	Intensive care and mechanical ventilation for acute respiratory distress syndrome	$3,100

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
125	Intensive care for young patients with polyradiculitis	$3,600
1208	Intensive care and mechanical ventilation for acute respiratory failure	$4,700
854	Intensive care for unstable patients with unpredictable clinical course	$21,000
1208	Intensive care for patients with heart disease and respiratory failure	$21,000
125	Intensive care for patients with multiple trauma	$26,000
89	Coronary care unit for emergency patients with acute chest pain	$250,000
602	Intensive care for very ill patients undergoing major vascular surgery	$300,000
602	Intensive care for very ill patients with operative complications	$390,000
602	Intensive care for seriously ill patients with multiple trauma	$460,000
602	Intensive care for very ill patients undergoing neurosurgery for head trauma	$490,000
125	Intensive care for men with advanced cirrhosis, kidney and liver failure	$530,000
602	Intensive care for very ill patients with emergency abdominal catastrophes	$660,000
602	Intensive care for very ill patients undergoing neoplastic disease operations	$820,000
602	Intensive care for very ill patients undergoing major vascular operations	$850,000
602	Intensive care for very ill patients with gastrointestinal bleeding, cirhosis etc.	$950,000
Leukemia treatment and infection control		
1095	Bone marrow transplant (vs. chemotherapy) for acute nonlymphocytic leukemia	$12,000
1095	Bone marrow transplant for acute nonlymphocytic leukemia in adults	$20,000
1095	Chemotherapy for acute nonlymphocytic leukemia in adults	$27,000
672	Therapeutic leukocyte transfusion to prevent infection during chemotherapy	$36,000
672	Prophylactic (vs. therapeutic) leukocyte transfusion to prevent infection	$210,000
1239	Intravenous immune globulin to prevent infections in leukemia patients	$7,100,000
Neonatal intensive care		
335	Neonatal intensive care for infants weighing 1000–1499 grams	$5,700
83	Neonatal intensive care for infants weighing 751–1000 grams	$5,800
335	Neonatal intensive care for infants weighing 500–999 grams	$18,000
1249	Neonatal intensive care for low birth weight infants	$270,000
Newborn screening		
1195	PKU genetic disorder screening in newborns	≤ $0
1196	Congenital hypothyroidism screening in newborns	≤ $0
1141	Sickle cell screening for Black newborns	$240
1141	Sickle cell screening for non-Black high risk newborns	$110,000[e,f]
1141	Sickle cell screening for newborns	$65,000,000
1141	Sickle cell screening for non-Black low risk newborns	$34,000,000,000
Organized health services		
1249	Special supplemental food program for women, infants, and children	$3,400
653	Comprehensive (vs. fragmented) health care services	$5,700
653	Comprehensive (vs. fragmented) health care services for mothers and children	$11,000
1249	Organized family planning services for teenagers	$16,000
1191	No cost-sharing (vs. cost sharing) for health care services	$74,000
1249	Community health care services for women and infants	$100,000
Osteoporosis screening		
244	Bone mass screening and treat if < 0.9 g/(cm)^2 for perimenopausal women age 50	$13,000
244	Bone mass screening and treat if < 1.0 g/(cm)^2 for perimenopausal women age 50	$18,000
244	Bone mass screening and treat if < 1.1 g/(cm)^2 for perimenopausal women age 50	$41,000
Percutaneous transluminal coronary angioplasty (PTCA)		
358	PTCA (vs. medical management) for men age 55 with severe angina	$5,300
1200	PTCA (vs. medical management) for men age 55 with severe angina	$7,400
358	PTCA (vs. medical management) for men age 55 with mild angina	$24,000
1200	PTCA (vs. medical management) for men age 55 with mild angina	$110,000
Pneumonia vaccination		
812	Pneumonia vaccination for people age 65+	$1,800
782	Pneumonia vaccination for people age 65+	$2,000
347	Pneumonia vaccination for people age 65+	$2,200

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
693	Pneumonia vaccination for people age 65+	$2,200
812	Pneumonia vaccination for high risk immunodeficient people age 65+	$6,500
812	Pneumonia vaccination for people age 45–64	$10,000
782	Pneumonia vaccination for high risk people age 25–44	$14,000
812	Pneumonia vaccination for high risk immunodeficient people age 45–64	$28,000
782	Pneumonia vaccination for low risk people age 25–44	$66,000
782	Pneumonia vaccination for children age 2–4	$160,000
347	Pneumonia vaccination for children age 2–4	$170,000
693	Pneumonia vaccination for children age 2–4	$170,000
Prenatal care		
1253	Term guard uterine activity monitor (vs. self-palpation) to detect contractions	≤ $0
924	Financial incentive of $100 to seek prenatal care for low risk women	≤ $0
1250	Universal (vs. existing) prenatal care for women with < 12 years of education	≤ $0
1250	Universal (vs. existing) prenatal care for women with > 12 years of education	≤ $0
1250	Universal (vs. existing) prenatal care for women with 12 years of education	≤ $0
1251	Prenatal screening for hepatitis B in high risk women	≤ $0
1220	Brady method screening for group B streptococci colonization during labor	≤ $0
1256	Prenatal care for pregnant women	≤ $0
340	Antepartum Anti-D treatment for Rh-negative primiparae pregnancies	$1,100
1249	Prenatal care for pregnant women	$2,100
340	Antepartum Anti-D treatment for Rh-negative multiparae pregnancies	$2,900
1220	Isada method screening for group B streptococci colonization during labor	$5,000
Renal dialysis		
801	Home dialysis for chronic end-stage renal disease	$20,000
1049	Home dialysis for end-stage renal disease	$22,000
157	Home dialysis for end-stage renal disease	$23,000
139	Home dialysis for people age 45 with chronic renal disease	$24,000
419	Home dialysis for people age 64 or younger with chronic renal disease	$25,000
1049	Hospital dialysis for end-stage renal disease	$31,000
418	Home dialysis for people age 55–60 with acute renal failure	$32,000
357	Dialysis for people age 35 with end-stage renal disease	$38,000
419	Hospital dialysis for people age 55–64 with chronic renal failure	$42,000
689	Home dialysis for end-stage renal disease	$46,000
418	Hospital dialysis for people age 55–60 with acute renal failure	$47,000
342	Dialysis for end-stage renal disease	$51,000
1049	Center dialysis for end-stage renal disease	$55,000
1050	Center dialysis for end-stage renal disease	$63,000
157	Center dialysis for end-stage renal disease	$64,000
139	Center dialysis for people age 45 with chronic renal disease	$67,000
801	Center dialysis for end-stage renal disease	$68,000
689	Center dialysis for end-stage renal disease	$71,000
342	Hospital dialysis for end-stage renal disease	$74,000
689	Home dialysis (vs. transplantation) for end-stage renal disease	$79,000
Renal dialysis and transplantation		
689	Home dialysis then transplant for end-stage renal disease	$40,000
689	Hospital dialysis then transplant for end-stage renal disease	$46,000
Renal transplantation and infection control		
1065	Cytomegalovirus immune globulin to prevent infection after renal transplant	$3,500
1065	Cytomegalovirus immune globulin to prevent infection after renal transplant	$14,000
157	Kidney transplant for end-stage renal disease	$17,000
419	Kidney transplant and dialysis for people age 15–34 with chronic renal failure	$17,000
139	Kidney transplant for people age 45 with chronic renal disease	$19,000
1050	Kidney transplant from live-related donor for end-stage renal disease	$19,000
357	Kidney transplant from cadaver with cyclosporine (vs. azathioprine)	$27,000
357	Kidney transplant from cadaver with cyclosporine	$29,000
357	Kidney transplant from cadaver with azathioprine	$29,000

APPENDIX A. Continued.

Ref no.[a]	Life-saving intervention[b]	Cost/life-year[c]
1065	Cytomegalovirus immune globulin to prevent infection after renal transplant	$200,000
Smoking cessation advice		
1185	Smoking cessation advice for pregnant women who smoke	≤ $0
952	Smoking cessation among patients hospitalized with myocardial infarction	≤ $0
773	Smoking cessation advice for men age 50–54	$990
773	Smoking cessation advice for men age 45–49	$1,100
773	Smoking cessation advice for men age 35–39	$1,400
773	Smoking cessation advice for women age 50–54	$1,700
773	Smoking cessation advice for women age 45–49	$1,900
773	Smoking cessation advice for women age 35–39	$2,900
771	Nicotine gum (vs. no gum) and smoking cessation advice for men age 45–49	$5,800
119	Nicotine gum (vs. no gum) and smoking cessation advice for men age 35–69	$7,500
771	Nicotine gum (vs. no gum) and smoking cessation advice for men age 65–69	$9,100
771	Nicotine gum (vs. no gum) and smoking cessation advice for women age 50–54	$9,700
86	Smoking cessation advice for people who smoke more than one pack per day	$9,800
119	Nicotine gum (vs. no gum) and smoking cessation advice for women age 35–69	$11,000
771	Nicotine gum (vs. no gum) and smoking cessation advice for women age 65–69	$13,000
Tuberculosis treatment		
784	Isoniazid chemotherapy for high risk White male tuberculin reactors age 20	≤ $0
784	Isoniazid chemotherapy for low risk White male tuberculin reactors age 55	$17,000
Venous thromboembolism prevention		
230	Heparin (vs. anticoagulants) to prevent venous thromboembolism	≤ $0
769	Compression stockings to prevent venous thromboembolism	≤ $0
770	Compression stockings to prevent venous thromboembolism	≤ $0
770	Heparin to prevent venous thromboembolism	≤ $0
770	Heparin and dihydroergotamine to prevent venous thromboembolism	≤ $0
770	Intermittent pneumatic compression to prevent venous thromboembolism	≤ $0
770	Heparin and stockings to prevent venous thromboembolism	≤ $0
770	Warfarin sodium to prevent venous thromboembolism	≤ $0
769	Intermittent pneumatic compression and stockings to prevent thromboembolism	$400
230	Dextran (vs. anticoagulants) to prevent venous thromboembolism	$640
769	Heparin to prevent venous thromboembolism	$960
769	Heparin and stockings to prevent venous thromboembolism	$1,000
769	Heparin and dihydroergotamine to prevent venous thromboembolism	$1,700
769	Intermittent pneumatic compression to prevent venous thromboembolism	$2,400
787	Heparin, 1 day, for women with prosthetic heart valves undergoing surgery	$5,100
769	Heparin/dihydroergotamine (vs. stockings) to prevent venous thromboembolism	$42,000
787	Heparin, 3 days, for women with prosthetic heart valves undergoing surgery	$4,300,000
Medicine miscellaneous		
443	Broad-spectrum chemotherapy for cancer of unknown primary origin	≤ $0
728	Cefoxitin/gentamicin (vs. ceftizoxime) for intra-abdominal infection	$880
728	Mezlocillin/gentamicin (vs. ceftizoxime) for hospital acquired pneumonia	$1,400
646	Computed tomography in patients with severe headache	$4,800
709	Continuous (vs. nocturnal) oxygen for hypoxemic obstructive lung disease	$7,000
906	Preoperative chest X-ray to detect abnormalities in children	$360,000

[a] Reference numbers correspond to records in the database and to the references listed in Appendix B.

[b] Due to space limitations, life-saving interventions are described only briefly. When the original author compared the intervention to a baseline of "the status quo" or "do nothing" the baseline intervention is omitted here. Other baseline interventions appear as "(vs.)." Cost-effectiveness estimates are based on the particular life-saving intervention, base case intervention, target population, data, and methods as detailed by the original author(s). It is suggested the reader review the original document to gain a full appreciation of the origination of the estimates.

[c] All costs are in 1993 U.S. dollars and were updated with the general consumer price index. To emphasize the approximate nature of estimates, they are rounded to two significant figures.

APPENDIX B. REFERENCES FOR COST-EFFECTIVENESS ANALYSES[a]

2. Zeckhauser R, Shepard D (1976). Where now for saving lives? *Law & Contemporary Probl,* **40,** 4–45.
6. Brandeau ML, Owens DK, Sox CH, Wachter RM (1992). Screening women of childbearing age for human immunodeficiency virus. *Arch Intern Med,* **152,** 2229–37.
9. Clotfelter CT, Hahn JC (1978). Assessing the national 55 mph speed limit. *Policy Sci,* **9,** 281–94.
12. Dardis R, Aaronson S, Ying-Nan L (1978). Cost-benefit analysis of flammability standards. *Am J Agricultural Econ,* **60,** 697–9.
13. Waterman TE, Mniszewski KR, Spadoni DJ (1978). Cost-benefit analysis of fire detectors. Federal Emergency Management Agency, US Fire Administration, National Fire Data Center.
19. Potter JM, Smith ML, Panwalker SS (1976). Cost-effectiveness of residential fire detector systems. Texas Technical University, Lubbock.
31. Muller A (1980). Evaluation of the costs & benefits of motorcycle helmet laws. *Am J Public Health,* **70,** 586–92.
38. Mendelsohn R (1980). An economic analysis of air pollution from coal-fired power plants. *J Environ Econ Manage,* **7,** 30–43.
42. Clark RM, Goodrich JA, Ireland JC (1984). Cost & benefits of drinking water treatment. *J Environ Syst,* **14,** 1–30.
44. Okrent D (1980). Comment on societal risk. *Science,* **208,** 372–5.
52. Kahane CJ (1983). A preliminary evaluation of two braking improvements for passenger cars. Office of Program Evaluation, National Highway Traffic Safety Administration.
56. Arnould RJ, Grabowski H (1981). Auto safety regulation: An analysis of market failure. *Bell J Econ,* **12,** 27–48.
59. Sheffi Y, Brittain DB (1982). Motor vehicle safety: Passive restraints vs. mandatory seat belt wearing. *Inst of Transportation Eng J,* **52,** 26–9.
64. Loeb PD, Gilad B (1984). The efficacy & cost-effectiveness of vehicle inspection: A state specific analysis using time series data. *J Transport Econ & Policy,* **18,** 145–64.
65. Albritton RB (1978). Cost-benefits of measles eradication: Effects of a federal intervention. *Policy Anal,* **4,** 1–21.
67. Graham JD, Henrion M (1984). A probabilistic analysis of the passive-restraint question. *Risk Anal,* **4,** 25–40.
68. Main T (1985). An economic evaluation of child restraints. *J Transport Econ & Policy,* **19,** 23–39.
81. Eddy DM (1990). Screening for cervical cancer. *Ann Intern Med,* **113,** 214–26.
83. Kaufman SL, Shepard DS (1982). Costs of neonatal intensive care by day of stay. *Inquiry,* **19,** 167–78.
86. Kristein MM (1977). Economic issues in prevention. *Prev Med,* **6**(2), 252–64.
88. Schweitzer SO (1974). Cost effectiveness of early detection of disease. *Health Serv Res,* **9,** 22–32.
89. Fineberg HV, Scadden D, Goldman L (1984). Care of patients with a low-probability of acute myocardial infarction: Cost effectiveness of alternatives to coronary care unit admission. *N Engl J Med,* **310,** 1301–7.
90. Weinstein MC (1980). Estrogen use in postmenopausal women - Costs, risks & benefits. *N Engl J Med,* **303,** 308–16.
91. Stason WB, Weinstein MC (1977). Allocation of resources to manage hypertension. *N Engl J Med,* **296,** 732–9.
96. Neuhauser D, Lewicki AM. National health insurance & the sixth stool guaiac. *Policy Analysis,* **2,** 175–196.
99. Weinstein MC, Stason WB (1982). Cost-effectiveness of coronary artery bypass surgery. *Circulation,* **66**(5, Suppl 3), III56–66.
101. Johnson LL (1982). Cost-benefit analysis & voluntary safety standards for consumer products. Santa Monica CA: Rand Institute for Civil Justice.
106. Energy & Environmental Analysis Inc (1977). Benefit cost analysis of laws & regulations affecting coal case studies on reclamation, air pollution & health & safety laws & regulations: Final report. Washington DC: Office of Minerals Policy & Research Analysis, Dept. of the Interior.
111. Jordan J (1985). A benefit-cost analysis of hypertension treatment programs: Implications for targeting & public policy. Thesis.
119. Oster G, Huse DM, Delea TE, Colditz GA (1986). The cost-effectiveness of nicotine chewing gum as an adjunct to physician's advice against cigarette smoking. Cambridge, MA: Institute for the Study of Smoking Behavior & Policy, John F. Kennedy School of Government, Harvard University.
120. Schweitzer SO, Luce BR (1979). A cost effective approach to cervical cancer detection. Hyattsville, MD: United States Dept of Health, Education & Welfare, Public Health Service, Office of Health Research, Statistics & Technology, National Center for Health Services Research. DHEW Publication no. 79–32371.
122. Ray DR (1987). Cigarette lighters: Accident cost update. Internal memo to Paul H. Rubin, AED/Economic Analysis. US Consumer Product Safety Commission.
125. Bendixen HH (1977). The cost of intensive care. JP Bunker, BA Barnes, F Mosteller, *Costs, Risks & Benefits of Surgery.* New York: Oxford University Press.
139. Klarman HE, Francis JO, Rosenthal GD (1968). Cost-effectiveness analysis applied to the treatment of chronic renal disease. *Med Care,* **6,** 48–54.
142. Kodlin D (1972). A note on the cost-benefit problem in screening for breast cancer. *Methods Inf Med,* **11,** 242–7.
143. Koplan JP, Schoenbaum SC, Weinstein MC, Fraser DW (1979). Pertussis vaccine - An analysis of benefits, risks & costs. *N Engl J Med,* **301,** 906–11.
148. Neuhauser D (1977). Elective inguinal herniorrhaphy versus truss in the elderly. JP Bunker, BA Barnes, F Mosteller, *Costs, Risks & Benefits of Surgery.* New York: Oxford University Press.
156. Schoenbaum SC, McNeil BJ, Kavet J (1976). The swine influenza decision. *N Engl J Med,* **295,** 759–65.
157. Smith WF (1968). Cost-effectiveness & cost-benefit analyses for public health programs. *Public Health Rep,* **83,** 899–906.
172. Asin JS (1984). Regulatory evaluation: Final regulatory flexibility analysis, trade impact assessment, floor proximity emergency lighting. Washington DC: Regulatory analysis branch.
173. Smith JJ (1984). Regulatory evaluation: Final regulatory flexibility analysis & trade impact assessment, flammability requirements for aircraft seat cushions. Washington DC: Regulatory analysis branch.
174. Lewis AM (1984). Regulatory evaluation, regulatory, flexibility determination & trade impact assessment, airplane cabin fire protection: Smoke detector & fire extinguisher requirements for part 121 passenger aircraft (Project No. VS-83-324-R). Washington DC: Regulatory analysis branch.
175. Tarrants WE, Voas RB (1981). Highway needs study: 1981 update of 1976 report to Congress. Washington DC: Office of Program & Demonstration Evaluation, Traffic Safety Programs, National Highway Traffic Safety Programs, National Highway Traffic Safety Administration, US Dept. of Transportation.
176. Goldman L, Sia STB, Cook EF, Rutherford JD, Weinstein MC (1988). Costs & effectiveness of routine therapy with long-term beta-adrenergic antagonists after acute myocardial infarction. *N Engl J Med,* **319,** 152–7.
185. Kamerud DB (1988). Benefits & costs of the 55 mph speed limit: New estimates & their implications. *J Policy Anal & Manage,* **7,** 341–52.

186. Hartunian NS, Smart CN, Willemain TR, Zador PL (1983). The economics of safety deregulation: Lives & dollars lost due to repeal of motorcycle helmet laws. *J Health Polit Policy Law*, **8**, 76–98.
189. Kahane CJ (1982). An evaluation of side structure improvements in response to federal motor vehicle safety standard 214. Washington DC: Office of Program Evaluation, National Highway Traffic Safety Administration.
190. Kahane CJ (1985). An evaluation of windshield glazing & installation methods for passenger cars.
192. Rodgers GB, Rubin PH (1989). Cost-benefit analysis of all-terrain vehicles at the CPSC. *Risk Anal*, **9**, 63–9.
193. Jensen DD, Tome AE, Darby WP (1989). Applying decision analysis to determine the effect of smoke detector laws on fire loss in the United States. *Risk Anal*, **9**, 79–89.
217. Ray DR (1982). Safety standard for citizen's band omnidirectional base station antennas: Final economic assessment. US Consumer Product Safety Commission.
225. Harvald B, Christiansen T, Pederson KM, Rasmussen K, Strate M (1983). Cost-benefit in treatment of mild hypertension. *Acta Med Scand (Supplement)*, **686**, 81–7.
227. Weinstein MC, Schiff I (1983). Cost-effectiveness of hormone replacement therapy in the menopause. *Obstet Gynecol Surv*, **38**, 445–55.
230. Hull RD, Hirsh J, Sackett DL, Stoddart GL (1982). Cost-effectiveness of primary & secondary prevention of fatal pulmonary embolism in high-risk surgical patients. *Can Med Assoc J*, **127**, 990–5.
235. Culyer AJ, Maynard AK (1981). Cost-effectiveness of duodenal ulcer treatment. *Soc Sci Med*, **15C**, 3–11.
237. Urban N, Bergner L, Eisenberg MS (1981). The costs of a suburban paramedic program in reducing deaths due to cardiac arrest. *Med Care*, **19**, 379–92.
244. Tosteson AN, Rosenthal DI, Melton LJ (1988). Cost-effectiveness of screening perimenopausal white women for osteoporosis: Bone densitometry & hormone replacement therapy.
251. Papageorge BN, Schweitzer SO (1988). A cost-effectiveness comparison of surgical treatments for mitral valve disease. *Int J Tech Assess Health Care*, **4**, 447–61.
258. Charny MC, Farrow SC, Roberts CJ (1987). The cost of saving a life through cervical cytology screening: Implications for health policy. *Health Policy*, **7**, 345–59.
283. Knox EG (1988). Evaluation of a proposed breast cancer screening regimen. *Br Med J*, **297**, 650–4.
292. Dardis R (1980). Economic analysis of current issues in consumer product safety: Fabric flammability. *J Consumer Aff*, **14**, 109–23.
299. Lave LB, Weber WE (1970). A benefit-cost analysis of auto safety features. *Appl Econ*, **2**, 265–75.
303. Garbacz C (1989). Smoke detector effectiveness & the value of saving a life. *Econ Lett*, **31**, 281–6.
306. Helzer SG, Buchbinder B, Offensend FL (1979). Decision analysis of strategies for reducing upholstered furniture fire losses. Washington DC: US Dept. of Commerce, National Bureau of Standards.
311. Viscusi WK (1984). *Regulating Consumer Product Safety*, Washington DC: American Enterprise Institute for Public Policy Research.
315. Karr AR (1988). OSHA proposes rules on repairing powered machines. *Wall Street Journal*, May 2, p. 28.
335. Boyle MH, Torrance GW, Sinclair JC, Horwood SP (1983). Economic evaluation of neonatal intensive care of very-low-birth-weight infants. *N Engl J Med*, **308**, 1330–7.
340. Torrance GW, Zipursky A (1984). Cost-effectiveness of antepartum prevention of Rh immunization. *Clin Perinatol*, **11**, 267–81.
342. Churchill DN, Lemon BC, Torrance GW (1984). A cost-effectiveness analysis of continuous ambulatory peritoneal dialysis & hospital hemodialysis. *Med Decis Making*, *4*, 489–500.
346. Hatziandreu EI, Koplan JP, Weinstein MC, Caspersen CJ, Warner KE (1988). A cost-effectiveness analysis of exercise as a health promotion activity. *Am J Public Health*, **78**, 1417–21.
347. Willems JS, Sanders CR, Riddiough MA, Bell JC (1980). Cost-effectiveness of vaccination against pneumococcal pneumonia. *N Engl J Med*, **303**, 553–9.
349. White CC, Koplan JP, Orenstein WA (1985). Benefits, risks & costs of immunization for measles, mumps & rubella. *Am J Public Health*, **75**, 739–44.
350. Lee TH, Fukui T, Weinstein MC, Tosteson AN, Goldman L. Cost-effectiveness of screening strategies for left main coronary artery disease in patients with stable angina. *Med Decis Making*, **8**, 268–78, (1988).
352. Ransohoff DF, Gracie WA, Wolfenson LB, Neuhauser D (1983). Prophylactic cholecystectomy or expectant management for silent gallstones. *Ann Intern Med*, **99**, 199–204.
353. Mannering F, Winston C. Recent automobile occupant safety proposals. *Blind Intersection? Policy & the Automobile Industry*, Washington DC: Brookings Institute for Transportation Research Programs.
357. Simon DG (1986). A cost-effectiveness analysis of cyclosporine in cadaveric kidney transplantation. *Med Decis Making*, **6**, 199–207.
358. Williams A (1985). Economics of coronary artery bypass grafting. *Br Med J*, **291**, 326–9.
372. Organization for Economic Cooperation & Development (1983). Risk management in connection with consumer product safety. New York: OECD.
387. Occupational Safety & Health Administration (1986). Final regulatory impact & regulatory flexibility analysis of the revised asbestos standard. Washington DC: US Dept. of Labor, Occupational Safety & Health Administration, Office of Regulatory Analysis.
403. Environmental Protection Agency (1979). Determination pursuant to 40 CFR 162.11(a)(5) concluding the rebuttable presumption against registration of pesticide products containing amitraz. *Federal Register*, **44**, 2678–83.
418. Buxton MJ, West RR (1975). Cost-benefit of long-term hemodialysis for chronic renal failure. *Br Med J*, **2**, 376–9.
419. Ludbrook A (1981). A cost-effectiveness analysis of the treatment of chronic renal failure. *Appl Econ*, **13**, 337–50.
422. Reynell PC, Reynell MC (1972). The cost-benefit analysis of a coronary care unit. *Br Heart J*, **34**, 897–900.
443. Levine MN, Drummond MF, Labelle RJ (1985). Cost-effectiveness of the diagnosis & treatment of carcinoma of unknown effectiveness in the diagnosis & treatment of carcinoma of unknown primary origin. *Can Med Assoc J*, **133**, 977–87.
455. US Congress Office of Technology Assessment (1981). Cost Effectiveness of Influenza Vaccination. Washington DC: Office of Technology Assessment.
456. Eddy DM (1981). Appropriateness of cervical cancer screening. *Gynecologic Oncol*, **12**(2, Part 2), S168–87.
468. Sagan LA (1972). Human costs of nuclear power. *Science*, **177**, 487–93.
497. Environmental Protection Agency (1983). National emission standards for hazardous air pollutants; Proposed standards for inorganic arsenic. *Federal Register*, **48**, 33112–80.
518. Stason WB, Fineberg HV (1982). Implications of alternative strategies to diagnose coronary artery disease. *Circulation*, **66**(Suppl 3), III80–6.
528. Kristein MM (1980). The economics of screening for colo-rectal cancer. *Soc Sci & Med*, **14C**, 275–84.
544. Haberman S (1980). Heart transplants: Putting a price on life. *Health & Soc Serv J*, **90**, 877–9.
577. McPhail JF, Tolls RM (1987). Esophageal cancer. B Eisman, L Stahlgren, *Cost Effective Surgical Management*. Philadelphia: WB Saunders.

578. Clark JR (1987). Cost-effective treatment of esophageal varices. B Eisman, L Stahlgren, *Cost Effective Surgical Management.* Philadelphia: WB Saunders.

584. Twomey PL, Patching SC (1985). Cost effectiveness of nutritional support. *J Parenteral & Enteral Nutr,* **9,** 3–10.

587. O'Donnell TF, Gembarowicz RM, Callow AD, Pauker SG, Kelly JJ (1980). The economic impact of acute variceal bleeding: Cost effectiveness implications for medical & surgical therapy. *Surgery,* **88,** 693–701.

602. Barnes BA (1977). Cost-benefit analysis of surgery: Current accomplishments & limitations. *Am J Surg,* **133,** 438–46.

603. Barnes BA, Barnes AB (1977). Evaluation of surgical therapy by cost-benefit analysis. *Surgery,* **82,** 21–33.

605. Berwick DM, Keeler E, Cretin S, Cann C (1976). Screening for cholesterol: Costs & benefits. HA Lubs, F de la Cruz, *Genetic Counseling.* New York: Raven Press.

611. Christie D (1977). Screening for breast cancer: The role of mammography. *Med J Aust,* **2,** 398–400.

618. Dickinson L (1972). Evaluation of the effectiveness of cytologic screening for cervical cancer: Cost-benefit analysis. *Mayo Clinic Proc,* **47,** 550–5.

646. Knaus W, Wagner DP, Davis DO (1980). CT for headache: Cost-benefit for subarachnoid hemorrhage. *Am J Neuroradiol,* **1,** 567–72.

650. Leslie AC (1971). A benefit/cost analysis of New York City heroin addiction problems & programs - 1971. I Leveson, J Weiss, *Analysis of Urban Health Problems.* New York: Spectrum.

651. Environmental Protection Agency (1986). Asbestos; Proposed mining & import restrictions & proposed manufacturing, importation & processing prohibitions. *Federal Register,* **51,** 3738–59.

653. Levin AL (1968). Cost-effectiveness in maternal & child health: Implications for program planning & evaluation. *N Engl J Med,* **278,** 1041–7.

658. Moskowitz M, Fox S (1979). Cost analysis of aggressive breast cancer screening. *Radiology,* **130,** 253–6.

672. Rosenshein M, Farewell V, Price TH, Larson EB, Dale DC (1980). The cost effectiveness of therapeutic & prophylactic leukocyte transfusion. *N Engl J Med,* **302,** 1058–62.

689. Stange PV, Sumner AT (1978). Predicting treatment costs & life expectancy for end-stage renal disease. *N Engl J Med,* **298,** 372–8.

693. US Congress Office of Technology Assessment (1979). A case study: Cost-effectiveness analysis of vaccination against pneumoccal pneumonia. *A Review of Selected Federal Vaccine & Immunization Policies.* Washington DC: Government Printing Office.

707. Coppleson LW, Brown B (1976). The prevention of carcinoma of the cervix. *Am J Obstet Gynecol,* **125,** 153–9.

709. Roberts SD (1980). Cost effective oxygen therapy. *Ann Intern Med,* **93,** 499–500.

710. Deutsch P (1990). Summary of preliminary findings to date, studies of unreinforced masonry buildings program alternatives. Memo to CAO's unreinforced masonry building task force & interested parties.

713. Environmental Protection Agency. Notice of intent to cancel registrations & deny applications for registration of pesticide products containing chlorobenzilate pursuant to section 6(b)(1) & 3(d) of federal insecticide, fungicide & rodenticide act. *Federal Register,* **44,** 9548–67.

716. Environmental Protection Agency (1981). Urea-Formaldehyde foam insulation; Proposed ban; Denial of petition. *Federal Register,* **46,** 11188–211.

718. Environmental Protection Agency (1985). National emission standards for hazardous air pollutants; Vinyl chloride. *Federal Register,* **50,** 1182–201.

721. Occupational Safety & Health Administration (1985). Occupational exposure to benzene. *Federal Register,* **50,** 50512–86.

725. Occupational Safety & Health Administration (1990). Process safety management of highly hazardous chemicals. *Federal Register,* **55,** 29150–73.

728. Winstein MC, Read JL, MacKay DN, Kresel JJ, Ashley H (1986). Cost-effective choice of antimicrobial therapy for serious infections. *J Gen Intern Med,* **1,** 351–63.

745. Haigh JA, Harrison DJ, Nichols AL (1984). Benefit-cost analysis of environmental regulation: Case studies of hazardous air pollutants. *Harvard Environ Law Rev,* **8,** 395–434.

747. US Dept. of Transportation, FHA (1988). The 1988 annual report on highway safety improvement programs. Washington DC: US Dept. of Transportation.

748. Weinstein MC, Tosteson AN (1990). Cost-effectiveness of hormone replacement. *Multidisciplinary Perspectives on Menopause: Annals of the New York Academy of Sciences,* **592,** 162–72.

750. Sandberg SI, Barnes BA, Weinstein MC, Braun P (1985). Elective hysterectomy: Benefits, risks & costs. *Med Care,* **23,** 1067–85.

758. Cole P, Berlin J (1977). Elective hysterectomy. *Am J Obstet & Gynecol,* **129**(2), 117–23.

761. Bryers E, Hawthorne J (1978). Screening for mild hypertension: Costs & benefits. *J Epidemiol & Community Health,* **32,** 171–4.

768. Oster G, Epstein AM (1987). Cost-effectiveness of antihyperlipemic therapy in the prevention of coronary heart disease. The case of cholestyramine. *JAMA,* **258,** 2381–7.

769. Oster G, Tuden RL, Golditz GA (1987). Prevention of venous thromboembolism after general surgery. Cost-effectiveness analysis of alternative approaches to prophylaxis. *Am J Med,* **82,** 889–99.

770. Oster G, Tuden RL, Colditz GA (1987). A cost-effectiveness analysis of prophylaxis against deep-vein thrombosis in major orthopedic surgery. *JAMA,* **257,** 203–8.

771. Oster G, Huse DM, Delea TE, Colditz GA (1986). Cost-effectiveness of nicotine gum as an adjunct to physician's advice against cigarette smoking. *JAMA,* **256,** 1315–8.

773. Cummings SR, Rubin SM, Oster G (1989). The cost effectiveness of counseling smokers to quit. *JAMA,* **261.** 75–9.

782. Shepard DS, Zeckhauser RJ (1982). The choice of health policies with heterogeneous populations. *Economic Aspects of Health.* Chicago: University of Chicago Press.

783. Fahs MC, Mandelblatt JS (1990). Cost effectiveness of cervical cancer screening among elderly low-income women. *Preventing Disease: Beyond the Rhetoric.* New York: Springer-Verlag.

784. Rose DN, Schechter CB, Silver A, Fahs MC (1990). Cost-effectiveness of isoniazid chemoprophylaxis. *Preventing Disease: Beyond the Rhetoric.* New York: Springer-Verlag.

785. Taylor WC, Pass TM, Shepard DS, Komaroff AL (1990). Cost effectiveness of cholesterol reduction for the primary prevention of coronary heart disease in men. *Preventing Disease: Beyond the Rhetoric.* New York: Springer-Verlag.

787. Eckman MH, Bashansky JR, Durand-Zaleski I, Levine HJ, Pauker SJ (1990). Anticoagulation for noncardiac procedures in patients with prosthetic heart valves: Does low risk mean high cost? *JAMA,* **263,** 1513–21.

791. Kinosian BP, Eisenberg JM (1988). Cutting into cholesterol: Cost-effective alternatives for treating hypercholesterolemia. *JAMA,* **259,** 2249–54.

797. Detsky AS, McLaughlin JR, Abrams HB, Whittaker JS, Whitwell J (1986). A cost-utility analysis of the home parenteral nutrition program at Toronto General Hospital: 1970-1982. *J Parenteral & Enteral Nutr,* **10,** 49–57.

801. Pearson DA, Stranova TJ, Thompson JD (1976). Patient & program costs associated with chronic hemodialysis care. *Inquiry,* **13,** 23–8.

812. Sisk JE, Sanders CR (1983). Analyzing the cost-effectiveness & cost-benefit of vaccines. *World Health Forum,* **4,** 83–8.

819. Dewees D, Daniels R (1986). The cost of protecting occupational health: The asbestos case. *J Hum Resources,* **21,** 381–96.
834. National Highway Traffic Safety (1985). Federal motor vehicle safety standards; Occupant crash protection. *Federal Register,* **50,** 23041–3.
835. Pennock JL, Oyer PE, Reitz BA, Jamieson SW, Bieber CP (1982). Cardiac transplantation in perspective for the future: Survival, complications, rehabilitation & cost. *J Thoracic & Cardiovasc Surg,* **83,** 168–77.
844. Luken RA (1990). Efficiency in environmental regulation: A benefit-cost analysis of alternative approaches. *Studies in Risk & Uncertainty.* Boston: Kluwer Academic Publishers.
854. Cullen DJ, Ferrara LC, Briggs BA, Walker PF, Gilbert J (1976). Survival, hospitalization charges & follow-up results in critically ill patients. *N Engl J Med,* **294,** 982–7.
863. Occupational Safety & Health Administration (1990). Preliminary regulatory impact analysis of the standard on occupant protection in motor vehicles.
864. Van Matre JG, Overstreet GA (1982). Motor vehicle inspection & accident mortality: A reexamination. *J Risk & Insurance,* **49,** 423–5.
881. Van Houtven GL, Cropper ML (1993). When is a life too costly to save? The evidence from environmental regulations. Discussion Paper CRM 93-02. Center for Risk Management, Resources for the Future.
906. Neuhauser D (1977). Cost-effective clinical decision making. *Pediatrics,* **60**(5), 756–9.
909. Occupational Safety & Health Administration (1989). Underground construction; Final rule. *Federal Register,* **54,** 23824–57.
910. Occupational Safety & Health Administration (1989). Occupational safety & health standards – excavations. *Federal Register,* **54,** 45894–991.
923. Organization for Economic Cooperation & Development (1981). *The Costs & Benefits of Sulphur Oxide Control,* Paris: The Organization for Economic Co-operation & Development.
924. Murray JL, Bernfield M (1988). The differential effect of prenatal care on the incidence of low birth weight among blacks & whites in a prepaid health care plan. *N Engl J Med,* **319,** 1385–91.
926. Kelsey CA, Mettler FA (1990). Flexible protective gloves: The emperor's new clothes? *Radiology,* **174,** 275–6.
952. Wilhelmsson C, Vedin A, Wilhelmsson L (1981). Cost-benefit aspects of post-myocardial infarction intervention. *Acta Med Scand,* **651,** 317–20.
986. Rowley JM, Garner C, Hampton JR (1990). The limited potential of special ambulance services in the management of cardiac arrest. *Br Heart J,* **64,** 309–12.
987. Ornato JP, Craren EJ, Gonzalez ER, Garnett AR, McClung BK (1988). Cost-effectiveness of defibrillation by emergency medical technicians. *Am J Emerg Med,* **6,** 108–12.
990. Kuppermann M, Luce BR, McGovern B, Podrid PJ, Bigger JT (1990). An analysis of the cost-effectiveness of the implantable defibrillator. *Circulation,* **81,** 91–100.
1004. Hay JW, Robin ED (1991). Cost-effectiveness of Alpha-1 antitrypsin replacement therapy in treatment of congenital chronic obstructive pulmonary disease. *Am J Public Health,* **81,** 427–33.
1005. Rodgers GB (1985). Preliminary economic assessment of the chain saw standard. Directorate for Economic Analysis, Consumer Products Safety Commission.
1006. Rodgers GB (1990). The effectiveness of helmets in reducing all-terrain vehicle injuries & deaths. *Accident Anal Prev,* **22,** 47–58.
1030. Environmental Protection Agency (1983). Regulatory impact analysis of final environmental standards for uranium mill tailings at active sites. (NTIS #PB84-106780).
1046. Read L, Pass TM, Komaroff AL (1982). Diagnosis & treatment of dyspepsia: A cost-effectiveness analysis. *Med Decis Making,* **2,** 415–38.
1049. Bulgin RH (1981). Comparative costs of various dialysis treatments. *Peritoneal Dial Bull,* **1,** 88–91.
1050. Roberts SD, Maxwell DR, Gross TL (1980). Cost-effective care of end-stage renal disease: A billion dollar question. *Ann Intern Med,* **92,** 243–8.
1065. Tsevat J, Snydman DR, Pauker SG, Durand-Zaleski I, Werner BG (1991). Which renal transplant patients should receive cytomegalovirus immune globulin? A cost-effectiveness analysis. *Transplantation,* **52,** 259–65.
1066. Doubilet P, Weinstein MC, McNeil BJ (1985). The decision concerning coronary angiography in patients with chest pain: A cost-effectiveness analysis. *Med Decis Making,* **5,** 293–309.
1067. Edelson JT, Tosteson AN, Sax P (1990). Cost-effectiveness of misoprostol for prophylaxis against nonsteroidal-antiinflammatory-drug-induced gastrointestinal bleeding. *JAMA,* **264,** 41–7.
1068. Edelson JT, Weinstein MC, Tosteson AN, Williams L, Lee TH (1990). Long-term efficacy hypertension. *JAMA,* **263,** 408–13.
1071. Goldman L, Weinstein MC, Goldman PA, Williams LW (1991). Cost-effectiveness of HMG-CoA reductase inhibition for primary & secondary prevention of coronary heart disease. *JAMA,* **265,** 1145–51.
1089. National Highway Traffic Safety Administration Plans & Policy Office of Regulatory Analysis (1990). Final regulatory impact analysis extension of the automatic restraint requirements of FMVSS 208 to trucks, buses & multipurpose passenger vehicles with a gross vehicle weight rating of 8500 pounds or less & an unloaded vehicle weight of 5500 pounds or less.
1091. National Highway Traffic Safety Administration Office of Plans & Policy (1991). Extension of FMVSS No. 216, roof crush standards to light trucks, vans & multipurpose vehicles.
1095. Welch HG, Larson EB (1989). Cost effectiveness of bone marrow transplantation in acute nonlymphocytic leukemia. *N Engl J Med,* **321,** 807–12.
1096. Scitovsky AA, Cline MW, Abrams D (1990). Effects of the use of AZT on the medical care costs of persons with AIDS in the first 12 months. *J Acquired Immune Deficiency Syndromes,* **3,** 904–12.
1097. Eisenstaedt RS, Getzen TE (1988). Screening blood donors for human immunodeficiency virus antibody: Cost-benefit analysis. *Am J Public Health,* **78,** 450–4.
1100. Mendelson DN, Sandler S (1990). A model for estimating incremental benefits & costs of testing donated blood for human immunodeficiency virus antigen (HIV-Ag). *Transfusion,* **30,** 73–5.
1102. Stock SR, Gafni A, Bloch RF (1990). Universal precautions to prevent HIV transmission to health care workers: An economic analysis. *Can Med Assoc J,* **142,** 937–46.
1105. Zeeger CV, Parker MR (1985). Cost-effectiveness of countermeasures for utility pole accidents & appendices. (Project #FHWA/RD).
1107. Zeeger CV, Mayes JG (1989). Cost-effectiveness of lane & shoulder widening of rural two lane roads in Kentucky. Federal Highway Administration.
1117. Schulman KA, Lynn LA, Glick HA, Eisenberg JM (1991). Cost effectiveness of low-dose zidovudine therapy for asymptomatic patients with human immunodeficiency virus (HIV) infection. *Ann Intern Med,* **114,** 798–802.
1121. Freedberg KA, Tosteson AN, Cohen CJ, Cotton DJ (1991). Primary prophylaxis for pneumocystit carinii pneumonia in HIV-infected people with CD4 counts Below 200/mm3: A cost-effectiveness analysis. *J Acquired Immune Deficiency Syndromes,* **4,** 521–31.
1122. Krupnick AJ, Portney PR (1991). Controlling urban air pollution: A benefit-cost assessment. *Science,* **252,** 522–8.
1124. Transportation Research Board National Research Council (1989). Improving school bus safety, Special report #222.
1126. National Highway Traffic Safety Administration Plans & Policy Office of Regulatory Analysis (1989). Preliminary regulatory impact analysis proposed extension of FMVSS 214 quasi static

test requirements to trucks, buses & multi-purpose passenger vehicles with a gross vehicle weight rating of 10,000 pounds or less.

1127. National Highway Traffic Safety Administration, Office of Regulatory Analysis Plans & Policy (1989). Rear seat lap shoulder belts in passenger cars: Final regulatory evaluation.

1128. National Highway Traffic Safety Administration Plans & Policy Office of Regulatory Analysis (1990). Final regulatory impact analysis new requirements for passenger cars to meet a dynamic side impact test FMVSS 214.

1129. National Highway Traffic Safety Administration Plans & Programs Office of Planning & Analysis (1984). Final regulatory impact analysis amendment to FMVSS No. 208 passenger car front seat occupant protection.

1132. Occupational Safety & Health Administration (1989). Regulatory impact & regulatory flexibility analysis of the underground construction standard.

1134. Urban N, Baker M (1989). The women's health trial as an investment. *Med Decis Making,* **9,** 59–64.

1135. England WL, Halls JJ, Hunt VB (1989). Strategies for screening for colorectal carcinoma. *Med Decis Making,* **9,** 3–13.

1137. Occupational Safety & Health Administration (1988). Final regulatory impact assessment of the standard on concrete & masonry construction. (1926, 700–705, subpart Q). OSHA Office of Regulatory Analysis, US Dept. of Labor.

1138. Occupational Safety & Health Administration (1989). Preliminary regulatory impact & regulatory flexibility analysis of the 1,3-butadiene standard. OSHA Office of Regulatory Analysis, US Dept. of Labor.

1139. Occupational Safety & Health Administration (1987). Final regulatory impact & regulatory flexibility analysis of the benzene standard.

1141. Tsevat J, Wong JB, Pauker SG, Steinberg MG (1991). Neonatal screening for sickle cell disease: A cost-effectiveness analysis. *J Pediatr,* **118,** 546–54.

1160. Occupational Safety & Health Administration (1988). Preliminary regulatory impact & regulatory flexibility analysis of the occupational safety standard for electric power generation, transmission & distribution (29 CFR Part 1910.269). OSHA Office of Publications, US Dept. of Labor.

1161. Occupational Safety & Health Administration (1988). Regulatory impact & regulatory flexibility analysis of the occupational safety & health standard for hazardous waste operations & emergency response (29 CFR Part 1910).

1164. Occupational Safety & Health Administration (1987). Regulatory impact & regulatory flexibility analysis of the formaldehyde standard. OSHA Office of Publications, US Dept. of Labor.

1165. Eastern Research Group, I (1987). Economic impact analysis of the proposed revision of OSHA subpart P standard (1926.650-652) governing trenching & excavation work.

1172. Fuchs VR (1986). Motor accident mortality & compulsory inspection of vehicles. *The Health Economy.* Cambridge: Harvard University Press.

1178. Axnick NW, Shavell SM, Witte JJ (1969). Benefits due to immunization against measles. *Public Health Rep,* **84,** 673–80.

1183. Luken RA (1990). Setting national standards for inorganic arsenic emissions from primary copper smelters: A case study. *Valuing Health Risks, Costs & Benefits for Environmental Decision Making.* Washington DC: National Academy Press.

1185. Marks JS, Koplan JP, Hogue CJ, Dalmat ME (1990). A cost-benefit/cost-effectiveness analysis of smoking cessation for pregnant women. *Am J Prev Med,* **6**(5), 282–9.

1191. Himmelstein DU, Woolhandler S (1984). Free care, cholestyramine & health policy. *N Engl J Med,* **311,** 1511–4.

1195. Barden HS, Kessel R, Schuett VE (1984). The costs & benefits of screening for PKU in Wisconsin. *Soc Biol,* **31,** 1–17.

1196. Barden HS, Kessel R (1984). The costs & benefits of screening for congenital hypothyroidism in Wisconsin. *Soc Biol,* **31,** 185–200.

1199. Paltiel AD, Kaplan EH (1991). Modeling zidovudine therapy: A cost-effectiveness analysis. *J Acquired Immune Deficiency Syndromes,* **4,** 795–804.

1200. Wong JB, Sonnenberg FA, Salem DN, Pauker SG (1990). Myocardial revascularization for chronic stable angina. *Ann Intern Med,* **113,** 852–71.

1202. Littenberg B, Garber AM, Sox HC (1990). Screening for hypertension. *Ann Intern Med,* **112,** 192–202.

1208. Schmidt CD, Elliott CG, Carmelli D, Jensen RL, Cengiz M (1983). Prolonged mechanical ventilation for respiratory failure: A cost-benefit analysis. *Crit Care Med,* **11,** 407–11.

1215. McKone TE (1986). The implicit valuation of environmental cancer by United States Regulatory Agencies. *Toxics Law Rep,* **1,** 442–9.

1216. Environmental Protection Agency (1984). OMB position on use of risk assessment, cost-effectiveness analysis, benefit-cost review in setting standards for toxic air pollutants and EPA's standard-setting for toxic pollutants. *Environ Rep,* **14,** 1493.

1217. Nichols AL (1985). The role of analysis in regulatory decisions: The case of lead in gasoline.

1220. Strickland DM, Yeomans ER, Hankins GD (1990). Cost-effectiveness of intrapartum screening & treatment for maternal group B streptococci colonization. *Am J Obstet Gynecol,* **163**(1. Part 1), 4–7.

1221. Petak WJ, Atkisson AA (1982). Natural hazard mitigation costs & impacts. *Natural Hazard Risk Assessment & Public Policy.* New York: Springer-Verlag.

1230. Eddy DM, Hasselblad V, McGivney W, Hendee W (1988). The value of mammography screening in women under age 50 years. *JAMA,* **259,** 1512–9.

1238. Hillner BE, Smith TJ (1991). Efficacy & cost effectiveness adjuvant chemotherapy in women with node-negative breast cancer. *N Engl J Med,* **324,** 160–8.

1239. Weeks JC, Tierney M, Weinstein M (1991). Cost effectiveness of prophylactic intravenous immune globulin in chronic lymphocytic leukemia. *N Engl J Med,* **325,** 81–6.

1249. Joyce T, Corman H, Grossman M (1988). A cost-effectiveness analysis of strategies to reduce infant mortality. *Med Care,* **26,** 348–60.

1250. Gorsky RD, Colby JP (1989). The cost-effectiveness of prenatal care in reducing low birth weight in New Hampshire. *Health Serv Res,* **24,** 583–98.

1251. Arevalo JA, Washington AE (1988). Cost-effectiveness of prenatal screening & immunization for hepatitis B virus. *JAMA,* **259,** 365–9.

1253. Morrison JC, Martin JN, Martin RW, Hess LW, Gookin KS (1989). Cost-effectiveness of ambulatory uterine activity monitoring. *Inter J of Gynecol,* **28,** 127–32.

1256. Korenbrot CC (1984). Risk reduction in pregnancies of low-income women: Comprehensive prenatal care through the OB Access Project. *Mobius,* **4,** 34–43.

1264. Ramsey SD, Nettleman MD (1992). Cost-effectiveness of prophylactic AZT following needlestick injury in health care workers. *Med Decis Making,* **12,** 142–8.

1265. Puskin JS, Nelson CB (1989). EPA's perspective on risks from residential radon exposure. *J Air Pollut Control Assoc,* **39,** 915–20.

1266. Nero AV (1988). Elements of a strategy for control of indoor radon. *Radon & Its Decay Products in Indoor Air,* New York: John Wiley.

1267. Mossman KL, Sollitto MA (1991). Regulatory control of indoor Rn. *Health Phys,* **60,** 169–76.

1269. Hillner BE, Smith TJ, Desche CE (1992). Efficacy & cost-effectiveness of autologous bone marrow transplantation in metastatic breast cancer. *JAMA,* **267,** 2055–61.

1316. Fahs MC, Mandelblatt J, Schechter C, Muller C (1992). Cost-effectiveness of cervical cancer screening for the elderly. *Ann of Intern Med,* **117,** 520–7.

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[a] Reference numbers correspond to records in the database and to interventions described in Appendix A. Missing numbers reflect documents that were retrieved but did not contain suitable cost-effectiveness data.

ACKNOWLEDGMENTS

We are grateful to our other colleagues on the Life-Saving Priorities Research Team who helped read economic analyses, including Amy Bensen, Paul Eisenstadt, David Paltiel, Laura Rose, and Alex Zaleski. For their efforts in searching the literature we are thankful to Brian Ash, Michael Kamat, Kayla Laserson, Lori Leonard, Adil Najam, Francine Wiest, and Karen Worthington. In addition, we appreciate Deborah Servi's help with managing the project database. Helpful suggestions were made by Magnus Johannesson, Cynthia Lopez, and Richard Zeckhauser.

This work was conducted at the Harvard Center for Risk Analysis and supported by Research Grant SES-9110225 from the National Science Foundation (Drs. Tengs, Weinstein, and Graham), Medical Informatics Training Grant Number 1T15LM07092 from the National Library of Medicine (Dr. Tengs), a Pre-Doctoral Fellowship from the Merck Foundation (Dr. Tengs), and unrestricted funds from the Harvard Center for Risk Analysis (Drs. Tengs, Adams, and Safran).

REFERENCES

1. M. J. Bailey, *Reducing Risks to Life: Measurement of the Benefits* (American Enterprise Institute, Washington, D.C., 1980).
2. J. D. Graham and J. Vaupel, "Value of a Life: What Difference Does it Make?" *Risk Analysis* **1**, 692–704 (1981).
3. J. Morrall, "A Review of the Record," *Regulation* 25–34, November/December (1986).
4. R. Schwing, "Longevity Benefits and Costs of Reducing Various Risks," *Technological Forecasting and Social Change* **13**, 1–23 (1979).
5. R. Zeckhauser and D. Shepard, "Where Now for Saving Lives?" *Law and Contemporary Problems* **40**, 5–45 (1976).
6. U.S. Preventive Services Task Force, *Guide to Clinical Preventive Services: An Assessment of the Effectiveness of 169 Interventions* (Williams & Wilkins, Baltimore, 1989).
7. T. O. Tengs, "The Opportunity Costs of Haphazard Societal Investments in Life-Saving," Optimizing Societal Investments in the Prevention of Premature Death (Chap. 2), Unpublished doctoral dissertation, Harvard University (1994).

Appendix 33

COMMENTS ON “FIVE-HUNDRED LIFE-SAVING INTERVENTIONS AND THEIR COST EFFECTIVENESS” BY TENGS ET AL, RISK ANALYSIS, VOLUME 15, NUMBER 3, 1995, PAGES 369-390.

This long paper has a simple moral: there are enormous variations in cost of potentially life-saving interventions, from no cost to nearly 600 billions of dollars per life saved. The costs for various radiation and radon control measures are given on pages 377 and 378, and range from $6,100 to $34,000,000,000 cost per life year. The paper’s point is that we will use our resources much more wisely if we go after the inexpensive interventions that affect large numbers of people than if we go after the extraordinarily expensive interventions that might not even save a single life, because so few people are involved.

Nancy Standler MD, PhD

Appendix 34

Public Health Assessment for

LINCOLN PARK/COTTER URANIUM MILL
CAÑON CITY, FREMONT COUNTY, COLORADO
EPA FACILITY ID: COD042167585
SEPTEMBER 9, 2010

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
PUBLIC HEALTH SERVICE
Agency for Toxic Substances and Disease Registry

Comment Period Ends:

NOVEMBER 9, 2010

THE ATSDR PUBLIC HEALTH ASSESSMENT: A NOTE OF EXPLANATION

This Public Health Assessment-Public Comment Release was prepared by ATSDR pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund) section 104 (i)(6) (42 U.S.C. 9604 (i)(6), and in accordance with our implementing regulations (42 C.F.R. Part 90). In preparing this document, ATSDR has collected relevant health data, environmental data, and community health concerns from the Environmental Protection Agency (EPA), state and local health and environmental agencies, the community, and potentially responsible parties, where appropriate. This document represents the agency's best efforts, based on currently available information, to fulfill the statutory criteria set out in CERCLA section 104 (i)(6) within a limited time frame. To the extent possible, it presents an assessment of potential risks to human health. Actions authorized by CERCLA section 104 (i)(11), or otherwise authorized by CERCLA, may be undertaken to prevent or mitigate human exposure or risks to human health. In addition, ATSDR will utilize this document to determine if follow-up health actions are appropriate at this time.

This document has previously been provided to EPA and the affected state in an initial release, as required by CERCLA section 104 (i) (6) (H) for their information and review. Where necessary, it has been revised in response to comments or additional relevant information provided by them to ATSDR. This revised document has now been released for a 30-day public comment period. Subsequent to the public comment period, ATSDR will address all public comments and revise or append the document as appropriate. The public health assessment will then be reissued. This will conclude the public health assessment process for this site, unless additional information is obtained by ATSDR which, in the agency's opinion, indicates a need to revise or append the conclusions previously issued.

Agency for Toxic Substances and Disease Registry....................................Thomas R. Frieden, M.D., M.P.H., Administrator
Christopher J. Portier, Ph.D., Director

Division of Health Assessment and Consultation………………………………………..William Cibulas, Jr., Ph.D., Director
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Please address comments regarding this report to:

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Attn: Records Center
1600 Clifton Road, N.E., MS F-09
Atlanta, Georgia 30333

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1-800-CDC-INFO or
Visit our Home Page at: http://www.atsdr.cdc.gov

PUBLIC HEALTH ASSESSMENT

LINCOLN PARK/COTTER URANIUM MILL

CAÑON CITY, FREMONT COUNTY, COLORADO

EPA FACILITY ID: COD042167585

Prepared by:

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Agency for Toxic Substances and Disease Registry
Division of Health Assessment and Consultation
Site and Radiological Assessment Branch

This information is distributed by the Agency for Toxic Substances and Disease Registry for public comment under applicable information quality guidelines. It does not represent and should not be construed to represent final agency conclusions or recommendations.

Foreword

The Agency for Toxic Substances and Disease Registry, ATSDR, was established by Congress in 1980 under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as the Superfund law. This law set up a fund to identify and clean up hazardous waste sites. The Environmental Protection Agency (EPA) and the individual states regulate the investigation and clean up of the sites.

Since 1986, ATSDR has been required by law to conduct a public health assessment at each of the sites on the EPA National Priorities List. The aim of these evaluations is to find out if people are being exposed to hazardous substances and, if so, whether that exposure is harmful and should be stopped or reduced. If appropriate, ATSDR also conducts public health assessments when petitioned by concerned individuals. Public health assessments are carried out by environmental and health scientists from ATSDR and from the states with which ATSDR has cooperative agreements. The public health assessment process allows ATSDR scientists and public health assessment cooperative agreement partners flexibility in document format when presenting findings about the public health impact of hazardous waste sites. The flexible format allows health assessors to convey to affected populations important public health messages in a clear and expeditious way.

Exposure: As the first step in the evaluation, ATSDR scientists review environmental data to see how much contamination is at a site, where it is, and how people might come into contact with it. Generally, ATSDR does not collect its own environmental sampling data but reviews information provided by EPA, other government agencies, businesses, and the public. When there is not enough environmental information available, the report will indicate what further sampling data is needed.

Health Effects: If the review of the environmental data shows that people have or could come into contact with hazardous substances, ATSDR scientists evaluate whether or not these contacts may result in harmful effects. ATSDR recognizes that children, because of their play activities and their growing bodies, may be more vulnerable to these effects. As a policy, unless data are available to suggest otherwise, ATSDR considers children to be more sensitive and vulnerable to hazardous substances. Thus, the health impact to the children is considered first when evaluating the health threat to a community. The health impacts to other high-risk groups within the community (such as the elderly, chronically ill, and people engaging in high risk practices) also receive special attention during the evaluation.

ATSDR uses existing scientific information, which can include the results of medical, toxicologic and epidemiologic studies and the data collected in disease registries, to evaluate possible the health effects that may result from exposures. The science of environmental health is still developing, and sometimes scientific information on the health effects of certain substances is not available.

Community: ATSDR also needs to learn what people in the area know about the site and what concerns they may have about its impact on their health. Consequently, throughout the evaluation process, ATSDR actively gathers information and comments from the people who live or work near a site, including residents of the area, civic leaders, health professionals, and community groups. To ensure that the report responds to the community's health concerns, an early version is also distributed to the public for their comments. All the public comments that related to the document are addressed in the final version of the report.

Conclusions: The report presents conclusions about the public health threat posed by a site. Ways to stop or reduce exposure will then be recommended in the public health action plan. ATSDR is primarily an advisory agency, so usually these reports identify what actions are appropriate to be undertaken by EPA or other responsible parties. However, if there is an urgent health threat, ATSDR can issue a public health advisory warning people of the danger. ATSDR can also recommend health education or pilot studies of health effects, full-scale epidemiology studies, disease registries, surveillance studies or research on specific hazardous substances.

Comments: If, after reading this report, you have questions or comments, we encourage you to send them to us.

Letters should be addressed as follows:

Attention: Rolanda Morrison
ATSDR Records Center (MS F-09)
4770 Buford Hwy, NE
Building 106, Room 2108
Atlanta, GA 30341

Table of Contents

APPENDIX C - ATSDR'S EVALUATION PROCESS AND EXPOSURE DOSE CALCULATIONS

Acronyms and Abbeviations

CCAT	Colorado Citizens Against Toxic Waste
CDPHE	Colorado Department of Public Health and Environment
CREG	cancer risk evaluation guide
CV	comparison value
D	dissolved
EMEG	environmental media evaluation guide
EPA	US Environmental Protection Agency
LPWUS	Lincoln Park Water Use Survey
LTHA	lifetime health advisory for drinking water
MCL	maximum contaminant level
mg/L	milligrams per liter
µR/hr	microroentgen per hour
N	not defined in the CDPHE database
NA	not available
ND	not detected
NPL	National Priorities List
OU	operable units
pCi/g	picocuries per gram
pCi/L	picocuries per liter
ppm	parts per million
RAP	Remedial Action Plan
RBC	risk based concentration
RMEG	reference dose media evaluation guide
S	suspended
SCS	Soil Conservation Service
SSL	soil screening level
T	total
UMTRCA	1978 Uranium Mill Tailings Radiation Control Act
USGS	United States Geological Survey

I. SUMMARY

Introduction

ATSDR’s top priority is to ensure that the community of Lincoln Park and surrounding communities have the best information possible to safeguard their health.

The purpose of this public health assessment (PHA) is to evaluate available data and information on the release of hazardous substances from the Cotter Uranium Mill to determine if people could be harmed by coming into contact with those substances. This PHA will also list actions, as needed, to be taken to protect the public’s health.

Background

The Cotter Uranium Mill (Cotter) is located approximately two miles south of downtown Cañon City in Fremont County, Colorado. The community of Lincoln Park borders the site to the north and the housing developments of Dawson Ranch, Wolf Park, and Eagle Heights are located along Cotter’s western boundary. The nearest residence is about 0.25 miles from the mill (Galant et al. 2007).

The 2,500-acre site includes two inactive mills, ore stockpile areas, a partially reclaimed tailings pond disposal area (i.e., the old ponds area), and a current tailings pond disposal area (i.e., the lined “main impoundment area”). A large portion of the site is used to store waste products in the impoundment area. The former mill area is fenced and is known as the “restricted area”.

The Cotter Mill began operations in 1958, extracting uranium ore using an alkaline leach process. In 1979, the facility switched to an acid leach process for extracting uranium. Cotter suspended primary operations in 1987, and only limited and intermittent processing occurred until the facility resumed operations in 1999 with a modified alkaline-leaching capability until 2001. Cotter refabricated the mill circuits between 2002 and 2005 to operate using an acid process when it went into stand down in March 2006. Cotter is currently evaluating whether to re-engineer the mill for future operation.

Wastes containing metals and radionuclides were released from Cotter and entered the nearby environment. People could potentially be exposed to these wastes if they come into contact with them in drinking water, soil, sediment, biota (fruits and vegetables) or ambient air.

Conclusions

After evaluating the available data, ATSDR reached four important conclusions in this public health assessment:

Conclusion 1

ATSDR concludes that drinking water from contaminated private wells could harm people’s health. This is a public health hazard.

Basis for Conclusion

Private well sampling data collected from 1984 to 2007 revealed the presence of molybdenum at levels that could harm people’s health. A water use survey conducted in Lincoln Park in 1989 revealed that at least seven people used groundwater (from their private wells) for personal consumption. These and other residents whose private wells were affected by the highest molybdenum contamination may be at increased risk for health effects such as gout-like conditions. Individuals who do not take in enough dietary copper or who cannot process it correctly will be affected the most.

The lack of consistent monitoring over the years and the unknown usage of wells before the installation of the public water supply makes these past exposures difficult to accurately assess.

Most town residents are now connected to the public water supply and have thus eliminated their exposure to contaminated water. However, some residents are reported to have refused public water supply connections, and many may still have operational private wells. Additionally, no formal institutional controls exist to control groundwater use in Lincoln Park. Therefore, current and future uses of private wells for domestic purposes are still possible.

Conclusion 2

ATSDR concludes that accidentally eating or touching soil and sediment near the Cotter Mill property or in Lincoln Park will not harm people’s health. However, ATSDR cannot make conclusions about whether lead in soils near Cotter Mill could harm people’s health in the future.

Basis for Conclusion

Currently, the property near the Cotter Mill property is restricted access, vacant or used for industrial purposes; therefore, contact with soils near the property should be minimal. The soil sampling conducted at the site does not allow ATSDR to accurately assess potential exposures if the area is ever developed for residential, commercial or recreational uses. Therefore, a conclusion regarding future exposures cannot be made because not enough information is available about future development of this area.

ATSDR recommends that lead contamination in soil be re-evaluated if

Next Steps	the area is considered for development for residential or non-industrial uses.
Conclusion 3	ATSDR concludes that eating locally-grown fruits and vegetables irrigated with private well water will not harm most people's health. However, a person eating above-average amounts of fruits and vegetables (4 times the average consumer) might have a low increased risk for developing cancer over a lifetime. As a precaution, residents should limit their use of contaminated well water to irrigate their crops. In all cases, the crops should be thoroughly cleaned prior to eating.
Basis for Conclusion	Sampled locally-grown fruits and vegetables did not indicate the presence of contaminants at levels that would cause non-cancer health effects. The increased cancer risk is based on a person consuming more fruits and vegetables (95th percentile range) than a typical consumer. The cancer estimate is conservative because it assumes that a person would grow and eat fruits and vegetables that contain arsenic every day for 30 years. The amount of fruits and vegetables eaten will likely be much less than estimated, mainly because the growing season is not year-round. The amount of a contaminant ingested would depend upon the type of crop eaten, the likelihood of the crop bioaccumulating any of the contaminants, how often the crop is eaten, if contaminated well water is used to irrigate the crop, and if the crop is thoroughly cleaned prior to eating them.
Conclusion 4	ATSDR concludes that ambient air emissions of particle bound radionuclides have not resulted in exposures to the public at levels that could cause adverse health outcomes.
Basis for Conclusion	With the exception of thorium-230 levels observed in 1981 and 1982, associated with excavation of contaminated tailings, every radionuclide monitored has been more than a factor of ten below annual dose based health limits to the public. The excavation releases appear to have only exposed on-site workers, but still below occupational limits at that time.
	ATSDR is taking the following follow-up actions at this site:
Next Steps	ATSDR's Health Promotion and Community Involvement Branch (HPCIB) will conduct health-related educational activities in the community, as necessary.

ATSDR's HPCIB will coordinate community outreach and community involvement activities for the site.

ATSDR will continue to work with appropriate state and federal agencies and review additional relevant environmental data (including the water use survey) as it becomes available.

ATSDR will update the action plan for this site as needed. New environmental, toxicological, health outcome data, or implementing the above proposed actions may necessitate the need for additional or alternative actions at this site.

For More Information

If you have concerns about your health, you should contact you health care provider. You can also call ATSDR at 1-800-CDC-INFO for more information on the Lincoln Park/Cotter Uranium Mill site.

II. BACKGROUND

A. Site description and operational history

The Cotter Mill is located approximately two miles south of downtown Cañon City in Fremont County, Colorado (see Figure 1) [Galant et al. 2007]. The community of Lincoln Park borders the site to the north and the housing developments of Dawson Ranch, Wolf Park, and Eagle Heights are located along Cotter's western boundary. The nearest residence is about 0.25 miles from the mill [Galant et al. 2007].

The 2,500-acre site includes two inactive mills, ore stockpile areas, a partially reclaimed tailings pond disposal area (i.e., the old ponds area), and a current tailings pond disposal area (i.e., the lined "main impoundment area"). A large portion of the site is used to store waste products in the impoundment area. The former mill area is fenced and is known as the "restricted area" [Galant et al. 2007].

The Cotter Mill began operations in 1958, extracting uranium ore using an alkaline leach process. In 1979, the facility switched to an acid leach process for extracting uranium. Cotter suspended primary operations in 1987 [Weston 1998], and only limited and intermittent processing occurred until the facility resumed operations in 1999 with a modified alkaline-leaching capability until 2001 [EPA 2002]. Cotter refabricated the mill circuits between 2002 and 2005 to operate using an acid process when it went into stand down in March 2006 [Cotter 2007]. Cotter is currently evaluating whether to re-engineer the mill for future operation [CDPHE 2008].

Additional information about the history and licensing of the Cotter Mill can be found on the Colorado Department of Public Health and Environment's (CDPHE) and the US Environmental Protection Agency's (EPA) Web sites at http://www.cdphe.state.co.us/hm/cotter/sitedescript.htm and http://www.epa.gov/region8/superfund/co/lincolnpark/.

B. Remedial and regulatory history

Originally, mill tailings (i.e., solid ore processing waste), raffinate (liquid waste that remains after extraction), and other liquids from the alkaline leach process were stored in ten on-site unlined ponds. In 1978, lined impoundments were built on site to store process waste products. The main impoundment contained two cells to segregate acid-leach tailings and liquids in the primary impoundment cell from alkaline-leach tailings in the secondary impoundment cell (EPA 2002). By 1983, more than 2.5 million cubic yards of waste products from historic operations were transferred from the original unlined ponds to the secondary impoundment. All new process wastes are stored in the lined primary impoundment [Galant et al. 2007].

Because Cotter Mill operations released radionuclides and metals into the environment, soil around the mill and groundwater in the nearby Lincoln Park community became contaminated, primarily with molybdenum and uranium [CDPHE 2008]. In 1984, the Lincoln Park/Cotter Mill Site was added to the Superfund National Priorities List (NPL) [EPA 2008]. EPA divided the site into two operable

According to a signed Memorandum of Understanding, CDPHE is the lead regulatory agency overseeing cleanup at the Cotter Mill.

units (OUs)—OU1 consists of the on-site contamination and OU2 is the neighborhood of Lincoln Park (i.e., the off-site impacted area) [CDPHE 2008; EPA 2007]. Together, the Lincoln Park/Cotter Mill Superfund Site encompasses about 7.8 square miles (5,000 acres) [EPA 2004].

In 1988, the Cotter Corporation and CDPHE signed a Consent Decree and Remedial Action Plan (RAP) [Galant et al. 2007]. The purpose of the court-ordered action was to assess and mitigate human and environmental impacts from the Cotter Mill. As part of the settlement, Cotter agreed to clean up the site at the corporation's expense [EPA 2008]. The cleanup was estimated to take 16 years and cost $11 million [Galant et al. 2007]. EPA and the US Department of Energy have also contributed to cleanup costs [DOE 2003]. Remedial activities have focused on eliminating the sources of contamination at the Cotter Mill and eliminating exposures to Lincoln Park residents [CDPHE 2008]. Many of the activities outlined in the 1988 RAP have been completed, including the following:

- Connecting Lincoln Park residents to city water;
- Constructing a groundwater barrier at the Soil Conservation Service (SCS) Flood Control Dam to minimize migration of contaminated groundwater into Lincoln Park;
- Moving tailings and contaminated soils into a lined impoundment to eliminate them as a source of contamination; and
- Excavating contaminated stream sediments in Sand Creek.

The old ponds area was undergoing reclamation in late 2008 [Pat Smith, EPA Region 8, personal communication, August 2008]. Remaining activities include groundwater remediation and final site cleanup [CDPHE 2008; Galant et al. 2007]. Groundwater remediation activities have shown some positive results. However, the balance of the remedial activities listed in the Consent Decree have not been successful enough in mitigating the plume, and most have been discontinued (e.g., barrier wall, dam to ditch flushing, calcium-polysulfide fix/flush, and permeable reactive treatment wall). Table 1 below lists a timeline of process events, remedial activities, and government actions for the Lincoln Park/Cotter Mill Superfund Site.

Table 1. Lincoln Park/Cotter Mill Superfund Site Activity Timeline

Date	Type of Event[1]	Event[2]
July 1958	Process	Cotter Corporation began alkali leach process operations (licensing by the Atomic Energy Commission)
June 1965	Event	Flood that caused the unlined tailings ponds at the Cotter Mill to overflow into Lincoln Park
1971	Remediation	SCS Dam completed; dam pumps impounded surface water back to the main impoundment (groundwater barrier completed at a later date after 1988 RAP)
July 1972	Remediation	Pond 2 lined
June 1976	Remediation	Pond 10 lined
1978–1979	Remediation	A new lined impoundment consisting of two cells (primary and secondary) constructed adjacent to the old ponds area for management of wastes from the new mill (alkali process)
1979	Remediation	The old mill was demolished and new mill construction began
1979–present	Remediation	Impounded water at the SCS Dam pumped back to the main impoundment
1979–1998	Process	Operations switched from an alkali leach process to an acid leach mill; continuing operations intermittently
1980	Remediation	Old upstream method tailings ponds replaced by a full-height compacted earth embankment
1980	Remediation	Construction of Well 333 just north of Cotter; well removes contaminated water flowing from the old ponds area
June 1981	Remediation	Pond 3 lined
1981–1983	Remediation	Tailings from the unlined old ponds area (~2.5 million cubic yards) removed and placed in the new impoundment
December 9, 1983	Government Action	State of Colorado files a complaint against Cotter under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA)
September 21, 1984	Government Action	Cotter (OU1) and Lincoln Park (OU2) added to the NPL
1985–1986	Investigation	Remedial Investigation and Feasibility Study (GeoTrans 1986)
April 1986	Government Action	Memorandum of Agreement between EPA and the state of Colorado
April 8, 1988	Government Action	Consent decree signed, including a RAP that required cleanup activities
1988	Remediation	An additional 2 feet of soil was removed from the old ponds area and placed in the lined primary impoundment
1988	Remediation	Lined water distribution/surge pond constructed over Pond 7
1988	Remediation	Installation of a hydrologic clay barrier upgradient from the SCS Dam
1989	Remediation	The secondary impoundment cell was covered with liquid for dust control and to create evaporative capacity; additional contaminated soils were removed from the old ponds area and placed in the primary impoundment cell

Date	Type of Event[1]	Event[2]
1989–2000	Remediation	Installation of two hydraulic barriers (injection/withdrawal systems) to control groundwater flow from the old ponds area; discontinued in 2000 because the system was unproductive
1990–1996	Remediation	SCS Dam to DeWeese ditch flushing project
1990–1998	Remediation	Four pilot tests to evaluate the effectiveness of active flushing of vadose zone and aquifer for contaminant removal in OU1
October 29, 1991	Report	Health Risk Assessment of the Cotter Uranium Mill Site: Phase I (HRAP 1991)
January 7, 1993	Report	RAP final report, Willow Lakes (Cotter)
1993–1999	Remediation	Sand Creek Soil Cleanup Action identified and removed approximately 9,000 cubic yards of tailings, soil, and sediment from Sand Creek (Cotter 2000)
1995	Licensing	Cotter filed a license amendment with the state for alkaline leach processing of uranium ore (approved 2/97)
November 19, 1996	Report	Supplemental Human Health Risk Assessment: Phase II Final Report (Weston 1996)
1996–1998	Remediation	Flush/fixation process using Calcium Polysulfide in surface infiltration cells
February 1997	Government Action	Radioactive materials license amendment became effective
1998	Process	Mill reconverted to an alkaline leach process
September 29, 1998	Report	Ecological Risk Assessment, Lincoln Park Superfund Site (Stoller Corporation and Schafer & Associates)
1998	Report	Supplemental Human Health Risk Assessment, Phase III Final Report (Weston 1998)
1999	Remediation	Old ponds area surface soils (~100,000 cubic yards) were removed and placed in the lined primary impoundment
May 1999	Process	Cotter resumed operations (which had been intermittent since 1979) with modified alkaline-leaching capability
September 30, 1999	Investigation	Final Focused Feasibility Study, Lincoln Park
June 2000	Remediation	Installation of a permeable reactive treatment wall across Sand Creek channel, north of SCS Dam in DeWeese Dye Ditch flush (to fulfill EPA requirement to address contaminated groundwater that was bypassing the SCS Dam barrier)
2000–2005	Process	Cotter proposes modifications to the circuit to process zircon ore. Process was not successful and discontinued by 2005.
January 2002	Government Action	EPA issued a Record of Decision for Lincoln Park requiring “No Further Action” for surface soils within Lincoln Park (EPA 2002)
April 2002	Government Action	The governor of Colorado passed an emergency bill requiring an Environmental Assessment be conducted before shipping out-of-state radioactive waste to Cotter
July 9, 2002	Government Action	CDPHE denied Cotter’s license amendment request, preventing receipt of shipments for direct disposal

Date	Type of Event[1]	Event[2]
September 13, 2002	Government Action	State of Colorado allowed Cotter to receive limited amounts of waste material as a test of its handling/storage capability
2002/2003	Investigation	Sampling for plutonium, uranium, lead and molybdenum in the Canon City vicinity (CDPHE 2003)
January 3, 2003	Government Action	EPA issued a notice of unacceptability under the Off-Site Rule regarding the five Proposed Units and impoundments previously found acceptable
2003	Remediation	Permeable reactive treatment wall not functioning as designed
September 9, 2004	Investigation	Cotter submits Feasibility Study for Old Ponds Area with six alternatives
December 15, 2004	Government Action	State health officials approved a 5-year extension of Cotter's uranium-processing license but denied requests to become a disposal facility for off-site radioactive materials
February 1, 2005	Government Action	Cotter filed a request for a hearing regarding the conditions of the license renewal
October 2005	Investigation	Survey of lead in indoor dust, soils, and blood in Lincoln Park to investigate potential impacts of historic smelters (ATSDR 2006a, 2006b, 2006c, 2006d)
April 2006	Government Action	A judge recommended in CDPHE's favor and Cotter filed an exception on the direct disposal issue only
2006	Remediation	To replace the permeable reactive treatment wall, water building up behind barrier is pumped back to the impoundments
January 2007	Government Action	CDPHE signed a Final Agency Decision, affirming the judge's Decision on the license. Cotter filed an appeal to be able to dispose of out-of-state soils in its primary impoundment.
2008	Process	Cotter decides not to take the case to the Court of Appeals, effectively ending the licensing issues from the 2004 renewal.

[1] Describes the general nature of events/actions relating to the Lincoln Park/Cotter Mill Superfund Site.

[2] Includes events/actions most pertinent to ATSDR's evaluation of exposures and potential health effects. Not all site-related events and reports are included.

C. Demographics

ATSDR examines demographic data to identify sensitive populations, such as young children, the elderly, and women of childbearing age, and to determine whether these sensitive populations are exposed to any potential health risks. Demographics also provide details on population mobility and residential history in a particular area. This information helps ATSDR evaluate how long residents might have been exposed to contaminants. According to the 2000 census, 1,170 people live within one mile of the Cotter Mill property—90 of whom are age 6 or younger, 190 are women of childbearing age (15–44 years), and 243 are age 65 or older. Figure 2 in Appendix B shows the demographics within one mile of the mill.

Cañon City is the largest population center in Fremont County with 15,760 residents (see Table 2 below). The Cañon City Metro area includes Cañon City, North Cañon, Lincoln Park, Brookside, Prospect Heights, Four Mile Ranch, Shadow Hills, Dawson Ranch, and the Colorado State Correctional Facilities. Florence is the second largest community in the area with a population of 3,816. The unincorporated portions of Fremont County represent 55% of the population and include Lincoln Park, Prospect Heights, and Shadow Hills [Cotter 2007].

Table 2. Population of communities near the Cotter Mill

Community	2000 Census Population	2006 Population Estimate
Brookside	219	218
Cañon City	15,431	15,760
Coal Creek	303	380
Florence	3,653	3,816
Lincoln Park	3,904	Not available
Rockvale	426	432
Williamsburg	714	700
Fremont County	46,145	47,727

Source: Cotter 2007; Galant et al. 2007

The unincorporated community of Lincoln Park is located in the greater Cañon City area, south of the Arkansas River and north of the Cotter Mill (see Figure 1). The community consists of single and multi-family homes, trailer parks, and rural single family homes. Many of the residents are retired and own their homes. The Lincoln Park area is currently experiencing growth [Galant et al. 2007].

The largest employers in Fremont County are the Colorado Department of Corrections and the Federal Bureau of Prisons. Tourism is the second largest employer in the Cañon City area [Cotter 2007; Galant et al. 2007]. Additional industry and manufacturing employers in Fremont County include Portec, Inc.; Holcim, Inc.; Thermal Ceramics; and Cañon Industrial Ceramics [Cotter 2007]. The health care and school systems also employ a substantial number of people in the county [CCAT, personal communication, August 2008].

D. Land use and natural resources

The Cotter Mill is located within an industrial zone. All abutting lands are zoned for agriculture-forestry. The semi-rural community of Lincoln Park is comprised predominantly of residential developments, agricultural plots and orchards, and small grazing parcels. The Shadow Hills Golf Course is located to the north of the Cotter Mill complex. The land to the south and east of the site is largely undeveloped. Recently, several high end homes have been built near the golf course and in the Wolf Park and Dawson Ranch areas. The distance from Cotter Mill's restricted area to the nearest home is about 0.25 mile [Galant et al. 2007].

Fremont County contains a large amount of public land managed by the US Department of the Interior Bureau of Land Management and the US Department of Agriculture Forest Service. Some of these areas are leased for livestock grazing, aggregate mining, and firewood removal. Visiting the many scenic attractions in Colorado's High Country (e.g., the Royal Gorge Bridge) and rafting in the Arkansas River are popular recreational activities [Cotter 2007].

1. Hydrogeology

In the vicinity of the Cotter Mill, contaminated groundwater primarily migrates along the near surface alluvium and fractured, weathered bedrock immediately underlying the alluvium (<100 feet deep) [USGS 1999a]. Groundwater migration is generally in northerly directions from the mill area, along the Sand Creek drainage area, through a gap in Raton Ridge, and into Lincoln Park. However, groundwater contamination has also been found in the vicinity of the Shadow Hills Golf Course, which is west of the Sand Creek drainage [EPA 2007]. The hydrogeology of the Lincoln Park/Cotter Mill Superfund Site can be conceptually divided into two areas: the upgradient area near the mill and the downgradient area to the north-northeast in Lincoln Park [USGS 1999a].

- In the upgradient area near the mill, the rate of groundwater flow is limited by small hydraulic conductivities [USGS 1999a]. However, cracks in the bedrock, fractures, and weathering enhance water transmission and allow groundwater to travel at considerable rates. Monitoring wells in the upgradient area, specifically in the Poison Canyon Formation, yield small amounts of water.

- The downgradient area in Lincoln Park is characterized by an "alluvial aquifer" comprised of alluvium and terrace alluvium, to a depth of 0–60 feet, and the underlying weathered and/or fractured bedrock below the alluvium. In this area, groundwater can be transmitted at substantial rates. The mix of gravel, sand, silt, and clay in this aquifer yields 10 to 400 gallons per minute to wells in Lincoln Park. The aquifer discharges to Sand Creek, as well as to multiple springs and seeps as far downgradient as the Arkansas River, approximately 2.5 miles downgradient from the Cotter site.

2. Geology

The Cotter Mill is located in a topographic depression resulting from an underlying structure called the Chandler syncline. The core of the syncline is the Poison Canyon formation, which is the uppermost bedrock unit beneath the site. Soils near the mill are shallow and well drained.

The top layer consists of brown loam. The subsoil is a pale brown loam, grading into a yellowish brown sandy loam. Areas north of the mill are covered with Quaternary alluvium consisting of gravel, cobble, boulders, and sand [EPA 2002].

3. *Hydrology*

An ephemeral creek has flowing water only during, and for a short duration after, precipitation. A perennial creek has flowing water year-round.

The Cotter Mill lies within the Sand Creek watershed [HRAP 1991]. The main hydrologic feature of the Lincoln Park/Cotter Mill Superfund Site is Sand Creek, a primarily ephemeral creek [EPA 2007]. The creek originates at Dawson Mountain (south of the Cotter Mill), travels north through the Cotter Mill, intersects the DeWeese Dye Ditch, and runs north-northeast through Lincoln Park. It becomes perennial for the last 0.25–0.5 mile before its confluence with the Arkansas River. The DeWeese Dye Ditch is one irrigation ditch that flows between the Cotter Mill and Lincoln Park.

Alluvial material (sediment deposited by flowing water) associated with Sand Creek is the predominant migration pathway for mill-derived contaminants in groundwater. Sand Creek carved a channel into the Vermejo formation at the Raton outcrop in the vicinity of the SCS Dam, which filled with permeable sediments, creating a preferential pathway for alluvial groundwater into Lincoln Park. The alluvial aquifer in Lincoln Park receives recharge from the DeWeese Dye Ditch, Crooked Ditch, Pump Ditch, ditch laterals, and ponds filled by the DeWeese Dye Ditch [EPA 2007].

4. *Prevailing Wind Patterns*

Cotter's monitoring network includes an on-site meteorological station that continuously measures a standard set of meteorological parameters (e.g., wind speed, wind direction, temperature, and relative humidity). The wind rose in Figure 3 in Appendix B depicts the statistical distribution of measured wind speeds and wind directions. During 2008, wind patterns at the station were principally westerly (i.e., winds out of the southwest to northwest) and accounted for 55% of the total winds [Cotter 2008b]. Easterly winds (i.e., winds out of the southeast to northeast) accounted for a smaller, but still significant, portion (26%) of the observed wind directions. Southerly and northerly winds were much less common. A nearly identical profile was observed in 2007. Other average parameters measured in 2008 follow: air temperature of 53.4 °F; relative humidity of 41%; and rainfall of 5.18 inches.

The prevailing westerly and easterly wind patterns are reasonably consistent with trends in the observed concentrations. Ambient air concentrations of selected site-related pollutants were highest at the perimeter monitoring stations directly east and west of the primary operations. There is a hilly ridge that straddles the western border of the site, blocking much east/west wind flow. However, it should be noted that prevailing wind patterns measured at Cotter Mill may not be representative of surface winds throughout the area, especially considering the proximity of nearby terrain features.

E. Past ATSDR involvement

ATSDR has been involved with the Lincoln Park site in the past. In October 1983, ATSDR completed a Public Health Assessment for the site. After reviewing available groundwater data, ATSDR concluded that the potential long term health effects from consumption of the contaminated water were:

- cancer and kidney damage, from uranium;
- gout-like symptoms, from molybdenum; and
- possibly a group of physiological and psychological symptoms, from selenium.

None of the potential health effects were definitive.

Numerous questions and concerns have been voiced by residents of Lincoln Park regarding the historical sites of numerous milling and smelting facilities in the Cañon City area. Among the various concerns were specific concerns about residual lead contamination from these milling and smelting operations. In response to these concerns, and after a specific request by the EPA, ATSDR evaluated the health risks associated with lead contamination in the area. ATSDR focused on two primary issues: 1) the blood lead level of children living in the area and 2) lead contaminated dust in homes in the Lincoln Park area.

In September and October 2005, ATSDR conducted an Exposure Investigation (EI) to answer the questions presented by the community and EPA. Previously, ATSDR concluded that lead levels in house dust and lead exposures to children represented an indeterminate health hazard because of a lack of available data. ATSDR conducted the EI to gather data on blood lead levels in the children, and soil and indoor dust level from homes.

The activities of the EI included:

- Collecting 44 indoor dust samples from 21 homes in Lincoln Park
- Collecting 80 composite soil samples from 22 properties (sampling conducted by EPA)
- Obtaining 45 blood samples from 21 households (42 blood samples were analyzed)

After evaluating the data obtained during the EI, ATSDR concluded that blood lead levels in adults and children, lead levels in dust in homes, and lead levels in soil did not represent a public health harard. ATSDR recommended no further actions related to lead in dust in homes, but did recommend routine monitoring of children’s blood lead levels in the Lincoln Park area.

In September 2005, ATSDR conducted a blood lead testing program as a service to the community of Lincoln Park. A total of 115 children from a local school were tested for blood lead. None of the children tested had elevated blood lead levels. Therefore, ATSDR concluded that the children tested did not have unusual exposures to lead at the time of testing. ATSDR recommended that local and state agencies continue routine monitoring of lead levels in area children.

Full reports discussed above may be obtained by contacting any of the contacts listed at the end of this report, by visiting our website at www.atsdr.cdc.gov or by calling our toll-free hotline at 800-232-4636.

III. EVALUATION OF EXPOSURE PATHWAYS

A. What is meant by exposure?

An exposure pathway has five elements: (1) a source of contamination, (2) an environmental media, (3) a point of exposure, (4) a route of human exposure, and (5) a receptor population. The *source* is the place where the chemical or radioactive material was released. The *environmental media* (such as groundwater, soil, surface water, or air) transport the contaminants. The *point of exposure* is the place where people come into contact with the contaminated media. The *route of exposure* (for example, ingestion, inhalation, or dermal contact) is the way the contaminant enters the body. The people actually exposed are the *receptor population*.

ATSDR’s public health assessments are driven by exposure to, or contact with, environmental contaminants. Contaminants released into the environment have the potential to cause harmful health effects. Nevertheless, *a release does not always result in exposure*. People can only be exposed to a contaminant if they come in contact with that contaminant—if they breathe, eat, drink, or come into skin contact with a substance containing the contaminant. If no one comes in contact with a contaminant, then no exposure occurs, and thus no health effects could occur. Often the general public does not have access to the source area of contamination or areas where contaminants are moving through the environment. This lack of access to these areas becomes important in determining whether people could come in contact with the contaminants.

The route of a contaminant’s movement is the *pathway*. ATSDR identifies and evaluates exposure pathways by considering how people might come in contact with a contaminant. An exposure pathway could involve air, surface water, groundwater, soil, dust, or even plants and animals. Exposure can occur by breathing, eating, drinking, or by skin contact with a substance containing the chemical contaminant. ATSDR identifies an exposure pathway as completed or potential, or eliminates the pathway from further evaluation.

- *Completed exposure pathways* exist for a past, current, or future exposure if contaminant sources can be linked to a receptor population. All five elements of the exposure pathway must be present. In other words, people have or are likely to come in contact with site-related contamination at a particular exposure point via an identified exposure route. As stated above, a release of a chemical or radioactive material into the environment does not always result in human exposure. For an exposure to occur, a completed exposure pathway must exist.

- *Potential exposure pathways* indicate that exposure to a contaminant could have occurred in the past, could be occurring currently, or could occur in the future. It exists when one or more of the elements are missing but available information indicates possible human exposure. A potential exposure pathway is one which ATSDR cannot rule out, even though not all of the five elements are identifiable.

- An *eliminated exposure pathway* exists when one or more of the elements are missing. Exposure pathways can be ruled out if the site characteristics make past, current, and future human exposures extremely unlikely. If people do not have access to contaminated areas, the pathway is eliminated from further evaluation. Also, an exposure pathway is eliminated if site monitoring reveals that media in accessible areas are not contaminated.

Contact with contamination at the Cotter Mill is an eliminated exposure pathway.

Because the mill site itself is fenced and access is restricted, exposure to on-site contamination by the public at the Cotter Mill is limited. Further, remediation efforts have removed some of the on-site soil contamination, including moving millions of cubic yards of tailings and contaminated soils from unlined ponds to lined impoundments (EPA 2002). In some areas, contaminated soil was removed down to bedrock. In addition, various process changes reduced the release of contaminated materials (EPA 2002). Any potential exposure by the occasional trespasser to remaining impacted soils at the Cotter Mill would be too infrequent to present a health hazard.

B. How does ATSDR determine which exposure situations to evaluate?

ATSDR scientists evaluate site conditions to determine if people could have been, are, or could be exposed (i.e., exposed in a past scenario, a current scenario, or a future scenario) to site-related contaminants. When evaluating exposure pathways, ATSDR identifies whether exposure to contaminated media (soil, sediment, water, air, or biota) has occurred, is occurring, or will occur through ingestion, dermal (skin) contact, or inhalation.

If exposure was, is, or could be possible, ATSDR scientists consider whether contamination is present at levels that might affect public health. ATSDR scientists select contaminants for further evaluation by comparing them to health-based comparison values. These are developed by ATSDR from available scientific literature related to exposure and health effects. Comparison values are derived for each of the different media and reflect an estimated contaminant concentration that is *not likely* to cause adverse health effects for a given chemical, assuming a standard daily contact rate (e.g., an amount of water or soil consumed or an amount of air breathed) and body weight.

Comparison values are not thresholds for adverse health effects. ATSDR comparison values establish contaminant concentrations many times lower than levels at which no effects were observed in experimental animals or human epidemiologic studies. If contaminant concentrations are above comparison values, ATSDR further analyzes exposure variables (for example, duration and frequency of exposure), the toxicology of the contaminant, other epidemiology studies, and the weight of evidence for health effects.

Some of the comparison values used by ATSDR scientists include ATSDR's environmental media evaluation guides (EMEGs), reference dose media evaluation guides (RMEGs), and cancer risk evaluation guides (CREGs) and EPA's maximum contaminant levels (MCLs). EMEGs, RMEGs, and CREGs are non-enforceable, health-based comparison values developed by ATSDR for screening environmental contamination for further evaluation. MCLs are enforceable drinking water regulations developed to protect public health. Effective May 2008, Colorado established state groundwater standards for uranium and molybdenum.

You can find out more about the ATSDR evaluation process by calling ATSDR's toll-free telephone number, 1-800-CDC-INFO (1-800-232-4636) or reading ATSDR's Public Health Assessment Guidance Manual at http://www.atsdr.cdc.gov/HAC/PHAManual/.

C. If someone is exposed, will they get sick?

Exposure does not always result in harmful health effects. The type and severity of health effects a person can experience because of contact with a contaminant depend on the exposure concentration (how much), the frequency (how often) and/or duration of exposure (how long), the route or pathway of exposure (breathing, eating, drinking, or skin contact), and the multiplicity of exposure (combination of contaminants). Once exposure occurs, characteristics such as age, sex, nutritional status, genetics, lifestyle, and health status of the exposed individual influence how the individual absorbs, distributes, metabolizes, and excretes the contaminant. Together, these factors and characteristics determine the health effects that may occur.

In almost any situation, there is considerable uncertainty about the true level of exposure to environmental contamination. To account for this uncertainty and to be protective of public health, ATSDR scientists typically use worst-case exposure level estimates as the basis for determining whether adverse health effects are possible. These estimated exposure levels usually are much higher than the levels that people are really exposed to. If the exposure levels indicate that adverse health effects are possible, ATSDR performs more detailed reviews of exposure and consults the toxicologic and epidemiologic literature for scientific information about the health effects from exposure to hazardous substances.

D. What exposure situations were evaluated for residents living near the Cotter Mill?

ATSDR obtained information to support the exposure pathway analysis for the Lincoln Park/Cotter Mill Superfund Site from multiple site investigation reports; state, local, and facility documentation; and communication with local and state officials. The analysis also draws from available environmental and exposure data for groundwater, soil, surface water and sediment, and biota. Throughout this process, ATSDR examined concerns expressed by the community to ensure exposures of special concern are adequately addressed. ATSDR identified the following exposure pathways for further evaluation:

1. Exposure to site-related contaminants in groundwater in Lincoln Park.

2. Contact with site-related contaminants in soil adjacent to the Cotter Mill and in Lincoln Park.

3. Contact with site-related contaminants in surface water downstream from the Cotter Mill.

4. Exposure from eating produce locally grown in Lincoln Park.

5. Exposure from site-related soil contaminants in windborne dust.

6. Exposure from air emission sources (stacks and uncontrolled fugitive dust)

This exposure pathway analysis focuses on past, current, and future exposures for residents living near the Cotter Mill, with a focus on the community of Lincoln Park. Some attention is also paid to exposures at the Shadow Hills Golf Course and along the county road. Table 3 below provides a summary of exposure pathways evaluated in this public health assessment.

1. *Exposure to groundwater in Lincoln Park*

In the past, a number of residences used wells[1] on their property (GeoTrans 1986; IMS 1989). Based on a 1989 water use survey in Lincoln Park, 60 out of 104 wells, springs, and cisterns were used to obtain water for domestic purposes, including consumption and irrigation (IMS 1989). See Table 14 in Appendix A for the reported groundwater uses in the Lincoln Park area. Seven survey respondents indicated that they used groundwater for domestic consumption, accounting for 5 to 100% of their total water consumption. Based on the survey, five residents had private wells that were affected by contaminated groundwater; these residents were connected to the municipal water supply between 1989 and 1993 [EPA 2002]. The 1988 RAP requires Cotter to connect eligible affected users with legal water rights for a well to the town water supply [CDPHE 2005]. Cotter checks the State of Colorado's Engineer's Office database for new water permits and reports their findings in their annual ALARA reports [Pat Smith, EPA Region 8, personal communication, August 2008].

The use of private groundwater wells in the past was a completed exposure pathway. Most residences are now connected to the public water supply. The current and future use of these wells is a potential exposure pathway because the extent to which these wells are used is not well documented.

While the majority of town residents are now connected to the public water supply [Galant et al. 2007], several residences also have operational private wells. A 2005 summary of the RAP status reports that some residents have refused public water supply connections [CDPHE 2005]. Additionally, no formal institutional controls exist to control groundwater use in Lincoln Park [EPA 2007]. The United States Geological Survey (USGS) reports that existing private wells are used primarily for stock watering and irrigation [USGS 1999a]. However, a newspaper article reports that at least one residence, located on Grand Avenue in Lincoln Park, used private well water for consumption as recently as 2002 [Plasket 2002]. Based on a 2007 review of Colorado State well permits for residences in the plume configuration, at least one well is permitted for irrigation and domestic use, but no details of actual use are documented [EA 2007]. On properties that continue to use private wells, new purchasers are offered connection to the town's municipal water system [Galant et al. 2007]. In late 2008, EPA conducted another water use survey to verify whether groundwater is being utilized by residences in Lincoln Park. Well water samples were also collected and analyzed. Once available, ATSDR will review the information and will revise the public health assessment, if needed.

2. *Contact with soil adjacent to the Cotter Mill and in Lincoln Park*

People (especially children) might accidentally ingest soil or exposed sediment, and dust generated from these materials, during normal activities. Everyone ingests some soil or dust every day. Small children (especially those of preschool age) tend to swallow more soil or dust than any other age group because children of this age tend to have more contact with soil through play activities and have a tendency for more hand-to-mouth activity. Children in elementary school, teenagers, and adults swallow much smaller amounts of soil or dust. The amount of grass

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[1] The term "well" is used to represent all groundwater sources, and includes both wells and springs.

cover in an area, the amount of time spent outdoors, and weather conditions also influence how much contact people have with soil.

a) Contact with soil near the Cotter Mill

Contact with contaminated soil near the Cotter Mill (i.e., in the buffer zone) is a past, current, and future potential exposure pathway.

Soils adjacent to the Cotter Mill have been contaminated by wind-blown particulates [CDPHE 2005]. Elevated levels are primarily detected in soils directly east and west of the facility [Weston 1998]. This distribution of contaminated soils is consistent with wind patterns in the area, which blow mainly from west to east with occasional flows from east to west. The primarily vacant areas directly east and west of the facility are referred to as a "buffer zone" between the Cotter Mill and residential developments [EPA 2002]. Therefore, limited opportunities for exposure to impacted site-adjacent soils exist—people are not expected to be in this area on a daily basis and for an extended period of time. One exception may be at the Shadow Hills Golf Course, located immediately north of the Cotter mill complex. Exposure to potentially impacted soil at this public golf course is unlikely due to grass cover.

For nearly 50 years, Cotter has intermittently hauled materials by truck, possibly losing some materials along the county road leading to the facility and along the access road entering the mill site [MFG 2005]. The public could be exposed to potentially impacted soils along the county road. However, there is limited potential for exposure to contaminants along the access road, since access to the Cotter Mill is restricted and Cotter remediated soil adjacent to the access road in 2007 and 2008.

b) Contact with soil and sediment in the community of Lincoln Park

The community of Lincoln Park is located approximately 1.5 miles north-northeast of the restricted area of the Cotter Mill. Contaminated materials from the Cotter Mill may have contributed to soil contamination in Lincoln Park in two ways:

1. Dust from soil or tailings associated with site operations could be transported by wind to Lincoln Park. However, wind patterns in the area suggest that wind-blown contamination is not likely a considerable source of soil contamination in Lincoln Park (Weston 1998). Additionally, on-site remediation at the Cotter Mill substantially reduced the sources of soil contamination.

2. Potentially impacted groundwater used for irrigation could lead to the accumulation of chemicals in town soils [Weston 1998].

Contact with contaminated sediment in Sand Creek was a past potential exposure pathway. Due to the remediation of Sand Creek, current and future contact is an eliminated exposure pathway.

Further, in the past, contaminated surface water runoff from the Cotter Mill entered Sand Creek, where it was transported downstream toward Lincoln Park [EPA 2002]. However, Sand Creek is not believed to be used for recreational activities—the creek is ephemeral and on private land until it goes under the river walk and enters the Arkansas River [Phil Stoffey, CDPHE, personal communication, June 2007].

Contact with contaminated soil in Lincoln Park was a past completed exposure pathway. Cotter has performed all required off-site soil cleanup activities, as outlined in the RAP [EPA 2002]. CDPHE reports that the Cotter Mill poses no risk to the residents of Lincoln Park by exposure to soil [Weston 1998], and EPA and CDPHE have advised "No Further Action" in regards to Lincoln Park soils [EPA 2002]. EPA's Record of Decision states that surface-soil cleanup activities have eliminated or reduced risks to "acceptable" levels [EPA 2002, 2007]. Therefore, current and future contact with soil and sediment is an eliminated exposure pathway.

3. *Contact with surface water downstream from the Cotter Mill*

In the past, people could have come in contact with contamination in surface water during recreational activities. The Arkansas River is used primarily for fishing and boating or rafting, as well as some swimming [Phil Stoffey, CDPHE, personal communication, June 2007]. Sand Creek is on private land until it goes under the river walk and enters the Arkansas River, and is generally not used for recreational activities [Phil Stoffey, CDPHE, personal communication, June 2007]. Many Lincoln Park residents use water from the DeWeese Dye Ditch to irrigate their orchards and gardens [Galant et al. 2007].

Contact with contaminated surface water near the Cotter Mill was a past potential exposure pathway. Due to the construction of the SCS Dam and the remediation of Sand Creek, current and future contact is an eliminated exposure pathway.

4. *Exposure from eating locally grown produce*

Many Lincoln Park residents have orchards and gardens. Water from the DeWeese Dye Ditch is primarily used to irrigate the orchards and gardens, however, some residents use water from their groundwater wells [Galant 2007; IMS 1989]. If fruits and vegetables are grown in contaminated soil and/or irrigated with contaminated water, the people who eat this produce could be exposed to contamination.

5. *Exposure from breathing windborne dust*

Many Lincoln Park residents are concerned about the arid environment and the risks of breathing in contaminated dust from the site. The profile of air emission sources at Cotter Mill has changed considerably over the years. These sources include both releases through stacks and uncontrolled (or fugitive) dust emissions. Stack emissions occurred during times of active processing at Cotter Mill; however, the magnitude of these stack emissions has varied, depending on production rates and effectiveness of air pollution controls. The sources of fugitive dust emissions have also changed. In the past, the site had many uncontrolled sources of wind-blown dust, which would cause particulate matter (along with any chemical and radiological constituents) to be emitted into the air. Examples of these sources include ore handling operations, stockpiles, and the previous unlined holding ponds. Many of these sources of wind-blown dust have since been controlled or eliminated, causing facility-wide fugitive dust emissions to decrease considerably over the years, though some fugitive dust emissions (e.g., from unpaved roads) continue to occur.

Table 3. Exposure pathways for residents living near the Cotter Mill

Exposure Pathway	Exposure Pathway Elements					Time Frame	Comments
	Sources of Contamination	Fate and Transport	Point of Exposure	Exposed Population	Route of Exposure		
Groundwater							
Completed Exposure Pathway							
Private groundwater wells	Tailings and other wastes from the Cotter Mill (heavy metals and radionuclides)	Migration of groundwater into the Lincoln Park area	Residential tap water drawn from private wells	Residents, including children, who are not connected to the public water supply and rely on private wells	Ingestion, Dermal contact	Past	Past consumption of groundwater from private wells has been documented and was, therefore, a completed exposure pathway.
Potential Exposure Pathway							
Private groundwater wells	Tailings and other wastes from the Cotter Mill (heavy metals and radionuclides)	Migration of groundwater into the Lincoln Park area	Residential tap water drawn from private wells	Residents, including children, who are not connected to the public water supply and rely on private wells	Ingestion, Dermal contact	Current Future	The extent to which private wells are currently used in Lincoln Park is uncertain. Although most residents are supplied with town water, documents indicate that residents have been drinking private well water as recently as 2002, and are permitted to use wells for unspecified domestic purposes. However, it is believed that water from wells is used primarily for irrigation and other non-drinking purposes. Therefore, current and future use of water from private wells is a potential exposure pathway.

Exposure Pathway	Exposure Pathway Elements					Time Frame	Comments
	Sources of Contamination	Fate and Transport	Point of Exposure	Exposed Population	Route of Exposure		
Soil and Sediment							
Completed Exposure Pathway							
Surface soil and dust in Lincoln Park	Tailings, dusts, and other wastes from the Cotter Mill	Windblown dust; soil irrigated by contaminated groundwater	Residences and public areas	Residents, including children	Dermal contact, Incidental ingestion, Inhalation	Past	Prior to remediation, contaminants were detected in soil from residential lawns and gardens. Therefore, contact with contaminated soil in Lincoln Park was a past completed exposure pathway.
Potential Exposure Pathways							
Surface soil near the Cotter Mill	Tailings, dusts, and other wastes from the Cotter Mill	Windblown dust	The Shadow Hills Golf Course west of the Cotter Mill; along the county road leading to the Cotter Mill	Golfers at the public golf course; people on the county road	Dermal contact, Incidental ingestion, Inhalation	Past Current Future	Soils adjacent to the Cotter Mill have been contaminated by wind-blown particulates. Therefore, contact with soil near the Cotter Mill, especially at the public golf course and along the county road, is a past, current, and future potential exposure pathway.
Sediment in Sand Creek	Tailings, dusts, and other wastes from the Cotter Mill	Tailings carried in surface water runoff	Along Sand Creek	Recreational users; children playing along Sand Creek	Dermal contact, Incidental ingestion	Past	There were limited opportunities for exposure since Sand Creek was not used for recreational purposes. Therefore, exposure to sediments prior to the Sand Creek Cleanup project was a past potential exposure pathway.
Eliminated Exposure Pathways							
Surface soil at the Cotter Mill	Tailings, dusts, and other wastes from the Cotter Mill	Windblown dust; surface water runoff	Unauthorized access is not allowed	None	None	Past Current Future	Because the mill site itself is fenced and access is restricted, contact with on-site contamination is an eliminated exposure pathway. Further, remediation efforts have removed some impacted soils.

Exposure Pathway	Exposure Pathway Elements					Time Frame	Comments
	Sources of Contamination	Fate and Transport	Point of Exposure	Exposed Population	Route of Exposure		
Surface soil and dust in Lincoln Park	Tailings, dusts, and other wastes from the Cotter Mill	Windblown dust; soil irrigated with contaminated groundwater	Cleanup activities have eliminated or reduced risks to acceptable levels	None	None	Current Future	Due to the sampling and remediation in Lincoln Park, current and future contact with soil and dust is an eliminated exposure pathway.
Sediment in Sand Creek	Tailings, dusts, and other wastes from the Cotter Mill	Tailings carried in surface water runoff	Contaminated sediment was removed from Sand Creek	None	None	Current Future	Sediment in Sand Creek is no longer a hazard since the completion of the Sand Creek Cleanup project. Therefore, current and future contact with sediment in Sand Creek is an eliminated exposure pathway.
Surface Water							
Potential Exposure Pathway							
Surface water near the Cotter Mill	Tailings and other waste from the Cotter Mill	Surface water runoff; transport from Sand Creek to the Arkansas River	Along Sand Creek between the Cotter Mill and the Arkansas River; the DeWeese Dye Ditch; the Arkansas River	Recreational users (mostly in the Arkansas River, limited recreational use in Sand Creek); people irrigating with water from the DeWeese Dye Ditch	Incidental ingestion, Dermal contact	Past	In the past, surface water in Sand Creek was found to contain elevated levels of metals and radionuclides. Therefore, past contact with contaminated surface water near the Cotter Mill was a potential exposure pathway.
Eliminated Exposure Pathway							
Surface water near the Cotter Mill	Tailings and other waste from the Cotter Mill	Surface-water runoff; transport from Sand Creek to the Arkansas River	Contamination was removed from Sand Creek	None	None	Current Future	Due to the construction of the SCS Dam and the remediation of Sand Creek, current and future contact with contaminated surface water is an eliminated exposure pathway.

Exposure Pathway	Exposure Pathway Elements					Time Frame	Comments
	Sources of Contamination	Fate and Transport	Point of Exposure	Exposed Population	Route of Exposure		
Locally Grown Produce							
Potential Exposure Pathway							
Produce grown in Lincoln Park	Tailings, dusts, and other wastes from the Cotter Mill	Produce grown in contaminated soil or irrigated with contaminated water	Orchards and gardens in Lincoln Park	People who eat locally grown produce	Ingestion	Past Current Future	Because many Lincoln Park residents have orchards and gardens, eating locally grown produce is a past, current, and future potential exposure pathway.
Air Emissions							
Completed Exposure Pathway							
Ambient air near the Cotter Mill facility	Ground-level fugitive emissions (e.g., wind-blown dust) and elevated point sources (e.g., stacks)	Windblown dust; stack emissions into the air and transport to off-site locations	Off-site or down-wind locations	People who live in the vicinity of Cotter Mill or downwind of the stacks	Inhalation	Past Future Present	Cotter's air monitoring network monitors air concentrations at off-site locations. With the facility currently in "stand down" status, facility emissions are now predominantly fugitive; air quality impacts should be characterized by perimeter monitoring stations.

IV. EVALUATION OF ENVIRONMENTAL CONTAMINATION

A. Groundwater

Prior to 1980, Cotter disposed of waste in unlined ponds, which allowed contaminated liquids to leach into the groundwater [EPA 2002]. Groundwater was shown to be contaminated as far away as the Arkansas River, which is approximately 2.5 miles downgradient from the mill [EPA 2002]. Results from the 1984–1985 Remedial Investigation found that despite attempts at remediation, the new, lined impoundments were leaking and the old ponds area was a continuing source of groundwater contamination [GeoTrans 1986]. This study also found that a gap in the ridge at the SCS Dam, built in 1971 across Sand Creek on the Cotter property, was allowing shallow groundwater to move downgradient towards Lincoln Park, resulting in concentrations of molybdenum and uranium that were 2,000 times above background levels at that time.

Groundwater concentrations of molybdenum and uranium have decreased in recent years, but concentrations have not yet returned to background levels in some wells [Weston 1998]. Figures 4 and 5 show the extent of the molybdenum and uranium concentrations, respectively, above water quality standards (0.035 milligrams per liter [mg/L] for molybdenum and 0.03 mg/L for uranium). The highest levels in Lincoln Park were detected nearest to the Cotter property in the vicinity of the DeWeese Dye Ditch [Weston 1998]. Additionally, despite remediation efforts, the physical and chemical groundwater data suggest minor leakage from the primary impoundment at the Cotter site [CDPHE 2007a; EPA 2002; USGS 1999b].

1. Remedial actions for controlling groundwater contamination

Since the early- to mid-1980s, remedial actions aimed at controlling groundwater contamination and the spread of the resulting plume have taken place. Remediation has targeted the area along the primary surface groundwater migration pathway, which runs parallel to Sand Creek [USGS 1999a]. Remediation has included the following:

- In the early 1980s, contaminated materials were moved into lined impoundments [EPA 2002].

- In 1988, a hydrologic clay barrier was installed on the Cotter property to help contain the contaminated groundwater plume associated with the Cotter Mill.

- In 1989, a network of injection and withdrawal wells were constructed downgradient of the lined impoundment to reverse the hydraulic gradient and prevent the northward migration of contaminated groundwater. This system was discontinued in 2000, because the system had little or no discernable effect on groundwater conditions [CDPHE 2005].

- Dam to ditch flushing began in 1990. However, this effort was discontinued in 1996 due to citizens’ concerns about contaminant concentrations rising in groundwater wells as the plume was being flushed [CDPHE 2005].

- In 2000, a permeable reactive treatment wall was constructed across Sand Creek channel in the DeWeese Dye Ditch flush, downstream of the SCS Dam [EPA 2002]. Although the permeable reactive treatment wall has not performed as anticipated, it is acting as a barrier to additional groundwater flowing into Lincoln Park [Phil Egidi, CDPHE, personal communication, July 2008].

These efforts have reduced groundwater contamination downgradient of the Cotter Mill [CDPHE 2008; EPA 2002; USGS 1999a], although the rate at which groundwater quality is being restored is slower than anticipated [EPA 2007]. Cotter and CDPHE continue to explore options for cleaning the groundwater. Until a solution is reached, contaminated groundwater is captured at the SCS Dam and pumped back to the on-site lined impoundments [CDPHE 2008].

2. Nature and extent of groundwater contamination in Lincoln Park

CDPHE maintains a database containing environmental sampling data from various sources dating back to 1961. The most recent data entered into the database are from September 2007. To evaluate exposures to residents of Lincoln Park, ATSDR identified data within the CDPHE database for the wells reported to be in use during the 1989 water use survey (see Table 14 in Appendix A). After discussions with a CDPHE representative, the following assumptions were made while summarizing the data within the database.

- For chemicals, samples that were designated "Y" in the detect flag column and contained a zero in the result value column, but no value in the reporting detection limit column were excluded from the summary statistics. For radionuclides, however, these samples were included in the summary statistics since zero is considered a valid result.

- Samples that were designated "N" in the detect flag column and had the same value in the result value column as the reporting detection limit column were included in the summary statistics as ½ the reporting detection limit.

- Negative result values for manganese and iron were assumed to be not detected and were included in the summary statistics as ½ the reporting detection limit.

- Negative values[2] for radionuclides were included in the summary statistics.

a) Wells used for personal consumption

When this document was written, data from EPA's 2008 water use survey were not yet available. ATSDR will update well use information when the data are available.

The 1989 *Lincoln Park Water Use Survey* identified seven wells used for personal consumption (IMS 1989). Data for six of the wells are available in the CDPHE database (see Table 14). The seventh well had a broken pump at the time of the survey [IMS 1989]; no data for this well appear to be in the database. The data for wells reportedly used for personal consumption in 1989 are summarized in Table 15. Samples were collected intermittently from 1984 to 2007. The locations of these wells are shown in Figure 6. With the exception of molybdenum and uranium, the data are limited (e.g., only two wells were sampled for the majority of the chemicals and none were sampled for radionuclides).

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[2] Negative values for radionuclides occur when samples are not much different from background, since standard protocol is to subtract background radioactivity from the sample count.

However, all six wells were repeatedly tested for molybdenum and uranium, which were the only chemicals detected above comparison values (see Table 15). Of the personal consumption wells, Well 189 contains the highest molybdenum and uranium concentrations. Well 189 is the only well with levels of uranium consistently detected above the comparison value (see Figure 6).

It is difficult to evaluate the molybdenum and uranium data over time, because of the limited sampling data for these wells and the inconsistency of sampling the same wells over time. The molybdenum and uranium concentrations in the personal consumption wells over time are graphically shown in Figure 7 and Figure 8 in Appendix B, respectively. Well 168 (house well on Grand Avenue)[3] and Well 189 (house well on Hickory)[4] were sampled the most frequently. No clear pattern of decreasing concentrations from 1984 to 2007 exists.

The USGS identified Well 10 (So. 12th St.) and Well 114 (Pine) as representative of background for the Lincoln Park area [Weston 1998]. The data available in the CDPHE database for these two wells are summarized in Table 16.[5] The average concentration of molybdenum in the wells used for personal consumption (0.082 mg/L; see Table 15) is higher than the average concentration found in the background wells (0.023 mg/L; see Table 16). The average uranium concentration in the wells used for personal consumption (0.028 mg/L; see Table 15) is only slightly higher than the average concentration in the background wells (0.021 mg/L; see Table 16).

(1) Grand Avenue Well

In a 2002 newspaper article, a resident on Grand Avenue reported drinking water from their well [Plasket 2002]. Limited data (1 to 20 samples) are available in the CDPHE database for this location (see Figure 6). Samples were collected and analyzed for most chemicals in 1984, and then from either 2004 or 2005 to 2007. Samples from this well were also tested for molybdenum and uranium from 1988 to1991. The water from this well was tested for several chemicals, but not for radionuclides. None of the samples detected chemicals above comparison values (see Table 17).

b) Wells used to irrigate fruit and vegetable gardens

When this document was written, data from EPA’s 2008 water use survey were not yet available. ATSDR will update well use information when the data are available.

The 1989 *Lincoln Park Water Use Survey* identified 22 wells used to irrigate fruit and 21 wells used to irrigate vegetable gardens [IMS 1989].[6] Data for 28 of these wells are available in the CDPHE database (see Table 14). Samples were sporadically collected from these wells and analyzed for various chemicals between 1962 and 2007. Samples were collected and analyzed for radionuclides from

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[3] There are five non-detected molybdenum values for Well 168. Four of them are most likely due to the detection limit being too high for the level of molybdenum in that well. The detection limits were 0.01 mg/L for three of the samples and 0.05 mg/L for one of the samples. The concentrations in that well hover around 0.01 mg/L.

[4] One of the non-detected molybdenum concentrations in Well 189 is unexplainable. The detection limit (0.01 mg/L) is low enough to have detected the level of molybdenum typically found in the well. The detection limit (0.5 mg/L) for the other non-detected concentration is too high for the level of molybdenum typically found in the well.

[5] Groundwater samples from the background wells were not tested for radionuclides.

[6] Some wells were used for both purposes.

1995 to 2000. The data for wells reportedly used to irrigate fruit and vegetable gardens in 1989 are summarized in Table 18 (chemicals) and Table 19 (radionuclides). The locations of these wells are shown in Figure 9. The data for these wells are much more robust than the data available for the wells used for personal consumption, in part due to the increased number of wells. Molybdenum and uranium were sampled in all 28 wells used for irrigation. Five wells were tested for radionuclides.

The maximum concentrations in the wells used to irrigate fruit and vegetable gardens exceeded the comparison values for molybdenum, selenium, sulfate, total dissolved solids, and uranium. The average concentrations exceeded comparison values only for molybdenum, total dissolved solids, and uranium. Looking at data from 2000 to 2007, only the average molybdenum concentration (0.1 mg/L) continued to exceed the comparison value.

The average concentration of molybdenum in the wells used to irrigate fruit and vegetable gardens (0.99 mg/L; see Table 18) is higher than the average concentration found in the wells that USGS identified as background for Lincoln Park (0.023 mg/L; see Table 16). Similarly, the average uranium concentration in the wells used to irrigate fruit and vegetable gardens (0.13 mg/L; see Table 13) is higher than the average concentration in the background wells (0.021 mg/L; see Table 16). The average concentration for total dissolved solids in the wells used to irrigate fruit and vegetable gardens (550 mg/L; see Table 18) is also higher than the average concentration found in the background wells (429 mg/L; see Table 16).

c) Wells used to water livestock

The 1989 *Lincoln Park Water Use Survey* identified 22 wells used to water livestock [IMS 1989]. Data for 19 of these wells are available in the CDPHE database (see Table 14). Samples were sporadically collected from these wells and analyzed for various chemicals between 1962 and 2007. Samples were collected and analyzed for radionuclides from 1995 and 1996. The data for wells reportedly used to water livestock in 1989 are summarized in Table 20 (chemicals) and Table 21 (radionuclides). The locations of these wells are shown in Figure 10. Only one to four wells were sampled for the majority of the chemicals, however, molybdenum and uranium were sampled in all 19 wells used to water livestock. Two wells were tested for radionuclides.

When this document was written, data from EPA’s 2008 water use survey were not yet available. ATSDR will update well use information when the data are available

The maximum concentrations exceeded the comparison values for molybdenum, sulfate, total dissolved solids, and uranium. The average concentrations only exceeded comparison values for molybdenum and uranium. Looking at data from 2000 to 2007, only the average molybdenum concentration (0.08 mg/L) continued to exceed the comparison value.

The average concentration of molybdenum in the wells used to water livestock (0.212 mg/L; see Table 20) is an order of magnitude higher than the average concentration found in the wells that USGS identified as background for Lincoln Park (0.023 mg/L; see Table 16). The average uranium concentration in the wells used to water livestock (0.034 mg/L; see Table 20) is higher than the average concentration in the background wells (0.021 mg/L; see Table 16).

d) *Wells used to water lawns*

When this document was written, data from EPA's 2008 water use survey were not yet available. ATSDR will update well use information when the data are available.

The 1989 *Lincoln Park Water Use Survey* identified 42 wells used to water lawns [IMS 1989]. Data for all 42 wells are available in the CDPHE database (see Table 14). Samples were sporadically collected from these wells and analyzed for various chemicals between 1962 and 2007. Samples were collected and analyzed for radionuclides from 1995 to 2000. The data for wells reportedly used to water lawns in 1989 are summarized in Table 22 (chemicals) and Table 23 (radionuclides). The locations of these wells are shown in Figure 11. Several wells were sampled for each chemical, and molybdenum and uranium were tested in all 42 wells used to water lawns. Seven wells were sampled for radionuclides.

The maximum concentrations exceeded the comparison values for chloride, molybdenum, selenium, sulfate, total dissolved solids, and uranium. The average concentrations exceeded comparison values for molybdenum, sulfate, total dissolved solids, and uranium. Looking at data from 2000 to 2007, only the average molybdenum concentration (0.1 mg/L) continued to exceed the comparison value from 2000 to 2007, while the average uranium concentration (0.03 mg/L) was at the comparison value.

The average concentration of molybdenum in wells used to water lawns (2.2 mg/L; see Table 22) is two orders of magnitude higher than the average concentration found in the wells that USGS identified as background for Lincoln Park (0.023 mg/L; see Table 16). The average sulfate concentration in wells used to water lawns (351 mg/L; see Table 22) is almost six times higher than the average concentration in the background wells (61 mg/L; see Table 16). The average concentration for total dissolved solids in wells used to water lawns (746 mg/L; see Table 22) is higher than the average concentration found in the background wells (429 mg/L; see Table 16). The average dissolved uranium concentration in wells used to water lawns (0.233 mg/L; see Table 22) is an order of magnitude higher than the average concentration in the background wells (0.021 mg/L; see Table 16).

(1) <u>Well 138</u>

Well 138 (field well on Cedar Street; see Figure 11) was identified during the *1998 Supplemental Human Health Risk Assessment* as the maximally impacted off-site well [Weston 1998]. In 1989, Well 138 was used only to water the lawn [IMS 1989]. Adequate data for this well are available in the CDPHE database. Samples were collected from Well 138 and analyzed for various chemicals between 1968 and 2000. Samples were collected and analyzed for radionuclides from 1995 to 2000. The data for Well 138 are summarized in Table 24 (chemicals) and Table 25 (radionuclides).

The maximum concentrations exceeded the comparison values for chloride, molybdenum, selenium, sulfate, total dissolved solids, and uranium. The average concentrations also exceeded comparison values for molybdenum, sulfate, total dissolved solids, and uranium. A clear decrease in concentrations occurred over time for molybdenum (see Figure 12), selenium (see Figure 13), and uranium (see Figure 14).

Well 138 has higher levels of contamination than the wells that USGS identified as background for Lincoln Park. The average concentration of molybdenum in Well 138 (8.0 mg/L; see Table 244) is hundreds of times higher than the average concentration found in the background wells (0.023 mg/L; see Table 16). The average sulfate concentration in Well 138 (1,059 mg/L; see Table 24) is considerably higher than the average concentration in the background wells (61 mg/L; see Table 16). The average concentration for total dissolved solids in Well 138 (1,530 mg/L; see Table 24) is three times higher than the average concentration found in the background wells (429 mg/L; see Table 16). The average dissolved uranium concentration in Well 138 (0.73 mg/L; see Table 24) is more than an order of magnitude higher than the average concentration in the background wells (0.021 mg/L; see Table 16).

e) Groundwater trends over time

To evaluate the levels of molybdenum, selenium, and uranium in groundwater over time, ATSDR combined and graphed all the groundwater data for the wells used for personal consumption, irrigating fruit and vegetables, watering livestock, and watering lawns (Figures 15 through 17 in Appendix B). Figure 15 shows a pattern of decreasing concentrations of molybdenum in groundwater over time. The concentrations of selenium seem to hold steady, but do decrease slightly over time (see Figure 16). The concentrations of uranium also clearly decrease over time (see Figure 17).

B. Soil and sediment

1. Background levels

Cotter was required by the 1988 RAP to establish background levels of certain elements in soils and sediments. Twenty soil samples were collected from five sub-basins considered free from mill-related contamination to represent natural background typical of the area near the mill [HRAP 1991]. Table 4 below presents the results of that study, which were further supported by additional sampling [CDPHE 2005].

Table 4. Background soil and sediment levels

	Soil		Sediment	
	Average	**Upper Confidence Limit**	**Average**	**Upper Confidence Limit**
Molybdenum	2.4 ppm	4.6 ppm	2.3 ppm	4.7 ppm
Uranium	2.1 ppm	2.9 ppm	2.0 ppm	3.4 ppm
Radium-226	1.3 pCi/g	1.9 pCi/g	1.1 pCi/g	1.7 pCi/g
Thorium-230	1.8 pCi/g	3.2 pCi/g	1.5 pCi/g	3.1 pCi/g
Gamma Exposure Rates	9.4 µR/hr	--	--	--

Source: CDPHE 2005; HRAP 1991
pCi/g – picocuries per gram
ppm – parts per million
µR/hr – microroentgen per hour

2. *Off-site soil contamination and remediation*

As part of the 1988 RAP, Cotter was required to survey soils outside the restricted area (the fenced active mill site) and to remediate contaminated soils with levels of radium and molybdenum that are above the established background [CDPHE 2005].

As part of the *1998 Supplemental Human Health Risk Assessment* [Weston 1998], Weston (a contractor for Cotter) collected surface soil samples (0-2 inches) from eight zones around the mill property (see Figure 18 in Appendix B). Each zone was divided into 8 to 12 grids. Four samples were collected near the center of each grid and were composited (i.e., combined and homogenized) to form a single representative sample [Weston 1998]. The results of this sampling are shown in Table 26 (chemicals) and Table 27 (radionuclides). The maximum concentrations exceeded the comparison values for arsenic[7] in all eight zones, for cadmium in all zones except one (D), for lead in three zones (F, G, and H), and for radium-226 in four zones (A, B, C, and E). The average concentrations also exceeded comparison values for arsenic[7] in all eight zones, for cadmium in one zone (F), for lead in one zone (H), and for radium-226 in two zones (A and B). The average radium-226 and thorium-230 concentrations were higher than the established average background levels in all eight zones (see 4 for background).

There is limited potential for exposure to contaminants along the access road since access to the Cotter Mill is restricted and soils along the access road were remediated in 2007 and 2008.

Cotter has occasionally hauled ore and other materials by truck to the site for processing at their facility. To assess the potential that material has been lost alongside the county road leading to the mill and the access road entering the mill site, MFG (a contractor to Cotter) scanned the county road (assuming CR 143) from the road leading to the Shadow Hills Golf Course to the Cotter Mill access road for gamma radiation (see Figure 19). They also collected soil samples to establish a correlation between the gamma exposure rate and the concentration of gamma emitters in the soil. A total of 16 locations were sampled—five along the county road, five along the mill's access road, and six from background locations. The locations were not chosen to estimate an average concentration, but rather to provide data for a range of gamma exposure rates. Each sample was a composite of 10 aliquots within a 100 x 100 meter area [MFG 2005]. The results of this sampling are shown in Table 28. The maximum and average radium-226 and natural uranium concentrations exceeded the comparison values for samples taken along the mill's access road. The maximum and average radium-226 concentrations also exceeded the comparison value for samples taken along the county road. Average concentrations of all radionuclides sampled were higher along the county road and the mill's access road than from those areas designated as background (see Table 28).

To address public concerns about the impact of the Cotter Mill on the health of Cañon City residents, CDPHE collected 21 soil samples in January 2003 [CDPHE 2003]. Each sample was a composite of 30–40 scrape samples[8] from each location. Seven samples from Lincoln Park were

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[7] The *1998 Supplemental Human Health Risk Assessment* found no discernible spatial pattern for arsenic around the Cotter Mill, indicating that arsenic levels have not been measurably altered by airborne releases from the mill (Weston 1998).

[8] Surface soil samples were collected using a method developed specifically to look for airborne contamination that settled to the ground (CDPHE 2003).

collected, including one sample of suspected flood sediment (Pine Street near Elm Avenue), two samples of dust (one from a barn loft and one from a residential attic), and four samples of surface soil (one from the McKinley Elementary School playground). Seven samples were collected from areas east of the mill, including the Brookside Head Start School. Six samples were collected from areas west of the mill, including a private residence. One sample was collected from the extreme northern part of Cañon City to represent the regional background (corner of Orchard Avenue and High Street). The sampling event was intentionally biased toward finding the highest amounts of contamination possible [CDPHE 2003]. Sample locations are shown in Figure 20. The data from this sampling event are summarized in Table 29 (chemicals) and Table 30 (radionuclides). The maximum concentrations for lead and radium-226 exceeded the comparison values. The average concentration for lead also exceeded the comparison value. The average concentration for radium-226 did not exceed the comparison value.

Since 1994, Cotter has been annually collecting surface soil samples (0–6 inches) at 10 environmental air monitoring stations that are located along the facility’s boundary and in residential areas (see Figure 21). From 1979 to 1993, soils were collected every 9 months. The data from this effort are summarized in Table 31. The maximum concentration for radium-226 exceeded the comparison value; however, the average concentration of samples over the timeframe did not.

a) The nearest resident

The nearest resident is located 0.25 mile from the restricted area [Galant et al. 2007]. One of the air monitoring stations annually monitored by Cotter was established as “the nearest resident” (AS-212). This location is between the Cotter Mill and an actual residence [Cotter 2007]. The limited data for this location are shown in Table 32 (chemicals) and Table 33 (radionuclides). The maximum concentration for radium-226 exceeded the comparison value; however, the average concentration did not.

b) Lincoln Park

As part of the 1988 RAP, Cotter was required to conduct a gamma scintillometer survey in Lincoln Park to evaluate whether soils had been contaminated by windblown and waterborne contaminants from the facility. In December 1988, 127 scintillometer readings were taken near intersections in Lincoln Park. The average external gamma radiation for Lincoln Park was 9.8 microroentgen per hour (µR/hr), which is considered to show “no elevated gamma in Lincoln Park” [CDPHE 2005; HRAP 1991].

EPA determined that sediment and soil in Lincoln Park are no longer an issue since the completion of the Sand Creek Cleanup project in 1998 [EPA 2002, 2007].

As part of the *1996 Supplemental Human Health Risk Assessment* [Weston 1996], Weston compiled data from several past soil studies, including the following:

- Samples collected at the air monitoring location in Lincoln Park in 1987 and 1988

- Samples collected from yards of 10 participants in the Lincoln Park water use survey in 1989
- Samples collected from residential gardens in Lincoln Park in 1990
- Samples collected from lawns and gardens in Lincoln Park in 1996

The data from these studies are collectively summarized in Table 34 (chemicals) and Table 35 (radionuclides). Only the maximum and average concentrations for arsenic exceeded the comparison value.

The soil samples collected from yards of the participants in the 1989 *Lincoln Park water use survey* were also analyzed for molybdenum and uranium. The average molybdenum concentration was 2.0 ppm and the average uranium concentration was 2.8 ppm [HRAP 1991]. The samples collected as part of the 1990 residential garden soil survey were also analyzed for molybdenum. The average concentration was 0.13 ppm [HRAP 1991]. These concentrations are well below the comparison values for molybdenum (300 ppm) and uranium (100 ppm).[9]

As part of the *1998 Supplemental Human Health Risk Assessment* [Weston 1998], 73 surface soil samples were collected from lawns (0–2 inches) and gardens (0–6 inches) in Lincoln Park. For sampling purposes, Lincoln Park was divided into seven areas and 6–16 samples were taken from each area [Weston 1998]. The results of this sampling are shown in Table 26 (chemicals) and Table 27 (radionuclides). Only the maximum and average arsenic concentrations exceeded the comparison value.

The effect of irrigation with contaminated well water on the levels in the soil was also examined during the *1998 Supplemental Human Health Risk Assessment* [Weston 1998]. The soil samples from Lincoln Park were divided into two categories—those irrigated with well water that had been impacted by mill releases and those not believed to have been irrigated with contaminated well water. These data are shown in Table 36 (chemicals) and Table 37 (radionuclides). The concentrations of arsenic, molybdenum, and uranium were statistically higher in soil samples irrigated with impacted well water [Weston 1998].

(1) Lead in Lincoln Park

Residents of Lincoln Park expressed concerns about lead contamination in soil and dust due to historical and current mining and milling operations in the area. Six potential sources of lead are located near the community of Lincoln Park—the Cotter Mill, the Empire Zinc Smelter (also known as New Jersey Zinc and the College of the Cañons), the US Smelter Facility, the Cañon City Copper Smelter, the Ohio Zinc Company, and the Royal Gorge Smelter [EPA 2004]. The Lincoln Park neighborhood is located generally east-southeast of these facilities and the general wind direction is west to east.

To address the residents' concerns, EPA requested that ATSDR assess the health risk associated with lead contamination in Lincoln Park. After a site visit and discussions with the community,

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[9] The data for molybdenum and uranium are not summarized in Table because the raw data for these two chemicals are not presented in the *1996 Supplemental Human Health Risk Assessment* (Weston 1996).

ATSDR focused assessments on two primary issues—1) blood lead levels in children living in Lincoln Park and 2) lead contaminated dust in homes in Lincoln Park.

ATSDR reviewed the available data on blood lead levels in children and concluded that the rate of elevated blood lead levels for Fremont County is below the state average. However, it was not possible to evaluate whether area children, including "high risk" children, were being adequately screened for blood lead levels [ATSDR 2006a]. To further assess blood lead levels, ATSDR tested the blood level of 115 "at risk" school children in 2005. None of the children had elevated blood lead levels [ATSDR 2006b].

ATSDR reviewed the available data on lead levels in household dust and found the data to be sparse and/or lacking. ATSDR conducted a screening level evaluation of the available dust samples and concluded that the data were not sufficient to determine the magnitude or extent of the potential hazard associated with levels of lead in household dust [ATSDR 2006c]. To further assess the health impacts in Lincoln Park, ATSDR, in collaboration with the Colorado Citizens Against Toxic Waste (CCAT) and EPA, collected and analyzed 44 indoor dust samples, 80 surface soil samples (0–2 inches or 0–6 inches) from 22 properties, and 45 blood samples. The results of this exposure investigation did not indicate the presence of unusual levels of lead in residential indoor dust samples, the soil at those homes, or in the blood of occupants of those homes [ATSDR 2006d].

EPA's report documenting the residential soils sampling project can be accessed at the following site: http://www.epa.gov/region8/superfund/co/lincolnpark/.

c) Sand Creek

Sand Creek is primarily an ephemeral creek that passes through the Cotter Mill and runs north-northeast through Lincoln Park. It becomes perennial for the last 0.25–0.5 mile before its confluence with the Arkansas River. Prior to the construction of the SCS Dam north of the Cotter Mill in 1971, surface water and sediment from the facility flowed down the Sand Creek drainage into Lincoln Park [CDPHE 2005; GeoTrans 1986]. Mill tailings in the Old Tailings Pond Area are the source of the mill-derived contaminants (primarily radium-226 and thorium-230) in Sand Creek [Cotter 2000].

During the *1986 Remedial Investigation* [GeoTrans 1986], sediment samples were collected from the following locations in Sand Creek to evaluate present (i.e., 1985) and historical loadings from the Cotter Mill.

- SD01 – mouth near the Arkansas River
- SD02 – near spring where flow begins (reflects migration of contaminants in the groundwater)
- SD04 – below the SCS Dam in
  (1) an abandoned stock watering pond (formed by diversion of runoff water into a depression adjacent to Sand Creek)
  (2) in drainage (reflects historical picture of uncontrolled emissions)
  (3) in drainage above #2 (reflects historical picture of uncontrolled emissions)

- SD05 – above the SCS Dam adjacent to the west property edge

The results of this sampling are presented in Table 38 and Table 39. Only the concentrations for arsenic and radium-226 exceeded ATSDR's comparison values.

As part of the 1988 RAP, Cotter was required to evaluate the mill's potential impacts to Sand Creek and remove sediments that exceeded the radium-226 cleanup goal of 4.0 picocuries per gram (pCi/g), which allows unrestricted use of the creek [Cotter 2000]. A total of 721 samples were systematically collected along the 1.25 mile stretch from just north of the Cotter Mill to where Sand Creek becomes perennial (see Figure 22). Surveying and cleanup began in the spring of 1993 and continued until remediation was completed in December 1998. Approximately 9,000 cubic yards of soil were removed from Sand Creek and disposed of on Cotter property [Cotter 2000]. The excavated areas were backfilled with clean soil [CDPHE 2005]. Thirty confirmatory samples established that the average site-wide radium-226 concentration was 1.5 pCi/g (below the cleanup goal of 4.0 pCi/g) and the average site-wide thorium-230 concentration was 3.9 pCi/g after remediation [Cotter 2000]. In addition to the sampling and remediation for radium-226, seven of the confirmation samples were analyzed for 10 chemicals in 1998 [Cotter 2000]. These results are presented in Table 40. Only the maximum and average concentrations for arsenic exceeded ATSDR's comparison value.

At the time of mill closure, Cotter was required by the 1988 RAP to survey molybdenum and radium-226 in sediments in the perennial stream segments of Sand Creek and Willow (Plum) Creek to determine whether these areas have been impacted by the mill. If necessary, sediments above background will be removed and properly disposed of (CDPHE 2005).

d) The Fremont Ditch

The Fremont Ditch system is downstream of Sand Creek. It diverts water from near the confluence of Sand Creek and the Arkansas River downgradient toward Florence. The ditch receives substantial amounts of water from Sand Creek during low flows in the Arkansas River. During these periods, any contaminants moving down Sand Creek would likely be transported to Fremont Ditch [GeoTrans 1986].

As part of the 1988 RAP, Cotter was also required to conduct a gamma survey of the dry beds of the Fremont Ditch. Cotter sampled sediment in Fremont Ditch from its head gate near Sand Creek to about a quarter mile downstream. The average radium-226 level was 1.86 pCi/g, which was below the cleanup standard of 4 pCi/g. The state agreed with Cotter that the Fremont Ditch did not require remediation because the concentrations of gross alpha (3.8 pCi/g), uranium (6.6 ppm), and molybdenum (2.2 ppm) were also low [CDPHE 2005].

C. Surface water

1. Nature and extent of contamination

The Cotter Mill is a non-discharge facility, meaning that Cotter does not release wastewater to the surface water system. All remediation water is pumped to on-site impoundments for evaporation or recycling. However, prior to construction of the SCS Dam in 1971, storm events carried contaminated surface water and sediments from the facility down the Sand Creek drainage [CDPHE 2005]. One event in particular, a flood in June 1965, caused the unlined tailings ponds at the Cotter Mill to overflow into Lincoln Park. Sediment in the Lincoln Park portion of Sand Creek was contaminated with tailings that were carried in surface water runoff from the mill [EPA 2007].

CDPHE maintains a database containing surface water monitoring data dating back to 1962. The most recent data entered into the database are from September 2007. To evaluate exposures to people living near the Cotter Mill, ATSDR extracted surface water data collected from Sand Creek, the DeWeese Dye Ditch, and the Arkansas River. After discussions with a CDPHE representative, the following assumptions were made while summarizing data within the database.

The SCS Dam was built to prevent surface water and sediment from flowing into Lincoln Park during storm-generated floods. Since the construction of the dam, Lincoln Park no longer receives runoff from the Cotter Mill. Additionally, since 1979, impounded water collected at the dam has been pumped back to the lined impoundment on site [EPA 2002; GeoTrans 1986; HRAP 1991].

- Samples that were designated “N” in the detect flag column and had the same value in the result value column as the reporting detection limit column were included in the summary statistics as ½ the reporting detection limit.

- Negative result values for manganese and iron were assumed to be not detected and were included in the summary statistics as ½ the reporting detection limit.

- Negative values[10] for radionuclides were included in the summary statistics.

a) Sand Creek

From 1993 to 1998, Cotter conducted the Sand Creek Cleanup project to identify and remove mill tailings that had moved into the creek bed as the result of surface water runoff from the Cotter Mill prior to the construction of the SCS Dam. Sediments above the radium-226 cleanup goal of 4.0 pCi/g were removed, which allows unrestricted use of the creek [Cotter 2000; EPA 2002].

Two locations in Sand Creek—one at Ash Street (008) and one at the confluence with the Arkansas River (506)—are sampled as part of the surface water monitoring program (Cotter 2007). The CDPHE database contains surface water monitoring data from these two locations, which are summarized in Table 41 (chemicals) and Table 42 (radionuclides). The maximum concentrations for manganese, molybdenum, sulfate, and total dissolved solids exceeded the comparison values. However, for all four of these chemicals, only the maximum concentrations exceeded comparison values—the second highest detected concentrations were below comparison values. None of the average concentrations exceeded comparison values.

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[10] Negative values for radionuclides occur when samples are not much different from background, since standard protocol is to subtract background radioactivity from the sample count.

As part of the *1991 Health Risk Assessment of the Cotter Uranium Mill Site* [HRAP 1991], the Health Risk Assessment Panel (HRAP) reviewed over 18,000 samples collected from 1976–1989, from 55 different surface water locations. More than 95% of the surface water data were collected from 10 main locations. The location in Sand Creek at Ash Street (008, formerly known as 555) was one of these locations. The average molybdenum (0.009 mg/L) and uranium (0.016 mg/L) concentrations from this location were well below the comparison values (molybdenum: 0.035 mg/L; uranium: 0.03 mg/L).[11]

b) DeWeese Dye Ditch

The DeWeese Dye Ditch is an irrigation ditch that flows between the Cotter Mill and Lincoln Park. The ditch diverts water from Grape Creek to irrigate about 1,200 acres during the summer growing period [GeoTrans 1986]. The ditch crosses Sand Creek downstream from the SCS Dam, but does not join it. Seepage from the ditch recharges groundwater within the Sand Creek drainage. This process dilutes and flushes the contaminated groundwater under Lincoln Park [EPA 2002].

The CDPHE database contains surface water monitoring data from two locations in the DeWeese Dye Ditch—one upstream of the confluence with Forked Gulch (520) and one at Cedar Avenue (526). The location at Cedar Avenue is sampled as part of the surface water monitoring program [Cotter 2007]. The data for both locations are summarized in Table 43 (chemicals) and Table 44 (radionuclides). The maximum concentrations exceeded the comparison values for iron, manganese, total dissolved solids, and dissolved uranium. However, for iron and manganese, only the maximum concentrations exceeded comparison values—the second highest detected concentrations were below comparison values. Only three of the total dissolved solids samples and three of the dissolved uranium samples were detected above comparison values. None of the average concentrations exceeded comparison values.

Molybdenum and uranium data from 1984 to 1989, from the same two locations in the DeWeese Dye Ditch (520 and 526), are summarized in the *1991 Health Risk Assessment of the Cotter Uranium Mill Site* (HRAP 1991). The average molybdenum and uranium concentrations were well below the comparison values (see Table 5 below).

Table 5. Average molybdenum and uranium concentrations in the DeWeese Dye Ditch

Chemical	Average concentration at Location 520 (mg/L)	Average concentration at Location 526 (mg/L)	Comparison Value (mg/L)
Molybdenum	0.003	0.003	0.035
Uranium	0.002	0.0019	0.03

Source: HRAP 1991

Molybdenum data that were several orders of magnitude greater than any other observed sample (i.e., outliers) were not used to calculate the average concentrations (HRAP 1991).

It was not possible to determine whether these data are included in the CDPHE database.

c) Arkansas River

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[11] It was not possible to determine whether these data are included in the CDPHE database.

The Arkansas River sampling plan was approved by the CDPHE Water Quality Control Division [CDPHE 2005].

From April 1989 to June 1990, Cotter and their consultant, Western Environmental Analysts, conducted bi-weekly sampling in the Arkansas River at the following five locations:

1. Parkdale (background)
2. Grape Creek
3. 1st Street (upstream of where Sand Creek enters the Arkansas River)
4. Mackenzie Avenue Bridge (downstream from where Sand Creek enters the Arkansas River)
5. Where Highway 67 to Florence crosses the river

Water, sediment, autotrophs (algae), primary consumers/detrivores (tadpoles, macroinvertebrates), and carnivores (fish) were collected and tested for molybdenum, uranium, radium-226, and thorium-230. Extremely low concentrations were detected, which indicated no statistical evidence of an increase in contamination downstream on the Arkansas River [CDPHE 2005].

In addition, four synoptic sampling events (i.e., sampling of water in-flows) were conducted between Canyon Mouth and Highway 67. The purpose of the synoptic sampling was to determine whether tributary flows reflect unusual sources of uranium or molybdenum. The sampling showed that other sources such as Fourmile Creek, as well as Sand Creek and Plum Creek, contribute to increases in the Arkansas River [CDPHE 2005].

Two locations in the Arkansas River—one upstream of Sand Creek at 1st Street (907) and one downstream of Sand Creek at Mackenzie Avenue (904)—are sampled as part of the surface water monitoring program [Cotter 2007]. The CDPHE database contains surface water monitoring data from these two locations, which are summarized in Table 45 (chemicals) and Table 46 (radionuclides). At both locations, the maximum concentrations exceeded the comparison value for sulfate. The maximum concentration for total dissolved solids exceeded the comparison value for the upstream location, but not the downstream location. In all three instances, these maximum concentrations appear to be outliers and are the only concentrations that exceeded comparison values—the second highest detected concentrations were below comparison values. The maximum concentration for molybdenum also exceeded the Colorado state groundwater standard for the upstream location, but not the downstream location. None of the average concentrations exceeded comparison values.

Data from 1984 to 1989, from two locations in the Arkansas River—one upstream of Sand Creek near Grape Creek (502) and one downstream of Sand Creek near Fourmile Bridge (504)—are summarized in the *1991 Health Risk Assessment of the Cotter Uranium Mill Site* [HRAP 1991]. The average molybdenum and uranium concentrations were well below the comparison values (see Table 6 below).

Table 6. Average molybdenum and uranium concentrations in the Arkansas River

Chemical	Average concentration upstream of Sand Creek near Grape Creek (502) (mg/L)	Average concentration downstream of Sand Creek near Fourmile Bridge (504) (mg/L)	Comparison Value (mg/L)
Molybdenum	0.00391	0.0056	0.035
Uranium	0.00532	0.00574	0.03

Source: HRAP 1991

Molybdenum data that were several orders of magnitude greater than any other observed sample (i.e., outliers) were not used to calculate the average concentrations (HRAP 1991).

d) Willow Lakes

The Willow Lakes are comprised of several small ponds near the Arkansas River in the Willow Creek watershed, which lies directly to the east of the Sand Creek watershed. The Willow Lakes receive water from shallow groundwater and surface runoff [HRAP 1991].

Cotter was required by the 1988 RAP to evaluate whether the Willow Lakes had been contaminated by the mill. Water, sediment, autotrophs (algae), primary consumers/detrivores (tadpoles, macroinvertebrates), and carnivores (fish) from the Willow Lakes and three comparison lakes were collected and tested for molybdenum, uranium, and radium. The information showed that the Willow Lakes had not been contaminated by the Cotter Mill [CDPHE 2005].

D. Locally grown produce

1. Nature and extent of contamination

As part of the *1996 Supplemental Human Health Risk Assessment* (Weston 1996), Weston compiled available food data from several past studies. Samples included chicken meat, fruit (apples, cherries, grapes), and vegetables (asparagus, carrots, lettuce, tomatoes, turnips). The local samples were compared to food collected from supermarkets. The data are presented in Table 47 and Table 48 in Appendix A. The limited sample data suggest that the chemicals and radionuclides found in the foods are probably natural in origin, however, it was not possible to exclude the possibility that some food types may be influenced by mill-related contaminants [Weston 1996].

To further evaluate exposures to residents who eat locally grown fruits and vegetables, a sampling program was initiated in Lincoln Park during the *1998 Supplemental Human Health Risk Assessment* [Weston 1998]. People were asked to donate locally grown produce samples for analysis. The fruits and vegetables sampled are presented in the table below. The samples were tested for heavy metals and radionuclides. The analytical results of the sampling program are summarized in Table 49 and Table 50 in Appendix A.

Fruits Sampled

Apples
Cantaloupe
Grapes
Honey dew melon
Plums
Watermelon

Vegetables Sampled

Acorn squash
Beets
Carrots
Celery
Corn
Cucumbers
Green Beans
Green Onions
Kohlrabi
Patty pan squash
Peppers
Pumpkin
Rhubarb
Squash
Tomatoes
Turnip Greens
Turnips
Winter squash

The samples were divided into two categories—(1) produce that was grown in soil known to have been irrigated with contaminated well water (fruits n = 16; vegetables n = 43) and (2) produce that was grown in soil not believed to have been irrigated with contaminated well water (fruits n = 1; vegetables n = 6). A statistical comparison of the data for the two categories of vegetables indicated that irrigation with contaminated well water did not cause a significant increase in contaminant levels (Weston 1998). The following trends were also noted:

- The concentrations of most metals were higher in root vegetables than other types of vegetables and fruit.
- Concentrations were much lower in peeled turnips than in whole turnips, suggesting that most of the contamination was on or in the surface layer.
- There was high variability both within and between the different types of produce.
- Concentration values were below the limit of detection for many of the samples.

E. Ambient Air

ATSDR reviewed ambient air monitoring data and air sampling data collected from the following two sources:

- Cotter Mill has operated an ambient air monitoring program to characterize air quality impacts of radioactive particulates and radon for more than 20 years. ATSDR accessed summaries of the monitoring data from Cotter Mill's annual Environmental and Occupational Performance Reports, which are posted to the CDPHE's web site; and
- The state of Colorado operated three particulate monitoring stations in Fremont County, one each in Lincoln Park, Cañon City, and Florence. The station in Cañon City continues to operate today. ATSDR downloaded measured concentrations of particulate matter, and some chemical constituents of particulate matter, from EPA's Air Quality System (AQS) database—a publicly accessible online clearinghouse of ambient air monitoring data. Some of the measurements collected by these monitors date back 40 years.

Historically, Cotter Mill had two general types of air emission sources: ground-level fugitive emissions (e.g., wind-blown dust) that would be expected to have greatest air quality impacts nearest the source; and elevated point sources (e.g., stacks) that have the potential for having peak ground-level impacts at downwind locations. With the facility currently in "stand down" status, facility emissions are now predominantly fugitive and their air quality impacts should be adequately characterized by the perimeter monitoring stations.

1. Nature and extent of air contamination

ATSDR compiled and evaluated ambient air monitoring data to assess potential air quality impacts from Cotter Mill's past and ongoing operations. As will be discussed later, ambient air concentrations of some substances changed considerably from one year to the next—in some cases, annual average concentrations vary by more than a factor of 250 over the period of record. These substantial changes in measured air contamination levels can sometimes be traced back to site-specific activities.

To provide background information and context for the air quality trends documented later in this report, the following list identifies key milestones over the history of Cotter Mill's operations. The timeline is not intended to be a comprehensive listing of site-specific events, but rather focuses on events and activities expected to be *associated with notable changes in the facility's air emissions*.

- 1958: Cotter Corporation begins its uranium milling operations at the Cotter Mill site
- 1979: Continuous operations cease, but intermittent operations continue
- 1981-1983: Cotter excavates 2,500,000 cubic yards of contaminated tailings from unlined holding ponds and places the material in a newly constructed, lined surface impoundment
- 1987: Cotter suspends its primary milling operations and only limited and intermittent ore processing occurs for the next 12 years
- 1993-1999: Cotter excavates 9,000 cubic yards of contaminated tailings, soil, and sediment from 1.25 miles of Sand Creek near the facility
- 1999: Cotter excavates 100,000 cubic yards of contaminated soil in "near surface soils" from the on-site Old Pond Area and places this material into the lined, surface impoundment
- 1999: Milling operations using a different production process begin
- 2005: Cotter ceases its routine operations and enters "stand down" status; site remediation activities continue; stack emissions from most sources continue into 2006, after which the main operational stack is for the laboratory baghouse
- 2009: Cotter submits letter to CDPHE announcing its intent to refurbish the mill, rather than decommission it

The following sections summarize the data and air quality trends for particulate matter, selected particle-bound radionuclides, radon gas and gamma radiation.

a) Ambient Air Monitoring for Radioactive Substances

The Cotter Mill monitoring network is operated by Cotter Mill in accordance with guidelines and requirements set forth by the U.S. Nuclear Regulatory Commission (USNRC 1980) and the Radioactive Materials License established between Cotter Mill and the state of Colorado [CDPHE 2009]. The purpose of the network is to characterize the extent to which Cotter Mill's operations affect off-site air quality.

Cotter Mill's ambient air monitoring network has been operating from 1979 to the present, but the number of monitoring stations included in the network has changed over time. In 1979, four stations were fully operational; this increased to seven by 1981 and to ten by 1999. These ten monitoring stations continue to operate today. Each station is equipped with the same monitoring equipment: an environmental air sampler used to collect particulates for analysis of particle-bound radionuclides; a radon track etch measurement device; and an environmental thermoluminescent dosimeter (TLD) for measuring gamma exposure. The height of the sampling inlet probes was not specified in the reports that ATSDR reviewed to prepare this health assessment. Table 51 in Appendix A identifies the monitoring stations and their periods of operation. Figure 23 in Appendix B shows the approximate locations of the monitoring stations. For purposes of this evaluation, ATSDR has classified the ten monitoring stations as being either "perimeter" or "off-site." The five "perimeter" monitoring stations are located along or just within Cotter Mill's property line; and the five "off-site" monitoring stations are located off-site, anywhere from 0.5 mile to 4 miles from the Cotter Mill property line.

(1) Particulate Matter

At each of the 10 monitoring stations described above, Cotter Mill operates a high-volume total suspended particulate (TSP) sampling device. For each sampling period, the devices are loaded with glass fiber filters that collect airborne particulates as ambient air passes through the sampling apparatus. The TSP sampling devices collect 1-week integrated samples; when the sampling period ends, field personnel remove filters, record observations on chain-of-custody forms, and store filters for subsequent laboratory analysis.

Cotter prepares annual summary reports for its environmental monitoring network, and those reports document monthly average TSP concentrations measured at each station. ATSDR had access to the summary reports for 2006, 2007, and 2008. TSP data from earlier years can be accessed through data reports that CDPHE has on compact disk. Over the last three years, annual average TSP concentrations were consistently higher in the more populated areas (Lincoln Park and Cañon City) than at the perimeter monitoring stations. In 2008, for instance, the annual average TSP levels at Lincoln Park and Cañon City were 29.9 µg/m^3 and 26.5 µg/m^3, respectively; in contrast, annual average concentrations at the five perimeter monitoring stations ranged from 15.5 µg/m^3 to 21.4 µg/m^3.

Although quantitative quality control information was not available when summarizing Cotter's TSP data, these measurements can be compared to CDPHE's PM_{10} monitoring results in Cañon City during the same time frame. From 2006 to 2008, the annual average TSP levels measured by Cotter Mill in Cañon City were 26.6 µg/m^3, 26.3 µg/m^3, and 26.5 µg/m^3, respectively; the annual average PM_{10} levels measured by CDPHE in Cañon City during these same years were

16.5 µg/m^3, 16.4 µg/m^3, and 15.0 µg/m^3. The difference between the TSP and PM$_{10}$ annual average concentrations in Cañon City are within the expected range and direction (i.e., TSP levels exceeding PM$_{10}$ levels), which gives some assurance in the quality of the underlying data sets.

(2) Particle-Bound Radionuclides

Weekly particulate filters collected at the 10 stations mentioned in the previous section are not only weighed for mass loading but are also analyzed at Cotter Mill's analytical laboratory for concentrations of five radionuclides, identified below. All laboratory analyses are conducted according to methodologies approved by CDPHE.

Field sampling and laboratory analyses for particle-bound radionuclides are conducted according to specifications outlined in Cotter Mill's Quality Assurance Program Plan (QAPP). This document is revised periodically and submitted to CDPHE for review. The QAPP outlines many quality control and quality assurance procedures implemented to ensure that the network's measurements are of a known and high quality. Examples of specific procedures followed include: routine collection and analysis of blank samples to ensure sampling media and laboratory equipment are not contaminated; quarterly calibration of flow rates for the "high volume" samplers; audit of sampler flow rates using special equipment; collection of duplicate samples that are analyzed in replicate to quantify measurement precision; and participation in a "laboratory exchange program" through which a subset of environmental samples (mostly water samples, by all appearances) are split and sent to Cotter Mill's laboratory and two commercial laboratories for analyses. While these and other quality control procedures give some assurance that samples are collected and analyzed with fine attention to data quality, the reports available to ATSDR during this review generally did not present the actual data quality metrics (e.g., the relative percent difference in duplicate samples or for inter-laboratory audits, contamination levels found in blanks) for the particle-bound radionuclides.

The key findings from the monitoring program for the five radionuclides measured are below. For each substance, a section compares the measured concentrations to regulatory limits or health-based comparison values, comments on temporal and spatial variations, and then presents a brief summary.

- **Natural uranium (^{nat}U).** Table 52 in Appendix A presents the history of annual average ^{nat}U concentrations measured in Cotter Mill's monitoring network. The shaded cells in the table are the highest annual average concentration for the year.
    - *Screening.* Cotter Mill compares measured concentrations of ^{nat}U to an "effluent concentration" (9.0 x 10^{-14} µCi/ml), which is defined (10 CFR 20, Appendix B) as the radionuclide concentration which, if inhaled continuously over the course of a year, would produce a total effective dose equivalent of 50 mrem. None of the annual average concentrations in Table 52 exceed this derived concentration guide. The highest annual average concentration over the period of record (2.5 x 10^{-14} µCi/ml at a perimeter monitoring station in 1982) is 3.6 times below this screening value. The highest annual average in 2008 (4.4 x 10^{-16} µCi/ml at a

perimeter monitoring station) was approximately 200 times below the screening value, and larger margins are observed for the off-site monitoring stations.

- *Spatial and temporal variations.* Generally, the highest annual average concentrations of ^{nat}U were observed at perimeter monitoring stations, with lower levels observed at the off-site stations. During most years, the annual average values did not vary considerably (by more than an order of magnitude) across all of the stations. As an exception, the 1982 annual average ^{nat}U concentration observed at the west boundary monitoring station was roughly 50 times greater than the annual averages observed at the other monitoring stations during the same year; this "spike" at one station during one year was most likely caused by air emissions associated with an on-site tailings excavation project. As another exception, in several years between 1998 and 2006, annual average ^{nat}U concentrations at the mill entrance road monitoring station were more than an order of magnitude higher than those recorded at all other stations, which most likely reflects contributions from clean-up of the site entry road and delivery of ores (which mostly ended in 2006). As noted above, the highest annual average concentration of ^{nat}U was observed in 1982, and more recent (2004-2008) annual average levels are considerably lower.

- *Summary.* Every annual average concentration of ^{nat}U recorded to date has been lower than Cotter Mill's health-based regulatory limit. In the last five years, the annual average concentrations at every station have been at least 20 times below this limit. It seems unlikely that air emissions from the mill would lead to an off-site "hot spot" of ^{nat}U concentrations that could be considerably higher than the levels measured by the monitoring network.

- **Thorium-230 (^{230}Th).** Table 53 in Appendix A presents the history of annual average ^{230}Th concentrations measured in Cotter Mill's monitoring network. The shaded cells in the table are the highest annual average concentration for the year.

  - *Screening.* Cotter Mill compares measured concentrations of ^{230}Th to an "effluent concentration" (2.0×10^{-14} µCi/ml), which is defined (10 CFR 20, Appendix B) as the radionuclide concentration which, if inhaled continuously over the course of a year, would produce a total effective dose equivalent of 50 mrem. The annual average concentration at the west boundary monitoring station exceeded this value in 1981 and 1982, as did the annual average concentration in 1981 at the east boundary monitoring station. The highest annual average concentration recorded by this network (9.0×10^{-14} µCi/ml at the west boundary in 1982) was 4.5 times higher than the derived concentration guide. Concentrations decreased over the years, and the highest annual average in 2008 (7.2×10^{-16} µCi/ml at a perimeter monitoring station) was a factor of 28 times lower than the screening value, and larger margins are observed for the off-site monitoring stations.

  - *Spatial and temporal variations.* Without exception, the highest annual average concentrations of ^{230}Th were observed at perimeter monitoring stations, with considerably lower levels observed at the off-site stations—a spatial trend suggesting that Cotter Mill's emissions very likely account for a considerable portion of the measured levels. As with natural uranium, the ^{230}Th concentrations exhibited a notable "spike" in 1981-1982, when 2.5 million cubic yards of on-site tailings were excavated from the unlined ponds. As an illustration of this effect, the highest annual average concentration in 1981 (3.0×10^{-14} µCi/ml at a perimeter monitoring station) was nearly 370 times higher than the annual average concentration measured in Cañon City. Moreover, the highest concentrations were observed at the monitoring station closest to, and downwind from, the excavation activity. Average concentrations of ^{230}Th decreased markedly after the 1981-1982 peak: the most recent (2004-2008) annual average concentrations at perimeter stations are all at least 20 times lower than the highest levels from 1981-1982.

  - *Summary.* In 1981 and 1982, annual average concentrations of ^{230}Th at two perimeter monitoring stations exceeded Cotter Mill's health-based regulatory limit; however, for every other calendar year, every station's annual average concentration was lower than this limit. In the last five years, the annual average concentrations at every station were between six and 30 times below this limit. For the off-site monitoring stations, however, all annual average concentrations during this 5-year time frame were at least a factor of 40 below Cotter Mill's health-based regulatory limit.

- **Thorium-232 (^{232}Th).** Table 54 in Appendix A presents the history of annual average ^{232}Th concentrations measured in Cotter Mill's monitoring network. Laboratory analyses for this radionuclide first began in 2001. The shaded cells in the table are the highest annual average concentration for the year.

  - *Screening.* Cotter Mill compares measured concentrations of ^{232}Th to an "effluent concentration" (4.0×10^{-15} µCi/ml), which is defined (10 CFR 20, Appendix B) as the radionuclide concentration which, if inhaled continuously over the course of a year, would produce a total effective dose equivalent of 50 mrem. None of the annual average concentrations in Table 54 exceed this derived concentration guide. In 2008, the highest annual average concentration (3.1×10^{-17} µCi/ml in Lincoln Park) was a factor of 128 lower than the screening value.

  - *Spatial and temporal variations.* Unlike ^{nat}U and ^{230}Th, for which measured concentrations were consistently (if not always) highest at perimeter monitoring stations, the highest annual average concentrations of ^{232}Th have always been observed at off-site monitoring stations, most commonly at the Lincoln Park monitoring station. Moreover, of all the radionuclides measured, annual average concentrations of ^{232}Th exhibited the least variability from station to station. For any given year between 2001 and 2008, annual average concentrations at the ten monitoring stations fell within a factor of three of each other. The annual average concentrations did not exhibit considerable variability from one year to the next.

    - *Summary.* Over the last five years, annual average concentrations of ^{232}Th at every monitoring station were more than 60 times lower than Cotter Mill's health-based regulatory limit. The spatial variations in ^{232}Th concentrations have been limited, suggesting that air emissions from Cotter Mill may be relatively insignificant for this radionuclide.

- **Radium-226 (^{226}Ra).** Table 55 in Appendix A presents the history of annual average ^{226}Ra concentrations measured in Cotter Mill's monitoring network. The shaded cells in the table are the highest annual average concentration for the year.
    - *Screening.* Cotter Mill compares measured concentrations of ^{226}Ra to an "effluent concentration" (9.0×10^{-13} µCi/ml), which is defined (10 CFR 20, Appendix B) as the radionuclide concentration which, if inhaled continuously over the course of a year, would produce a total effective dose equivalent of 50 mrem. None of the annual average concentrations in Table 55 exceed this derived concentration guide. In 2008, the highest annual average concentration (7.9×10^{-16} µCi/ml at a perimeter monitoring station) was three orders of magnitude lower than the screening value.
    - *Spatial and temporal variations.* In almost every year between 1979 and 2008, the highest annual average concentrations of ^{226}Ra were measured at perimeter monitoring stations, and primarily at the west boundary and mill entrance road locations. For most years, the highest annual average value at the facility's perimeter was usually between one and two orders of magnitude greater than the lowest annual average concentration at off-site locations—a pattern that points to facility emissions as a likely source for contributing to at least part of the measured concentrations. At the four perimeter stations with the longest period of record, the highest annual average concentrations occurred prior to 1985, and the current (2008) levels at these stations are between 10 and 100 times lower than those peaks.
    - *Summary.* The spatial variations in ^{226}Ra concentrations suggest that Cotter Mill's emissions contribute to the measured levels. However, over the last five years, annual average concentrations of ^{226}Ra at every monitoring station were more than 390 times lower than Cotter Mill's health-based regulatory limit.

- **Lead-210 (^{210}Pb).** Table 56 in Appendix A presents the history of annual average ^{210}Pb concentrations measured in Cotter Mill's monitoring network. The shaded cells in the table are the highest annual average concentration for the year.
    - *Screening.* Cotter Mill compares measured concentrations of ^{210}Pb to an "effluent concentration" (6.0×10^{-13} µCi/ml), which is defined (10 CFR 20, Appendix B) as the radionuclide concentration which, if inhaled continuously over the course of a year, would produce a total effective dose equivalent of 50 mrem. None of the annual average concentrations in Table 56 exceed this derived concentration guide. In 2008, the highest annual average concentration (1.9×10^{-14} µCi/ml at a

perimeter monitoring station) was more than a factor of 30 lower than the screening value.

- *Spatial and temporal variations.* The main distinguishing feature of the ^{210}Pb monitoring data (when compared to data for the other radionuclides) is the low variability, both spatially and temporally. Since 1983, annual average concentrations across the ten monitoring stations tended to fall within a factor of two; and year-to-year variability was of a comparable magnitude. This lack of variability points to a "background effect" (i.e., the measured concentrations likely are not the result of Cotter Mill's emissions, but reflect typical atmospheric levels for this part of the country). In 1981-1982, annual average concentrations at a perimeter monitoring station were slightly higher than what was routinely measured at all other locations and years; and these slightly elevated levels likely reflected air quality impacts from the excavation of the unlined holding ponds.

- *Summary.* Of all the radionuclides considered, ^{210}Pb showed the least variability in annual average concentrations, suggesting that the monitoring data characterize background levels and not a site-specific contribution. From 1983 to the present, annual average concentrations during every year and at every station were generally at least 20 times below Cotter Mill's health-based regulatory limit.

With one exception, the five radioactive substances measured by Cotter Mill's network were below their corresponding health-based regulatory limits at all 10 monitoring stations and for the entire 30 years of record. As the exception, annual average ^{230}Th concentrations exceeded health-based regulatory limits during a tailing pond excavation project, but this was limited to a short time frame (1981-1982) and the immediate proximity of the facility (two fenceline monitoring locations). The spike in measured concentrations during this time frame was far less pronounced (if not completely imperceptible) at monitoring stations in Lincoln Park or Cañon City. Another spatial variation linked to site activities is the relatively elevated readings (e.g., for ^{nat}U) observed at the "mill entrance road" monitoring station between roughly 1997 and 2006.

Over the last five years, annual average concentrations of every radionuclide were at least 20 times lower than health-based screening limits at the five off-site monitoring stations. This large margin provides some assurance that the monitoring network has adequate coverage in terms of monitors—it is quite possible that annual average ambient air concentrations of radionuclides at some un-monitored off-site locations exceed what has been measured to date, but it is far less likely that the network is failing to capture a "hot spot" with concentrations more than 20 times higher than the levels that are currently measured.

b) *Radon Gas*

Cotter measures radon gas concentrations at the same ten monitoring stations where particle-bound radionuclides are sampled. The annual environmental monitoring reports provide very limited information on the sampling methodology, other than noting that the detectors are apparently exposed to ambient air for a calendar quarter and then retrieved for laboratory analysis. Recent data summary reports suggest that a new sampling and analytical method was implemented in the second quarter of 2002. This new method outputs combined ^{220}Rn (from natural thorium) and ^{222}Rn (from natural uranium). However, the report does not describe what the previous sampling and analytical method measured.

According to Cotter's radon sampling procedures (Cotter 2004b), the sampling devices are "Landauer Type DRNF Radon Detectors." The reports provided to ATSDR suggest that various quality control measures have been implemented for this sampling (e.g., collection and analysis of duplicate samples to characterize precision), but they do not document quantitative data quality metrics. The method detection limit for the combined ^{220}Rn/^{222}Rn measurement is 70 pCi/m^3 (Cotter 2004b). This appears to offer adequate measurement sensitivity, because most quarterly average concentrations measured since this method was implemented are at least an order of magnitude greater than the detection limit.

Table 57 presents the annual average ^{220}Rn/^{222}Rn concentrations that Cotter has measured from 2002 to the present. Data are not presented for earlier years (1979 to 2001), as they may not be directly comparable due to the use of different measurement technologies. Cotter has recently concluded that its radon monitoring data "demonstrate slightly elevated readings at boundary locations [when compared to] readings in residential areas at background levels" (Cotter 2008b). This statement seems to be supported, in a general sense, by the monitoring results, though the difference between the perimeter and the off-site concentrations is much lower in certain years, particularly in 2008.

The approach used for screening the ^{220}Rn/^{222}Rn concentrations differs from that used for other radionuclides. Cotter screens the ^{220}Rn/^{222}Rn using an approach approved by CDPHE. In this approach, Cotter derives an "effective effluent limit" based on a baseline regulatory limit, an equilibration factor for the measurements, and average background concentrations that are calculated semi-annually. The details of this derivation are documented in a letter that CDPHE sent to Cotter in June, 2004. The net effect of this calculation approach is that the "effective effluent limit" (i.e., the concentration used for screening purposes) can vary across the monitoring stations and years. To illustrate this point, between 2006 and 2008, the "effective effluent limit" of ^{220}Rn/^{222}Rn concentrations ranged from 1,290 to 1,981 pCi/m^3, depending on the magnitude of the background concentrations at the time. During this time frame, measured concentrations at perimeter monitoring stations reached as high as 85% of the "effective effluent limit."

c) *Gamma Radiation*

Cotter measures gamma radiation levels at the same ten monitoring stations where particle-bound radionuclides are sampled. Measurements are made using thermoluminescent dosimeters (TLDs) that are exposed for 3-month periods before being sent off-site for analysis. Every calendar quarter, an additional duplicate TLD is deployed to at least one monitoring station to assess measurement precision, and a control TLD is placed in a lead-shielded box at another location to serve as a "blank" sample. However, the site reports provided to ATSDR did not contain any quantitative metrics of data quality (e.g., relative percent difference in co-located samples).

Table 58 presents annual average gamma radiation exposure rates between 1979 and 2008, by monitoring station; these annual averages were calculated from the quarterly TLD measurements from each calendar year. For every year on record, the highest annual average exposure rate was observed at one of the perimeter monitoring stations. Since Cotter installed the monitoring station at the mill's entrance road in 1994, this station has recorded the highest annual average exposure rates every year through the present. The relatively high readings at this location are believed to result primarily from past spillage or incoming materials entering the facility (Cotter 2008b). Under oversight from CDPHE, Cotter removed contamination alongside the entrance road in 2006 and 2007, with exposure rates decreasing thereafter.

Cotter's monitoring reports do not include health-based screening evaluations for these measurements, but they do acknowledge that the exposure rates near the facility perimeter (and particularly along the entrance road) exceed background levels. Specifically, the reports assume that the Cañon City station's measurements reflect "background" contributions from all external sources. The report indicates that the reported background level at this station (10.2 µR/hr) is equivalent to a dose of 89 mrem/year.

d) *Ambient Air Monitoring for non-Radioactive Substances*

To prepare this summary, ATSDR accessed all ambient air monitoring data that the state of Colorado collected in Fremont County and reported to EPA's Air Quality System (AQS), an online clearinghouse of monitoring data that states collect to assess compliance with federal air quality standards. The AQS database included monitoring results for three locations in Fremont County: one in Cañon City, one in Lincoln Park, and one in Florence. This section summarizes only those data collected in Cañon City and in Lincoln Park given their closer proximity to Cotter Mill. However, the monitoring summarized in this section was not conducted to characterize air quality impacts associated with Cotter Mill's emissions; the measured concentrations at these locations likely reflect contributions from many different local emission sources (e.g., mobile sources, wind-blown dust, wood-burning stoves). The AQS database does not specify quality control parameters for the monitoring results; however, state agencies that submit data to AQS are supposed to thoroughly validate measured concentrations before entering them into the database.

(1) Particulate Matter (TSP, PM_{10}, and $PM_{2.5}$)

The state-operated Cañon City and Lincoln Park monitoring stations measured three different size fractions of particulate matter between 1969 and the present. Following standard practice, all three size fractions were measured in 24-hour average integrated samples that were typically collected once every 6 days, though more frequent monitoring occurred during some years. Measurements were collected using either standard technologies (e.g., high-volume samplers for TSP and PM_{10}) or EPA-approved Federal Reference Method devices. A brief summary of the measurements follows:

- **TSP measurements.** From 1969 through 1987, high-volume sampling devices were used to measure TSP. Table 59 in Appendix A presents the maximum and annual average TSP concentrations measured by the two monitoring stations over the period of record. Annual average TSP in Cañon City did not change considerably from 1969-1987. In Lincoln Park, only two calendar years have complete data sets; the annual average concentration in 1982 was below the range of annual averages observed at Cañon City.

The fact that TSP levels were lower in Lincoln Park than in Cañon City suggests that Cotter Mill's emissions are not the primary contribution to TSP levels in the area.

- **PM_{10} measurements.** The state of Colorado began monitoring PM_{10} in Cañon City in 1987 and continues this monitoring today. The monitoring station was originally located at the courthouse in Cañon City, but the state moved the monitoring equipment in 1987 to a less obstructed site at city hall. Annual average PM_{10} concentrations throughout the period of record range from 15 to 23 µg/m^3, well below EPA's former National Ambient Air Quality Standard for annual average levels (50 µg/m^3). Between 1987 and 2009, only one measured 24-hour average concentration exceeded EPA's current health-based standard; that occurred in 1988 and likely reflected contributions from many different local sources and should not be attributed solely to Cotter Mill's emissions.

- **$PM_{2.5}$ measurements.** In 1991 and 1992, the state conducted $PM_{2.5}$ monitoring at its Cañon City station. All measured 24-hour average concentrations and both annual average concentrations were lower than the health-based standards that EPA would develop later in the 1990s. This monitoring occurred before EPA designated Federal Reference Methods for $PM_{2.5}$ measurement devices.

(2) Constituents of Particulate Matter

Between 1978 and 1987, the state of Colorado analyzed some of the TSP filters collected in Cañon City and Lincoln Park for chemical constituents. This included analyses for metals (iron, lead, manganese, and zinc) and ions (nitrate and sulfate). Table 60 summarizes these measurements by presenting the highest 24-hour average concentration and the highest annual average concentration for the period of record.

V. PUBLIC HEALTH EVALUATION

A. Introduction

This section of the public health assessment evaluates the health effects that could possibly result from exposures to site-related contaminants at or near the Cotter Mill site. For a public health hazard to exist, people must contact contamination at levels high enough and for long enough time to affect their health. The environmental data and conditions at the site revealed five completed exposure pathways:

1. Exposure to site-related contaminants in groundwater in Lincoln Park.
2. Contact with site-related contaminants in soil adjacent to the Cotter Mill and in Lincoln Park.
3. Contact with site-related contaminants in surface water downstream from the Cotter Mill.
4. Exposure from eating produce locally grown in Lincoln Park
5. Exposure to ambient air near the Cotter Mill facility

B. How Health Effects are Evaluated

The potential health effects associated with completed exposure pathways (listed above) will be evaluated in this section. For chemicals found to exceed comparison values, ATSDR calculated exposure doses and estimated non-cancer and cancer risks, where applicable. The calculations estimate the amount of the chemical to which a person may have been exposed. Calculated exposure doses are then compared to the available health guidelines to determine whether the potential exists for adverse non-cancer health effects. In the event that calculated exposure doses exceed established health guidelines (e.g., ATSDR's Minimal Risk Levels or EPA's Reference Doses), an in-depth toxicological evaluation is necessary to determine the likelihood of harmful health effects. ATSDR also may compare the estimated amount of exposure directly to human and animal studies, which are reported in ATSDR's chemical-specific toxicological profiles. Not only do the toxicological profiles provide health information, they also provide information about environmental transport, human exposure, and regulatory status.

A detailed explanation of ATSDR's evaluation process for determining cancer and non-cancer health effects is contained in Appendix C of this document. The equations to calculate exposure doses, the exposure scenarios, and the exposure assumptions used to estimate exposures at this site are also in Appendix C.

ATSDR's **Minimal Risk Level (MRL),** which is derived from human and animal studies, is an estimate of daily exposure to a contaminant below which non-cancer health effects are unlikely to occur.

EPA's **Reference Dose** An estimate (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. It can be derived from a NOAEL, LOAEL, or benchmark dose, with uncertainty factors generally applied to reflect limitations of the data used. Generally used in EPA's noncancer health assessments.

C. Groundwater Pathway: Private wells used for personal consumption

As discussed above, the data from the 1989 *Lincoln Park Water Use Survey* survey indicated approximately 7 wells are used for personal consumption; sampling data for 6 of the 7 wells were available to ATSDR for evaluation. Samples were collected intermittently from 1984 to 2007.

Although most residents in Lincoln Park currently use municipal water for drinking purposes, the survey reveals that residents at 7 locations still use their private wells for drinking purposes. It is not verified whether residents who reported using their well water for personal consumption also use their well water for other household purposes, such as bathing and showering. Some residents report that they and others used their private wells for personal consumption and other household uses in the past (before the installation of the municipal water line). Therefore, it is reasonable to assume that many more people obtained their drinking water from private wells in the past, and that some people are continuing to use their private wells for drinking, and possibly, household purposes.

Very little quantitative information is known about what levels of contamination residents may have been exposed to in the past. However, ATSDR attempted to address this issue by assuming that the average resident would have been exposed to the average chemical concentration (i.e., temporal average per well) detected in the 6 private wells for which we have sampling data. There is some uncertainty in using this estimate because some people may have been exposed to more, and some to less, than the estimated amount. To capture the resident who may have been more highly exposed (or a worst case scenario), ATSDR used the average chemical concentration from the single private well that consistently contained the highest chemical concentrations (Well 189). ATSDR assumed that adults and children drank the water from this well for 350 days per year for 30 years (adults) and 6 years (children), respectively.

Molybdenum was the only chemical in private wells that had an average detected level (0.082 mg/L) that exceeded its comparison value (0.05 mg/L). The average level of molybdenum in Well 189 (0.16 mg/L) also exceeded the comparison value for molybdenum in drinking water. Therefore, molybdenum was retained as a chemical of concern and evaluated for possible adverse health effects. The maximum detected level of uranium (0.067 mg/L), but not the average detected level (0.028 mg/L), also exceeded the comparison value of 0.03 mg/L for uranium. Additionally, the average detected level of uranium in Well 189 (0.048 mg/L) exceeded the comparison value for uranium. Therefore, ATSDR evaluated uranium more closely for potential adverse health effects. Table 7 below summarizes the estimated child and adult doses for molybdenum and uranium that guide the health discussion below. (See Table C1 in Appendix C for a detailed discussion of how these values were derived.)

Table 7. Estimated Child and Adult Doses for Molybdenum and Uranium in Drinking Water

Chemical	Exposure Group	Adult Estimated Dose (mg/kg/day)	Child Estimated Dose (mg/kg/day)	Health Guideline (mg/kg/day)
Molybdenum	Well 189 (high exposures)	0.004	**0.010**	0.005 Chronic Oral RfD
	All wells (average exposures)	0.002	0.005	
Uranium	Well 189 (high exposures)	0.001	**0.003**	0.002 Intermediate Oral MRL
	All Wells (average exposures)	0.0008	0.002	

1. Molybdenum

Molybdenum is a naturally occurring element found in various ores. Molybdenum is also considered an essential dietary nutrient in humans and animals. Foods such as legumes, leafy vegetables, nuts and cereals tend to be higher in molybdenum than meats, fruits, and root and stem vegetables [WHO 2003]. The Food and Nutrition Board (FNB) of the Institute of Medicine has determined the Tolerable Upper Intake Level[12] (UL) for molybdenum in children and adults [FNB 2001] as follows:

- children 1 to 3 years of age - 0.3 mg/kg/day;
- children 4 to 8 years of age - 0.6 mg/kg/day;
- children 9 to 13 years of age - 1.1 mg/kg/day;
- adolescents 14 to 18 years of age - 1.7 mg/kg/day; and
- adults - 2.0 mg/kg/day.

a) Health Evaluation of Molybdenum

Drinking water from a private well contaminated with molybdenum would result in an estimated dose of 0.002 mg/kg/day for an average adult and 0.005 mg/kg/day for an average child. The adult dose is lower than the oral RfD of 0.005 mg/kg/day for molybdenum. The estimated child dose is equal to the oral RfD (0.005 mg/kg/day) for molybdenum. Therefore, adverse health

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[12] UL = maximum level of daily nutrient intake that is likely to pose no risk of adverse health effects in all individuals. The UL represents the total intake from food, water, and supplements.

effects are not expected for the average adult or child who drank from a private well contaminated with molybdenum.

Adults who may have had high exposures, such as those similar to Well 189, have an estimated dose of 0.004 mg/kg/day, and children who may have had high exposures have an estimated dose of 0.010 mg/kg/day. The adult high dose is less than the oral RfD for molybdenum. However, the estimated child high exposure dose is 2 times greater than the oral RfD of 0.005 mg/kg/day for molybdenum. Because the estimated exposure dose for children exceeds the long-term health guidelines for molybdenum, the possibility of health consequences from this exposure was evaluated further.

To further evaluate the possibility of adverse health effects, ATSDR divides the lowest observed adverse effect level (LOAEL) and/or the no observed adverse effect level (NOAEL) by the site-specific exposure doses. Interpretation of the resulting value is subjective and depends on a host of toxicological factors. Further evaluation consists of a careful comparison of site-specific exposure doses and circumstances with the epidemiologic and experimental data on the chemical. The purpose of the comparison is to evaluate how close the estimated exposure doses are to doses that cause health effects in humans or animals.

The oral RfD for molybdenum is based on a human epidemiological study that found a LOAEL of 0.14 mg/kg/day for increased serum uric acid levels and prevalence of gout-like condition in Armenian villagers [Koval’skiy 1961]. A higher incidence (18-31%) of a gout-like disease was associated with high intake of molybdenum (10-15 mg/day) from soil and plants. The gout-like condition was characterized by pain, swelling, inflammation and deformities of the joints, and, in all cases, an increase in the uric acid content of the blood. In a number of cases, illnesses of the GI tract, liver, and kidneys accompanied the condition [EPA IRIS]. In deriving the oral RfD, an uncertainty factor of 3 was used for protection of sensitive human populations and a factor of 10 was used for the use of a LOAEL instead of a NOAEL for a long-term study in a human population. The estimated child high dose (0.010 mg/kg/day) for molybdenum at the Cotter Mill/Lincoln Park site is 14 times lower than the LOAEL from this study. There was no NOAEL determination for molybdenum from this study.

Molybdenum is known to interfere with copper metabolism in ruminant animals (grazing animals that “chew their cud,” such as sheep or cows); the resulting copper deficiency is reported to cause the animal’s hair/wool to turn white [FNB 2001]. This is a problem with ruminant animals in particular because high dietary molybdenum reacts with moderate to high dietary sulfur in the rumen (the first stomach) to form thiomolybdates. These compounds greatly reduce copper absorption, and certain thiomolybdate species can be absorbed and interfere systemically with copper metabolism [Spear 2003]. This interaction between thiomolybdates and copper is not expected to occur to a significant degree in humans [Turnlund 2002]. Although the exact effect of molybdenum intake on copper status in humans remains to be clearly established, individuals who do not take in enough dietary copper or cannot process it correctly could be at increased risk of molybdenum toxicity [FNB 2001].

In conclusion, children who drink water containing high concentrations of molybdenum could be at increased risk of adverse health effects such as gout-like symptoms. However, molybdenum is not stored at high levels in the body, so it is unlikely that children will suffer long-term health effects once the exposure is stopped [FNB 2001]. In healthy people, excess molybdenum is not associated with adverse health outcomes. However, individuals who do not take in enough dietary copper or cannot process it correctly could be at increased risk for adverse health effects. The actual risk of adverse health effects occurring depends on the concentration of molybdenum in the water and how much water is drunk. Therefore, private wells known to be contaminated with molybdenum should not be used for drinking purposes.

b) Additional Comments about Molybdenum in Drinking Water

- ATSDR did not evaluate potential exposures to molybdenum that could occur if well water is used for other household purposes such as showering or bathing. If it is confirmed that residents are using their wells for other potable purposes, then exposure levels would increase, as well as the likelihood of adverse health effects. However, exposure to airborne and/or dermal molybdenum is not likely to be a major exposure pathway because of the physicochemical properties of molybdenum.

- The estimated dose for children and adults at this site did not exceed the Tolerable Upper Intake Level (UL) for molybdenum established by the Institute of Medicine. However, ATSDR's evaluation did not consider molybdenum intake from other sources, including food and supplements, which would increase total intake.

- Molybdenum is often found naturally in the geology of this region. The wells identified and sampled as background for the Lincoln Park area contained an average molybdenum concentration of 0.023 mg/L. This concentration is lower than the average of 0.082 mg/L found in private wells used for personal consumption. The maximum concentration of molybdenum in a background well (0.3 mg/L) was about the same as that in a private well (0.28 mg/L) used for personal consumption.

- Overall molybdenum levels in groundwater decreased over time. Molybdenum levels measured from 1968 to 2000 show a clear pattern of decrease in molybdenum concentrations. Therefore, exposures to molybdenum in groundwater were likely higher in the past, and may continue to decrease in the future.

People who currently own private wells are not prevented from using their private wells for any purpose. New residents who move to the area may install new wells in the contaminated zone and use their well for any purpose. Therefore, this exposure pathway will continue to exist as a potential exposure pathway in the future.

2. Uranium

Throughout the world uranium is a natural and common radioactive element. Uranium is a silver-white, extremely dense, and weakly radioactive metal. It is typically extracted from ores containing less than 1% natural uranium. Natural uranium is a mixture of three isotopes: 238U (99.2739%), 235U (0.7204%), and 234U (0.0057%). It usually occurs as an inorganic compound with oxygen, chlorine, or other elements [NHANES 2005]. Rocks, soil, surface and ground water, air, plants, and animals all contain varying amounts of uranium. Colorado ranks third, behind Wyoming and New Mexico, tied with Arizona and Utah, as the state with the most uranium reserves in the United States [EIA 2001].

a) Health Evaluation of Uranium

Natural uranium is radioactive but poses little radioactive danger—it releases only small amounts of radiation that cannot travel far from its source. Moreover, unlike other types of radiation, alpha radiation released by natural uranium cannot pass through solid objects, such as paper or human skin. You have to eat, drink, or breathe natural uranium in order to be exposed to the alpha radiation; however, no adverse effects from natural uranium's radiation properties have been observed in humans. The National Academy of Sciences determined that bone sarcoma is the most likely cancer from oral exposure to uranium; its report noted, however, that this cancer has not been observed in exposed humans and concluded that exposure to natural uranium may have no measurable effect [BEIR IV].

Scientists have seen chemical effects in people who have ingested large amounts of uranium. Kidney disease has been reported in both humans and animals that were exposed to large amounts of uranium; however, the available data on soluble (more bioavailable) and insoluble uranium compounds are sufficient to conclude that uranium has a low order of metallotoxicity in humans [Eisenbud and Quigley 1955].

When uranium is ingested most of it leaves the body through the feces and a small portion (approximately 2% for an adult) will be absorbed into the blood stream through the gastrointestinal (GI) tract. Most of the uranium in the blood is excreted from the body through urine excretion within a few days; however, a small amount will be retained in the kidneys, bone, and soft tissue for as long as several years. The percentage of the uranium retained in the kidneys over time is different for acute and chronic ingestion of uranium (as long as the individual continues to drink the water). When an individual discontinues drinking the uranium contaminated water, the percentage of retention in the kidney decreases similar to an acute exposure. In the case of chronic ingestion of drinking water containing uranium, the kidney retention (or kidney burden) increases rapidly in the first two weeks. After approximately 100 days, the amount present in the kidney is approximately 5% of the daily intake for an infant and approximately 3% for all other ages. After 25 years of chronic ingestion, the uranium kidney burden reaches equilibrium for all age groups at approximately 6.6% of the daily intake [Chen et al 2004].

Nephrotoxicity (kidney toxicity) occurs when the body is exposed to a drug or toxin such as uranium that causes temporary or permanent damage to the kidneys. When kidney damage occurs, blood electrolytes (such as potassium and magnesium) and chemical wastes in the blood (such as creatinine) become elevated indicating either a temporary condition or the development of kidney failure. Creatinine is a chemical waste molecule that is generated from muscle metabolism. The kidneys maintain the blood creatinine in the normal range. Creatinine is a fairly reliable indicator of kidney function. As the kidneys are impaired, the creatinine level in the blood will rise because of the poor clearance by the kidney. If detected early, permanent kidney problems may be avoided.

Several mechanisms for uranium-induced kidney toxicity have been proposed. In one of these, uranium accumulates in specialized (epithelial) cells that enclose the renal tubule, where it reacts chemically with ion groups on the inner surface of the tubule. This interferes with ion and chemical transport across the tubular cells, causing cell damage or cell death. Cell division and regeneration occur in response to cell damage and death, resulting in enlargement and decreased kidney function. Heavy metal ions, such as uranyl ions, may also delay or block the cell division process, thereby magnifying the effects of cell damage [Leggett 1989, 1994; ATSDR 1999].

Animal and human studies conducted in 1940s and 1950s provide evidence that humans can tolerate certain levels of uranium, suffering only minor effects on the kidney [Leggett 1989]. Most of these studies involved inhalation exposures to uranium; however, the kidney is the target organ for inhaled as well as ingested uranium. On the basis of this tolerance, the International Council on Radiologic Protection (ICRP) adopted a maximal permissible concentration of 3 μg of uranium per gram of kidney tissue for occupational exposure in 1959 [Spoor and Hursh 1973]. This level has often been interpreted as a threshold for chemical toxicity.

More recent papers have been published on effects of uranium at levels below 3 μg/g, and those papers have discussed possible mechanisms of uranium toxicity [Diamond 1989; Leggett 1989, 1994; Zhao and Zhao 1990; Morris and Meinhold 1995]. It is thought that the kidney may develop an acquired tolerance to uranium after repeated doses; however, this tolerance involves detectable histological (structural) and biochemical changes in the kidney that may result in chronic damage. Cells of the inner surface of the tubule that are regenerated in response to uranium damage are flattened, with fewer energy-producing organelles (mitochondria). Transport of ions and chemicals across the tubule is also altered in the tubule cells [Leggett 1989, 1994; McDonald-Taylor et al. 1997]. These effects may account for the decreased rate of filtration through the kidney and loss of concentrating capacity by the kidney following uranium exposure. Biochemical changes include diminished activity of important enzymes (such as alkaline phosphatase), which can persist for several months after exposure has ended. Therefore, acquired tolerance to uranium may not prevent chronic damage, because the kidney that has developed tolerance is not normal [Leggett 1989]. Acting on the basis of this recent information for uranium, researchers have suggested that exposure limits be reduced to protect against these chronic effects on the kidney.

Renal damage appears to be definite at concentrations of uranium per gram of kidney tissue above 3 μg/g for a number of different animal species, but mild kidney injury can occur at uranium concentrations as low as 0.1 to 0.4 μg/g in dogs, rabbits, guinea pigs, and rats after they inhale uranium hexafluoride or uranium tetrachloride over several months [Maynard and Hodge 1949; Hodge 1953; Stokinger et al. 1953; Diamond 1989]. Zhao and Zhao proposed a limit of uranium to the kidney of 0.26 μg/g based on renal effects in a man who was exposed to high concentrations of uranyl tetrafluoride dust for 5 minutes in a closed room [Zhao and Zhao 1990]. The man showed signs of kidney toxicity, including increased protein content in the urine (proteinuria) and nonprotein nitrogen. These signs persisted for 4.6 years, gradually returning to normal values. The kidney content 1 day after the accident was estimated to be 2.6 μg/g.

A study conducted in Finland and published in 2002 observed 325 people that had used their drilled wells for drinking water over a period of 13 years on average (range 1 – 34 years) [Kurttio et. al 2002]. The median uranium concentration in the water was 28 ppb (range 0.001 –

1,920 ppb). The study showed an association between increased uranium exposure through drinking water and tubular function, but not between uranium exposure and indicators of glomerular injury. The primary target is the proximal convoluted tubule of the kidney which is where most of the sodium, water, glucose, and other filtered substances are reabsorbed and returned to the blood. The authors of the study indicated that tubular dysfunction may merely represent a manifestation of subclinical toxicity, and it is unclear if it carries a risk of development into kidney failure or overt illness. This study concluded that “The public health implications of these findings remain uncertain, but suggest that the safe concentration of uranium in drinking water may be close to the guideline values proposed by the WHO and the U.S.EPA.” However, this study found that altered tubular function was statistically significant at water uranium concentrations exceeding 300 µg/L [Kurttio et. al 2002], or 0.3 mg/L, which is an order of magnitude higher than EPA’s guideline (0.035 mg/l) and the highest average concentration at the Lincoln Park site (0.048 mg/L). At 300 µg/L and assuming ingestion of two liters of water per day, the kidney burden after 25 years of chronic ingestion would be 39.6 µg of uranium with a uranium concentration per gram of kidney tissue of 0.13 µg/g.

A review of studies of uranium effects on the kidney [Morris and Meinhold 1995] suggests a probability distribution of threshold values for kidney toxicity ranging from 0.1 to 1 µg/g, with a peak at about 0.7 µg/g. The researchers proposed that the severity of effects increases with increasing dose to the kidney with probably no effects below 0.1 to 0.2 µg/g, possible effects on the kidney at 0.5 µg/g, more probable effects at 1 µg/g, and more severe effects at 3 µg/g and above [Morris and Meinhold 1995; Killough et al. 1998b].

If an adult in Lincoln Park drank 2 liters (L) of uranium-contaminated water per day (at the highest average exposure concentration of 0.048 mg/L, or 48 µg/L) for 25 years or longer, then the maximum daily ingestion would be 96 µg of uranium, resulting in a uranium kidney burden of 6.3 µg (96 µg × 0.066). The weight of both kidneys in adults is about 300 g [Madsden et al 2007]. Thus, the uranium concentration per gram of kidney tissue for an adult would be 0.02 µg/g. If a child drank 1 L of uranium-contaminated water per day (at the highest average exposure concentration of 0.048 mg/L, or 48 µg/L) for 100 days to 25 years, then the maximum daily ingestion would be 48 µg of uranium, resulting in a uranium kidney burden of 1.4 µg (48 µg x 0.03). The weight of both kidneys in a child is about 100 g; therefore, the uranium concentration per gram of kidney tissue to be 0.01 µg/g. The calculated kidney uranium concentration for adults and children is below the level found to cause harm in published studies.

ATSDR’s health-based guidelines for ingested (and inhaled) uranium are lower than the lower limit threshold for kidney toxicity proposed by Morris and Meinhold (1995). ATSDR’s guidelines are derived by use of levels of toxicity observed in animal studies, and those guidelines incorporate safety factors to account for uncertainty in extrapolating from animals to humans and to protect the most sensitive human individuals [ATSDR 1999].

Note that urinalysis has limitations as a test for kidney toxicity. First, the presence of substances in urine may indicate that kidney damage has occurred, but it cannot be used to determine whether the damage was caused by uranium. Second, most uranium leaves the body within a few days of exposure, so that urine tests can be used only to determine whether exposure has occurred in the past week or two. Finally, the tests may be used to detect mild effects on the kidney, but such effects are generally transient in nature and may not result in permanent damage. More severe effects involve greater damage to the kidney that is likely to be clinically manifest and longer lasting. The kidney has incredible reserve capacity and can recover even after showing pronounced clinical symptoms of damage; however, biochemical and functional changes can persist in a kidney that appears to have recovered structurally [Leggett 1989, 1994; CDC 1998].

The maximum average uranium concentration detected in a private well was 0.048 mg/L, or 48 µg/L. The residence where this concentration was detected is not connected to the municipal water supply and is noted to use a private well for personal consumption. Drinking water from this private well containing uranium would result in an estimated dose of 0.001 mg/kg/day for an adult and 0.003 mg/kg/day for a child. The adult dose is lower than the intermediate oral MRL. The estimated child dose slightly exceeds the MRL of 0.002 mg/kg/day for an intermediate-duration oral exposure. The MRL level for intermediate-duration oral exposure is also protective for chronic-duration oral exposure because the renal toxicity of uranium exposure is more dependent on the dose than on the duration of the exposure. The MRL is based on a LOAEL of 0.05 mg U/kg/day for renal effects in rabbits. The estimated child dose is an order of magnitude lower than the LOAEL; therefore, adverse health effects are not likely.

Although older evaluations suggested carcinogenicity of uranium among smokers, the U.S. EPA has withdrawn its classification for carcinogenicity for uranium; the International Agency for Research on Cancer (IARC) and the National Toxicology Program (NTP) have no ratings [NHANES 2005].

D. Soil Pathway: Surface Soil near Cotter Mill and Lincoln Park

As discussed above, surface soil samples were collected from areas around the Cotter Mill property, from property access roads and in the Lincoln Park area. Surface soil sampling data were available from eight designated zoned areas around Cotter Mill and in Lincoln Park. People who live or recreate in these areas could accidentally ingest some contaminated soil or get it on their skin. ATSDR evaluated these potential exposure scenarios to determine if concentrations of chemicals and radionuclides in soil are high enough to cause adverse health effects.

ATSDR assumed that the average adult would accidentally ingest 100 milligrams of soil per day and would also contact the contaminated soil with their skin (dermal). Small children were not assumed to access the soil around Cotter Mill because these areas are primarily industrial or vacant. The vacant area has been designated as a “buffer zone” between the Cotter Mill property and the residential areas. Therefore, it is unlikely that small children would access the area. A residential exposure scenario was used to evaluate potential exposures in Lincoln Park. For Lincoln Park, we assumed that a small child would ingest 200 mg of soil per day, and an adult would ingest 100 mg/day, for 350 days per year.

Concentrations of arsenic, cadmium and lead exceeded their comparison values in soil taken from the area surrounding Cotter Mill. The concentration of radium-226 was the only radionuclide to exceed its comparison value in soil near Cotter Mill. Arsenic was the only chemical to exceed its comparison value in soil in Lincoln Park. The highest zonal average concentration of arsenic, cadmium, lead and radium-226 was used to estimate exposure doses. If the highest zonal average concentration of a chemical would not result in adverse health effects, it follows that lower concentrations of the chemical would not as well.

1. *Soil Near Cotter Mill*

a) Arsenic

Arsenic is a naturally occurring element that is widely distributed throughout the earth's crust and may be found in air, water, and soil [ATSDR 2000]. Arsenic in soil exists as inorganic and organic arsenic. Generally, organic arsenic is less toxic than inorganic arsenic, with some forms of organic arsenic being virtually non-toxic. Inorganic arsenic occurs naturally in soil, and children may be exposed to arsenic by eating soil or by direct skin contact with soil containing arsenic [ATSDR 2007].

The estimated dose of arsenic for adolescents and adults at this site is 0.00002 mg/kg/day. This dose is lower than the Minimal Risk Level (MRL) of 0.0003 mg/kg/day for arsenic; therefore, non-cancer health effects are not likely from being exposed to arsenic in surface soil near Cotter Mill (Zones A through H). The chronic oral MRL of 0.0003 mg/kg/day for inorganic arsenic was derived by dividing the identified chronic No Observable Adverse Effect Levels (NOAEL) of 0.0008 mg/kg/day (obtained from human epidemiologic studies) by an uncertainty factor of three to account for the lack of data on reproductive toxicity and to account for some uncertainty as to whether the NOAEL accounts for all sensitive individuals [ATSDR 2007]. The Lowest Observed Adverse Effect Level (LOAEL) associated with these epidemiologic studies was 0.014 mg/kg/day, where exposure to arsenic above this level resulted in hyperpigmentation of the skin, keratosis (patches of hardened skin), and possible vascular complications [ATSDR 2007].

The U.S. Environmental Protection Agency (EPA), the International Agency for Research on Cancer (IARC), and the National Toxicology Program (NTP) classify arsenic as a human carcinogen. The EPA has developed an oral cancer slope factor to estimate the excess lifetime risk for developing cancer. Using EPA's cancer slope factor for arsenic, and based on a 30 year exposure scenario, ATSDR calculated a lifetime estimated cancer risk level of 1×10^{-5} for exposure to arsenic in soil near Cotter Mill. Qualitatively, we interpret this as a very low increased lifetime risk of developing cancer.

b) Cadmium

The estimated dose for adolescents and adults for cadmium is 0.00002 mg/kg/day, which is lower than the MRL of 0.0001 mg/kg/day for cadmium; therefore, non-cancer adverse health effects are not likely. The U.S. Department of Health and Human Services (DHHS), IARC, and EPA have determined that cadmium is carcinogenic to humans. Although cadmium can be carcinogenic when inhaled, human or animal studies have not provided sufficient evidence to show that cadmium is a carcinogen by oral routes of exposure (ATSDR 1999b). Therefore, a cancer evaluation for cadmium was not done as part of this assessment.

c) Lead

The highest average concentration of lead detected in any of the zones (Zone H) is 445 ppm, which is only slightly higher than the soil screening value of 400 ppm for lead. A value of 400 ppm is commonly used to evaluate lead in soil in residential properties. The property near the Cotter Mill site is currently restricted, vacant or used for industrial purposes; therefore contact with these soils should be minimal. Adverse health effects are not expected to occur from these limited exposures to soils near the site. Exposures to lead, however, should be re-evaluated should the area ever be considered for residential or other non-industrial use.

Maximum lead concentrations in zones F, G and H are 800 ppm, 450 ppm, and 1,400 ppm, respectively. To protect children from exposure to lead, it is important to know the average lead level in a yard or other frequent play area. The *1998 Supplemental Human Health Risk Assessment* provides the only characterization of surface soils adjacent to the Cotter Mill property (See Figure 17, Zones A through H). The soil sample results in this report were generated by collecting four samples from the center of a grid and compositing the samples to form a single representative sample. The size of each sampled grids, however, appears to be larger than 100 x 100 feet, which is the size that triggers additional sampling for lead (EPA 1995). Although the sampling in the *1998 Supplemental Human Health Risk Assessment* measured contamination in soils at several properties near Cotter Mill, it does not allow ATSDR to evaluate contamination in individual exposure units (yards, playgrounds, etc), as would be required to accurately assess exposures in a residential setting, commercial or recreational setting. The sample design is sufficient for making general public health decisions about exposure to lead in soil based on current use patterns. However, any future public health decision regarding the soil near the Cotter Mill property must be made with the limitations of the current sampling design in mind.

The Centers for Disease Control and Prevention (CDC) has established a level of concern for case management of 10 micrograms lead per deciliter of blood (µg/dL). This means that when blood lead levels in children exceed 10 µg/dL, CDC recommends that steps be taken to lower their blood lead levels. However, some agencies and public health officials have mistakenly used this level in blood as a safe level of exposure or as a no effect level. Recent scientific research has shown that blood lead levels below 10 µg/dL cause serious harmful effects in young children, including neurological, behavioral, immunological, and development effects. Specifically, lead causes or is associated with decreases in intelligent quotient (IQ), attention deficit hyperactivity disorder (ADHD), deficits in reaction time, visual-motor integration, fine motor skills, withdrawn behavior, lack of concentration, sociability, deceased height, and delays in puberty, such as breast and pubic hair development, and delays in menarche [CDC].

d) Radium-226

The average concentrations of radium-226 detected in Zones A and B are higher than allowed by the Uranium Mill Tailing Act (UMTRA). That standard does not apply in this case, since the Cotter Mill is still considered active.

The highest average soil concentration of 9.2 pCi/g in surface soil would result in a dose from radium's decay gammas of 58 mrem per year above background, assuming that residents spend 12 hours per day 365 days per year sitting or lying on the highest measured radium concentration of 9.2 pCi/g on the haul road. Since Zones A and B are buffer areas (actually haul roads), the time spent in these areas would be much lower (less than 2 hours per day) and the resulting dose would be roughly 10 mrem per year above background, to a maximally exposed individual.

2. Soil in Lincoln Park

a) Arsenic

The estimated arsenic dose for an adult in Lincoln Park is 0.00003 mg/kg/day, which is an order of magnitude lower than the MRL of 0.0003 mg/kg/day for arsenic. The estimated arsenic dose for a child in Lincoln Park is 0.0003 mg/kg/day, which is equal to the MRL of 0.0003 mg/kg/day for arsenic. Children are estimated to have higher arsenic doses than adults because they tend to engage in activities that increase their soil ingestion exposure, and because they weigh less than adults. Neither children nor adults should experience adverse health effects from exposure to arsenic in soil in Lincoln Park.

Arsenic is a naturally occurring element in soil. Arsenic has also historically been used in a variety of industrial applications, including bronze plating, electronics manufacturing, preserving animal hides, purifying industrial gases, and mining, milling and smelting activities. Studies of background levels of arsenic in soils have revealed that background concentrations range from 1 ppm to 40 ppm, with average values around 5 ppm [ATSDR 2007]. The average arsenic concentration detected in Lincoln Park was 31 ppm, a concentration within the observed background range but higher than the average background concentration. The maximum concentration of arsenic detected in Lincoln Park was 50 ppm.

Although the maximum arsenic concentration is higher than the observed background concentration, this fact alone does not definitely point to an anthropogenic source for the arsenic found in soil in Lincoln Park. Uncertainty exists regarding whether the arsenic levels detected are a natural occurrence or from past milling operations in the area.

Several factors contribute to whether people have contact with contaminated soil, including:

- grass cover, which is likely to reduce contact with contaminated soil when grass cover is thick but increase contact with soil when grass cover is sparse or bare ground is present,
- weather conditions, which is likely to reduce contact with outside soil during cold months because people tend to stay indoors more often,
- the amount of time someone spends outside playing or gardening, and
- people's personal habits when outside, for instance, children whose play activities involve playing in the dirt are likely to have greater exposure than other children

Using EPA’s cancer slope factor for arsenic, and based on a 30 year exposure scenario, ATSDR calculated a lifetime estimated cancer risk level of 5×10^{-5} for exposure to arsenic in Lincoln Park. Qualitatively, we interpret this as no apparent increased lifetime risk of developing cancer.

E. Surface Water: Sand Creek, DeWeese Dye Ditch, and the Arkansas River

People who swim or wade in the surface waters of Sand Creek, the DeWeese Dye Ditch, or the Arkansas River will get surface water on their skin and they might also accidentally ingest some of the surface water. To estimate exposures to adults and children who may have come into contact with contaminated surface water, ATSDR assumed that adults and children will swallow 50 mL of water per hour while swimming or wading, for 104 days per year for 30 and 6 years, respectively. Molybdenum exceeded its comparison value in Sand Creek and the Arkansas River. Manganese exceeded its comparison value in Sand Creek and the DeWeese Dye Ditch. ATSDR conservatively selected the maximum concentration for each chemical to estimate exposures.

1. Manganese

The estimated exposure dose for manganese is 0.0007 mg/kg/day for adults and 0.0006 mg/kg/day for children. Both adult and child doses are considerably lower than the reference dose of 0.05 mg/kg/day for manganese. Therefore, no adverse health effects are expected to occur as a result of exposure to manganese in surface waters.

2. Molybdenum

The estimated exposure dose for molybdenum is 0.00002 mg/kg/day for adults and 0.00006 mg/kg/day for children. Both adult and child doses are below the chronic oral reference dose (RfD) of 0.005 mg/kg/day for molybdenum. Therefore, no adverse health effects are expected to occur as a result of exposure to molybdenum in surface waters.

F. Homegrown Fruits and Vegetables

Ingestion of contaminated foods is a potential exposure pathway for this site. Residents may have been exposed to contaminants when they ate homegrown fruits and vegetables after using contaminated groundwater (either surface water or private well water) to irrigate their crops, or after growing their crops in contaminated soil. The soil may become contaminated from contaminated water or from tailings, dusts and other wastes deposited in the soil in the past.

Eating fruits, vegetables, herbs, or other produce grown in gardens with contaminated soil can cause exposure. This type of exposure occurs because some plants slowly absorb small amounts of the chemicals found in soil into their plant tissue or because contaminated soil can adhere to the exterior surface of produce, particularly low-growing leafy produce or produce where the underground portion is eaten. Some of these absorbed chemicals are essential nutrients and are actually good for humans to eat, but other chemicals can present health hazards if they are found at high enough levels and are consumed on a regular basis.

Generally, there is not a strong relationship between levels of heavy metals in soils and plants [Vousta 1996]. The uptake of heavy metal concentration depends on speciation of metal, soil characteristics, the type of plant species and other characteristics [Laizu 2007]. Table 8 below developed by Sauerbeck (1988) provides a qualitative guide for assessing heavy metal uptake into a number of plants.

Table 8. Plant Uptake of Heavy Metals

High	Moderate	Low	Very Low
Lettuce	Onion	Corn	Beans
Spinach	Mustard	Cauliflower	Peas
Carrot	Potato	Asparagus	Melons
Endive	Radish	Celery	Tomatoes
Crest		Berries	Fruit
Beet			
Beet leaves			
Source: USEPA (1991), Human Health Evaluation Manual, Supplemental Guidance: "Standard Default Exposure Factors."			

To address the concern regarding contaminated crops, residents contributed locally grown produce for sampling analysis. ATSDR used the sampling results to estimate an exposure dose for each contaminant using typical consumption rates for the average and above-average (95th percentile) consumer in the Western United States. Child and infant consumption rates were also used to assess exposures to these vulnerable populations. Table 9 below provides the consumption rates used by ATSDR for homegrown fruits and vegetables.

Table 9. Homegrown Fruit and Vegetable Consumption Rates for the Western United States

Food	Consumer Type†	Intake Rate (g/kg/day)	Standard Error
Homegrown fruits	Average consumer	2.62	0.3
	Above-average consumer	10.9	
	Child	4.1	NA
	Infant (1 to 2 years)	8.7	
Homegrown vegetables	Average consumer	1.81	0.1
	Above-average consumer	6.21	
	Child	2.5	NA
	Infant (1 to 2 years)	5.2	

Sources: EPA Exposure Factors Handbook, Volume II, 1997; Child-Specific Exposure Factors Handbook, 2008
g/kg/day: grams per kilogram per day
NA = not applicable
†An average consumer is represented here as a person who eats fruits and vegetables in the typical range (mean intake). An above average consumer is a person who eats more fruits and vegetables than is typical, represented here by the 95th percentile intake.

All of the estimated fruit and vegetable doses were below health guideline values except for those for arsenic (See Table C4 in Appendix C). The estimated doses for fruits for the above-average consumer (95th percentile intake rate) and for infants exceed the chronic health guideline for arsenic. The above-average consumer and infant doses for fruit are 0.0006 mg/kg/day and 0.0004 mg/kg/day, respectively. Also, the estimated doses for vegetables for the above-average consumer (95th percentile intake rate) and for infants exceed the chronic health guideline for arsenic. The vegetable doses are 0.0005 mg/kg/day for an above-average consumer and 0.0004 mg/kg/day for an infant. These doses exceed the chronic oral MRL of 0.0003 mg/kg/day for arsenic.

Next, ATSDR assumed that a person will eat both fruits and vegetables daily. To do this, we added the calculated doses for fruits and vegetables to derive a single dose. The estimated fruit and vegetable doses for the above-average consumer, child and infant exceed the health guideline of 0.0003 mg/kg/day for arsenic. The above-average consumer dose is 0.001 mg/kg/day; the child dose is 0.0004 mg/kg/day; and the infant dose is 0.0008 mg/day/day.

The chronic oral MRL of 0.0003 mg/kg/day for inorganic arsenic was derived by dividing the chronic No Observable Adverse Effect Level (NOAEL) of 0.0008 mg/kg/day (obtained from human epidemiologic studies) by an uncertainty factor of 3 to account for the lack of data on reproductive toxicity and to account for some uncertainty as to whether the NOAEL accounts for all sensitive individuals [ATSDR 2007]. The Lowest Observed Adverse Effect Level (LOAEL) associated with these epidemiologic studies was 0.014 mg/kg/day, where exposure to arsenic above this level resulted in hyperpigmentation of the skin, keratosis (patches of hardened skin), and possible vascular complications [ATSDR 2007]. The child and infant doses are below or equal to the NOAEL, and the above-average consumer dose is 14 times lower than the dose that caused adverse health effects in epidemiologic studies. Therefore, adverse health effects are not expected in infants, children or the above-average consumer.

Using EPA's cancer slope factor for arsenic and the above consumer exposure dose, and based on a 30 year exposure scenario, ATSDR calculated a lifetime estimated cancer risk level of 6×10^{-4} for exposure to arsenic in fruits and vegetables. Qualitatively, we interpret this as a low to moderate increased risk of developing cancer over a lifetime.

ATSDR conservatively assumed that every consumer ate homegrown fruits and vegetables every day for 30 years. In reality, it is likely that most people only eat homegrown fruits and vegetables during a defined season, usually a 3 to 4 month period during the summer/fall growing season. Therefore, the true risk to consumers is likely overestimated.

ATSDR also noted that the highest arsenic level detected in lawns and gardens in Lincoln Park was 50 ppm. This level is near what is typically observed as background arsenic levels (1 ppm to 40 ppm) in soil. This suggests that the contaminated well water used to irrigate crops is not contributing significantly to arsenic soil levels, or other soil additives may have been added that dilute soil contamination [ODEQ 2003]. The highest arsenic level detected in soil at the site was 86 ppm. There were no sampling data for arsenic in drinking or irrigation water. ATSDR is unsure if the arsenic found in soil at this site is a natural occurrence or from an anthropogenic (man-made) source.

Plants vary in the amount of arsenic they absorb from the soil and where they store arsenic. Some plants move arsenic from the roots to the leaves, while others absorb and store it in the roots only [Peryea 1999]. The best method of reducing exposure to external arsenic from homegrown vegetables is to soak and wash residual soil from produce before bringing it into the home and washing the produce again thoroughly indoors before eating [ATSDR 2007]. It is always a good health practice to wash all fruits and vegetables thoroughly before eating, whether they are bought or homegrown.

Molybdenum was the only other contaminant to approach a health guideline when calculating a single dose for fruits and vegetables. The above-average consumer and infant doses are 0.005mg/kg/day, which is equal to the chronic health guideline of 0.005mg/kg/day for molybdenum.

G. Air Pathway

ATSDR looked at all the air data collected from 1979 to present. Concentrations of radionuclides in air from direct release or re-suspension of radioactive contaminants in soil were less than a tenth of ATSDR's health based comparison value (100 millirem per year) at all off-site sampling locations (CC-1/2, LP-2, AS-210, AS-212, OV-3). ATSDR evaluated doses to all age groups and found that adults would have received the highest doses, because of their higher breathing rate. Infants only received one quarter the dose of an adult.

Table 10 below breaks down the dose estimates by age group and by the highest annual concentration measured for each radionuclide and by the highest location. The two highest doses were both in 1982, during the excavation of the unlined settling ponds and were measured at the on-site sampling location AS-204, that was directly adjacent to the dewatered ponds. Neither of those doses would have been to the public. The combined dose to a worker near AS-204 would have been less than a third of the sum in the table since the worker was there less than 8 hours per day for 5 days a week, or 70 mrem of inhalation dose for the year 1982, while the numbers in Table 10 reflect 24/7 exposure through the year. Doses listed in Table 10 did not result in any elevated exposures to the public.

Table 10. Annual Effective Doses by Highest Concentration, Location and Age Group

Radionuclide	Highest Year	Highest Location	Concentration (µCi/ml)	Dose to Infant (mrem/yr)	Annual Dose to Adult	Notes
Natural Uranium (µCi/ml)	1979	AS-204	2.48E-14	2.72	5.97	
Thorium-230 (µCi/ml)	1982	AS-204	8.95E-14	71.57	272.68	
Thorium-232 (µCi/ml)	2001	CC#2	8.33E-17	0.07	0.27	
Radium-226 (µCi/ml)	1985	AS-202	9.63E-15	1.25	2.75	
Lead-210 (µCi/ml)	1982	AS-204	9.95E-14	7.01	16.77	Dose from Radon Progeny
Radon-220/222 (pCi/l)	2004	AS-202	1.50E+00	NA	NA	No dose from Radon

Most of the calculated inhalation dose was from the isotope Thorium-230 (Th-230). Table 11 below lists just the dose from Th-230 for the highest annual average concentration at each sampling station. Again it can be seen that the on-site concentrations are consistently orders of magnitude higher than at off-site locations in Cañon City, Lincoln Park and west of the site boundary.

Outdoor concentrations of radon contributed zero dose to the public, because it is a noble gas and does not stay in the lungs long enough to radioactively decay. On the other hand, the dose from radon decay products (e.g., lead-210) attached to respirable dust held constant year over year and accounted for an annual inhalation dose of four to seven millirem annually. Radon decay product concentration off-site did not appear to be related to releases from the site. Radon and its decay products appear to be from natural background and do not represent any health threat at the reported concentrations.

Table 11. Annual Doses from Thorium-230 by Location and Year

Year	Highest Location	Concentration (µCi/ml)	Annual Dose to Infant (mrem/yr)	Annual Dose to Adult(mrem/yr)
1982	AS-204	8.95E-14	71.57	272.68
1982	AS-202	2.12E-14	16.95	64.59
1983	AS-203	9.79E-15	7.83	29.83
1982	AS-206	1.26E-14	10.08	38.39
2000	AS-209	4.16E-15	3.33	12.67
2005	AS-210	4.85E-16	0.39	1.48
2000	AS-212	6.69E-16	0.53	2.04
1982	LP-1/2	7.49E-16	0.60	2.28
1982	CC-1/2	9.18E-16	0.73	2.80
1982	OV-3	3.15E-15	2.52	9.60

VI. COMMUNITY HEALTH CONCERNS

Responding to community health concerns is an essential part of ATSDR's overall mission and commitment to public health. The community associated with a site is both an important resource for and a key audience in the public health assessment process. Community members can often provide information that will contribute to the quality of the health assessment. Therefore, during site visits and telephone conversations with community members, ATSDR obtained information from the community regarding their specific health concerns related to the site.

In some cases, ATSDR was unable to address a community health concern because 1) adequate scientific information on the particular health effect is not available or is limited or 2) the available scientific data are insufficient to assess whether the specific health effect is related to exposure to a particular chemical. Where feasible, ATSDR addressed the health concerns identified by the community. Below is a summary of the community concerns and ATSDR's response to those concerns.

1. How did the 1965 flood event affect my health?

In June 1965, prior to the construction of the SCS Dam in 1971, a flood caused the unlined tailings ponds at the Cotter Mill to overflow into Lincoln Park. According to the residents, the waters flowed north through the gap in the ridge, down Pine Street, and ultimately down 12th Street (Sharyn Cunningham, CCAT, personal communication, February 2008). There is concern that this flood event contaminated groundwater wells and that dust from soil or tailings may have been resuspended by wind and distributed in Lincoln Park. Community members are very concerned that current illnesses may be a result of this tailings pond flood event.

There is documentation that ponds at the Cotter Mill historically overflowed, which led to the construction of the SCS Dam. Aerial photography from October 1970 indicates that one of the evaporation ponds overflowed into an alluvial channel tributary to Sand Creek (Wilder et al. 1983). A chronology compiled by CDPHE states that in October 1970 and January 1971, an evaporation pond overflowed with high levels of total dissolved solids, sodium, molybdenum, sulfate, and high radiation (CDPHE 1975).However, since the construction of the SCS Dam, there are no recorded surface water discharges past the dam (GeoTrans 1986).

ATSDR tried to locate data to evaluate the potential health effects resulting from this flood event. No data from 1965 or 1966 exist in the CDPHE database. The *1986 Remedial Investigation* (GeoTrans 1986) states that off-site groundwater contamination in the Lincoln Park areas was first identified in 1968; therefore, any data prior to 1968 are unlikely to exist. The only data ATSDR found related to this flood event were from a sediment sample collected in January 2003 (CDPHE 2003). To address community concerns, CDPHE collected a sample of suspected flood sediment from Pine Street near Elm Avenue. This area was identified by a property owner who was present during the flood. The sample was collected from two locations. About 250 grams of soil were collected from each location to a depth of approximately 18 inches. No obvious soil horizons were identified, and no significant differences in gamma radiation were noted between shallow and deep soils. The results are presented in Table 12 below. All concentrations from this one sample are below comparison values.

The results of the sediment sample from the flood did not exceed any comparison values. If this sample was representative of the material moved by the floodwaters, it would not cause any adverse health effects.

Table 12. Concentrations found in a suspected flood sediment sample, January 2003

Chemical	**Concentration (ppm)**	**Comparison Value (ppm)**
Lead	87	400
Molybdenum	Not detected	300
Uranium	1.6	100
Radionuclide	**Concentration (pCi/g)**	**Comparison Value (pCi/g)**
Cesium-137	0.12	Not available
Lead-210	2.2	Not available
Plutonium-239, 240	Not detected	Not available
Potassium-40	22.5	Not available
Radium-226	2.2	15
Radium-228	1.3	15

Source: CDPHE 2003

2. Were an adequate number of soil samples collected during the *1998 Supplemental Human Health Risk Assessment*?

The community expressed concern that not enough samples were collected during the *1998 Supplemental Human Health Risk Assessment*. Weston, a contractor for Cotter, collected surface soil samples (0-2 inches) from eight zones around the mill property (see Figure). Each zone was divided into 8 to 12 grids. Four samples were collected near the center of each grid and were composited (i.e., combined and homogenized) to form a single representative sample (Weston 1998). The dates the samples were collected were not specified in the report; however, it is assumed to be in the 1994–1996 timeframe. In 1995, EPA released guidance for obtaining representative soil samples at Superfund sites (EPA 1995). The systematic grid sampling approach used by Weston conforms with EPA's guidance for delineating the extent of contamination. The number of samples taken from each grid for compositing, however, is not entirely consistent with EPA's guidance. For grids larger than 100 x 100 feet, which it appears that the grids established by Weston are, EPA recommends collecting nine aliquots from each grid. Compositing four aliquots from each grid is recommended for grids smaller than 100 x 100 feet (EPA 1995). Because the timeframe of the sampling is unclear, it is not known whether EPA's 1995 guidance was available during Weston's sampling effort.

3. Are there high levels of thorium near the Black Bridge?

The community expressed concern that high thorium levels were detected in surface water near the Black Bridge. This bridge is located where a railroad spur crosses the Arkansas River between the 4th Street and 9th Street bridges. The closest sampling location in the Arkansas River is upstream at 1st Street (907). Thorium-230 was sampled at this location as part of the surface water monitoring program between 1995 and 2007. These data are summarized below in Table 13. The highest thorium-230 concentration detected was 2.5 picocuries per liter (pCi/L) (suspended sample) in August 2007. This concentration is below levels known to cause adverse health effects. It should also be noted that the Black Bridge is located upstream of the confluence with Sand Creek.

Table 13. Thorium-230 data upstream of the Black Bridge

Chemical	Frequency of Detection	Minimum (pCi/L)	Average (pCi/L)	Maximum (pCi/L)
Thorium-230 (D)	121/127	-0.1	0.1	1
Thorium-230 (S)	115/120	0	0.2	2.5
Thorium-230 (T)	7/7	0.1	0.3	0.7

Source: CDPHE 2007b
Averages were calculated using ½ the reporting detection limit for non-detects.
Negative and zero result values were included in the summary statistics.
Thorium-230 “D” and “S” samples were collected between 1995 and 2007. Thorium-230 “T” samples were only collected in 1995.

D – dissolved
pCi/L – picocuries per liter
S – suspended
T – total

4. I grew up near the Cotter plant. Does this increase my risk of getting cancer?

Soil sampling data from the nearest residence to the Cotter plant did not indicate the presence of chemicals at levels above established guidelines. Soil sampling data from the Lincoln Park community did not reveal the presence of contaminants at levels associated with adverse health effects, including cancer. Air data do not indicate the presence of chemicals at levels associated with adverse health effects, including cancer. If you drank water from a contaminated private well, you might be at increased risk for gout-like conditions, such as pain, swelling, inflammation and deformities of the joints. However, once exposure is stopped, the risk of adverse health effects goes down.

5. I used water from my private well or surface water to irrigate my crops and garden vegetables. Am I going to get sick?

According to our evaluation, people who ate fruits or vegetables irrigated with contaminated well water are not at increased risk for non-cancer health effects. However, people who eat more than the average amount of fruits and vegetables (95th percentile consumers) might be at increased risk for developing cancer over a lifetime. This conclusion is based on a person eating approximately 4 times more fruits and vegetables than the average person every day for 30 years.

People who grew fruits and vegetables at their home and used their well water to irrigate their crops submitted crop samples for analysis. The analysis revealed that vegetables irrigated with well water did not cause a significant increase in contaminant levels (Weston 1998). As a precaution, however, we recommend washing all homegrown fruits and vegetables before eating them.

6. **I have lived in Lincoln Park since the 1960s. I know of many neighbors and family members who are sick. Is uranium from the mill making us sick?**

Uranium primarily acts as a heavy metal toxin. Renal toxicity is the hallmark effect of uranium exposure, specifically to the proximal tubules of the kidney. We looked at CDC's Compressed Mortality Database "WONDER" looking specifically at specific modes of kidney failure that could be associated with uranium toxicity. Fremont County in Colorado had an age adjusted rate for renal failure as the cause of death of 7.1 per 100,000, for the years 1999-2006. The state average during that same period was 12.1 per 100,000[13]. From the available health outcome data, it does not appear that residents in the area have elevated rates of kidney disease, which could be associated with uranium exposure.

7. **My husband worked at the plant. Was I possibly exposed when he brought his dirty work clothes home?**

Workers in industrial settings have the potential to expose their household members to work-related chemicals if residues attach to the worker's clothing, skin, shoes, or in their vehicles and is inadvertently brought into the home. Whether and to what magnitude these take-home exposures actually occur depends on a number of factors, including the nature of the job held by the worker, the occupational practices of the industrial facility (e.g., providing workers with disposable gowns and gloves), and the precautions/practices of the worker and other family members. ATSDR did not evaluate potential exposures to workers' families because the data needed to quantitatively or qualitatively make a determination on potential health effects were not available.

8. **I used contaminated water from my private well water for many years as a potable source of water for my family. Are we now at risk for adverse health effects?**

The levels of molybdenum were high enough in some wells to cause adverse health effects in individuals who were exposed for many years. Once exposure is stopped, the risk of adverse health effects goes down. Residents, particularly individuals who do not take in enough dietary copper or cannot process copper correctly, might be at increased risk for gout-like conditions. The levels of other contaminants are too low to cause adverse health effects.

9. **CCAT conducted a health survey and submitted it to ATSDR. Why didn't ATSDR use the results of this survey to determine if people are experiencing adverse health effects in the community?**

The community organization CCAT conducted a health survey in 2004–2005. The survey included responses from 239 individuals in the Lincoln Park area. Volunteers went door-to-door in Lincoln Park and the surrounding areas to administer the health surveys. Each person filled out a survey and submitted it to a volunteer. A tabulation of self-reported illnesses reported by respondents included occurrences of cancer; lung, health, skin, central nervous system, kidney, and thyroid problems; reproductive issues, including chromosomal and congenital defects;

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[13] Centers for Disease Control and Prevention, National Center for Health Statistics. Compressed Mortality File 1999-2006. CDC WONDER On-line Database, compiled from Compressed Mortality File 1999-2006 Series 20 No. 2L, 2009. Accessed at http://wonder.cdc.gov/cmf-icd10.html on Sep 30, 2009 10:42:05 AM

autoimmune disease, psychological disorders, and gout. Although ATSDR could not use the survey to make conclusions about disease associations, we did use the survey results to focus our attention and pursue a more in-depth scientific analysis of the health conditions identified by the community.

While the CCAT health survey was a good effort by the community to examine the frequency of their various health concerns, there are many issues that make it of limited use in determining the prevalence of adverse health effects present in the entire community and their potential associations with exposure to environmental contaminants. Some of these issues include the use of a relatively small convenience sample, the lack of medical verification of self-reported health outcomes, and the need for individual-level exposure data. Convenient samples are typically not representative of the entire population, so results cannot be extrapolated to the community. People who participate in nonrandomized surveys such as this may provide biased information because of perceived relationships between environmental contamination or other risk factors and their health. Many of the self-reported health outcomes measured in the survey are present in most populations and are related to several different potential causes beyond environmental exposures, such as lifestyle or genetics. Therefore, without any assessment of exposure, it is not possible to link the occurrence of disease to environmental concerns.

10. CDPHE previously ordered Cotter to have all environmental samples analyzed by an external laboratory until Cotter could demonstrate that its laboratory had addressed various deficiencies. Why was this done and how did it affect the data used by ATSDR?

Cotter’s license requires the company to collect and report a wide range of environmental measurements. Cotter’s own analytical laboratory conducted most of the measurements between the late 1970s and the present. The main exception is that an external analytical laboratory measured contamination levels in most of the samples collected in 2005 and 2006.

For many years, Cotter has participated in so-called “round robin” inter-laboratory performance evaluations. As part of these evaluations, selected environmental samples are split every calendar quarter and simultaneously sent to Cotter’s laboratory and to three external analytical laboratories for analysis. The measurement results are then compared to assess the performance of Cotter’s laboratory. CDPHE’s website presents data from these inter-laboratory comparisons from 2007 to the present. Earlier comparisons are not readily available, mostly because Cotter’s laboratory was not analyzing samples throughout much of 2005 and 2006 and data from earlier years have since been archived from CDPHE’s website.

In September 2008, Cotter submitted a letter to CDPHE documenting five quarters of inter-laboratory comparisons for groundwater samples [Cotter 2008]. These comparisons presented “round robin” data for more than two dozen substances or indicators, including uranium, molybdenum, selenium, nitrate, and selected radionuclides. In some cases, Cotter’s laboratory tended to measure higher concentrations than the other participating laboratories; but in other cases, the opposite was observed. With one exception, the differences between the measurements made by the various laboratories fell within the range typically observed or expected.

The exception is for molybdenum, for which Cotter's laboratory did not meet pre-established comparability limits for the "round robin" sampling. Specifically, in two out of the five quarters of samples that were collected, Cotter's laboratory did not meet the acceptable limits.[14] In contrast, the three external laboratories' molybdenum measurements met the pre-established comparability limits for all five quarters considered in this report. The table below presents the specific concentration measurements for the two quarters of interest, and these measurements show that (in these two instances) the molybdenum levels measured by Cotter were less than 50 percent of the average concentrations calculated from the three external laboratories' measurements.

After CDPHE requested that Cotter investigate the issue further, Cotter prepared a written response to the issue [Cotter 2009]. The response suggests that the poor performance on these samples resulted from the analytical method used. Cotter uses atomic adsorption to measure molybdenum levels in groundwater samples, and the external laboratories used a different method (inductively coupled plasma with mass spectrometry). When molybdenum concentrations are below roughly 0.5 mg/L, Cotter measures molybdenum by atomic adsorption *graphite furnace* analysis; but at higher concentrations, analysis is by atomic adsorption *flame* analysis. The two quarters with the poor comparisons both had concentration levels below 0.5 mg/L, leading Cotter to infer that the underreporting was associated with the graphite furnace analyses. In January 2009, Cotter proposed several measures that were believed to cause the graphite furnace analyses to perform better, and CDPHE approved of the proposed remedy.

Overall, the "round robin" studies have demonstrated that Cotter's analytical laboratory met pre-specified performance criteria for almost every one of the substances considered. Only for molybdenum was a performance issue noted, and it appears that Cotter's laboratory previously used a method that would understate molybdenum concentrations, but typically only when those concentrations were less than approximately 0.5 mg/L. This issue was observed for samples collected between January 2007 and March 2008, but it likely also affected earlier samples that Cotter's laboratory analyzed; and this negative bias should be considered in any uses of these data. Measurements collected since this timeframe likely do not exhibit the same negative bias, given the changes that Cotter proposed to its analytical methods.

Inter-Laboratory Comparison Results for Molybdenum: First Quarter 2007 & First Quarter 2008

Parameter	Analytical Laboratory			
	Cotter	Laboratory #1	Laboratory #2	Laboratory #3
Inter-Laboratory Comparison for First Quarter 2007				
Measurement 1 (mg/L)	0.012	0.0263	0.027	0.024
Measurement 2 (mg/L)	0.012	0.025	0.027	0.0232
Average (mg/L)	0.012	0.0257	0.027	0.0236
Avg across three comparison laboratories (mg/L)		0.025		
Inter-Laboratory Comparison for First Quarter 2008				
Measurement 1 (mg/L)	0.01	0.0281	0.029	0.0267
Measurement 2 (mg/L)	0.011	0.0274	0.029	0.0274
Average (mg/L)	0.011	0.0278	0.029	0.0271
Avg across three comparison laboratories (mg/L)		0.028		

Note: Every laboratory was supposed to analyze each sample twice, thus providing data allowing for intra-laboratory and inter-laboratory comparisons.

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[14] CDPHE actually voiced concern about three quarters of Cotter's molybdenum data, even though only two of these three quarters did not meet the pre-established comparability limits.

VII. CONCLUSIONS

ATSDR reached four important conclusions in this public health assessment:

1. ATSDR concludes that drinking water for many years from contaminated private wells could harm people’s health. This is a public health hazard.

   Private well sampling data collected from 1984 to 2007 revealed the presence of molybdenum at levels that could harm people’s health. A water use survey conducted in Lincoln Park in 1989 revealed that at least seven people used groundwater (from their private wells) for personal consumption. These and other residents whose private wells were affected by the highest molybdenum contamination may be at increased risk for health effects such as gout-like conditions, particularly individuals who do not take in enough dietary copper or cannot process copper correctly.

   The lack of consistent monitoring over the years and the unknown usage of wells before the installation of the public water supply make these past exposures difficult to accurately assess.

   Most town residents are now connected to the public water supply and have eliminated their exposure to the contaminated well water. However, some residents are reported to have refused public water supply connections, and many may still have operational private wells. Additionally, no formal institutional controls exist to control groundwater use in Lincoln Park. Therefore, current and future uses of private wells for domestic purposes are still possible.

2. ATSDR concludes that accidentally eating or touching soil and sediment near the Cotter Mill property or in Lincoln Park will not harm people’s health. However, ATSDR cannot make conclusions about soils near Cotter Mill if the properties closest to the facility are developed for residential or other non-industrial uses in the future.

3. ATSDR concludes that eating locally-grown fruits and vegetables irrigated with private well water will not harm most people’s health. However, a person eating above-average amounts of fruits and vegetables (4 times the average consumer) might have a low increased risk for developing cancer over a lifetime. As a precaution, residents should limit their use of contaminated well water to irrigate their crops. In all cases, the crops should be thoroughly cleaned prior to eating.

4. ATSDR concludes that ambient air emissions of particle bound radionuclides have not resulted in completed exposures to the public at levels that could cause adverse health outcomes. With the exception of thorium-230 levels observed in 1981 and 1982, associated with excavation of contaminated tailings, every radionuclide monitored has been more than a factor of ten below annual dose based health limits to the public. The excavation releases appear to have only exposed on-site workers, but still below occupational limits at that time.

VIII. RECOMMENDATIONS

Based upon ATSDR's review of the environmental data and the concerns expressed by community members, the following recommendations are appropriate and protective of the health of residents in and around the Lincoln Park area.

- Residents should be informed about the health risks associated with contaminated private wells and advised to connect to the public water supply if possible. Local officials should advise new residents who move to the area of the groundwater contamination and that they should have their water supply tested before using groundwater for household purposes.

- Residents should discontinue of use of any impacted private wells for household purposes, including watering livestock and crops.

- CDPHE should continue to monitor the groundwater contaminant plume to assess whether additional wells may be impacted in the future.

- CDPHE should conduct a water use survey in the affected area to determine how groundwater is being utilized by residents in Lincoln Park.

- CDPHE should evaluate the need for further analysis of lead in soil should the areas adjacent to the Cotter Mill property change current use patterns.

- ATSDR in the short-term, and CDPHE in the long-term, should advise residents who have fruit and vegetable gardens to wash the crops thoroughly before eating them. This measure is just a precaution to remove soil adhering to the surface of the crop.

IX. PUBLIC HEALTH ACTION PLAN

The public health action plan for the site contains a description of actions that have been taken or will be taken by ATSDR or other government agencies at the site. The purpose of the public health action plan is to ensure that this document both identifies public health hazards and provides a plan of action designed to mitigate and prevent harmful human health effects resulting from exposure to the hazardous substances at this site.

Public health actions COMPLETED:

- ATSDR conducted site visits to gather community health concerns, to communicate to identified stakeholders, and to gather relevant site-related data;

- ATSDR's Exposure Investigations and Site Assessment Branch (EISB) performed two Exposure Investigations to 1) evaluate blood lead levels in children living in the Lincoln Park area and 2) evaluate lead in dust in homes in the Lincoln Park area. (These documents are available on our website at www.atsdr.cdc.gov.)

Public health actions PLANNED:

- ATSDR's Health Promotion and Community Involvement Branch (HPCIB) will conduct health-related educational activities in the community, as necessary.

- ATSDR's HPCIB will coordinate community outreach and community involvement activities for the site.

- ATSDR will continue to work with appropriate state and federal agencies and review, if requested, additional relevant environmental data (including the water use survey) as it becomes available.

- ATSDR will re-evaluate and revise the public health action plan if needed. New environmental, toxicological, health outcome data, or implementing the above proposed actions may necessitate the need for additional or alternative actions at this site.

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XI. REFERENCES

[ATSDR] Agency for Toxic Substances and Disease Registry. 2006a. Health Consultation, Blood Lead Levels in Children in the Lincoln Park Neighborhood, Cañon City, Fremont County, Colorado. November 16, 2006. Available at: http://www.atsdr.cdc.gov/HAC/pha/LincolnParkBloodLeadLevels/LincolnPark-BloodLeadLevelsChildrenHC11.16.06.pdf.

[ATSDR] Agency for Toxic Substances and Disease Registry. 2006b. Health Consultation, Blood Levels in the Cañon City Vicinity, Fremont County, Colorado. November 16, 2006. Available at: http://www.atsdr.cdc.gov/HAC/pha/CanonCityBloodLevels/BloodLevels-CanonCityEI11.16.06.pdf.

[ATSDR] Agency for Toxic Substances and Disease Registry. 2006c. Health Consultation, Lead in Dust in Homes in the Lincoln Park Neighborhood, Cañon City, Fremont County, Colorado. November 16, 2006. Available at: http://www.atsdr.cdc.gov/HAC/pha/LincolnParkDustinLeadinHomes/LincolnPark-LeadinDustHC11.16.06.pdf.

[ATSDR] Agency for Toxic Substances and Disease Registry. 2006d. Health Consultation, Exposure Investigation Report: Lead in Indoor Dust, Outdoor Soil, and Blood of Lincoln Park Neighborhood Residents. November 16, 2006. Available at: http://www.atsdr.cdc.gov/HAC/pha/LincolnParkLeadinIndoo%20Dust/LincolnPark-LeadEI11.16.06.pdf.

[ATSDR] Agency for Toxic Substances and Disease Registry, 2007. Toxicological profile for arsenic (update). Atlanta: US Department of Health and Human Services. 2007.

[ATSDR] Agency for Toxic Substances and Disease Registry, 1999. Toxicological profile for uranium (update). Atlanta: US Department of Health and Human Services. September 1999.

[ATSDR] Agency for Toxic Substances and Disease Registry, 2006e. ToxFACTS Chemical Agent Briefing Sheet - Arsenic. Atlanta: US Department of Health and Human Services. January 2006.

[ATSDR] Agency for Toxic Substances and Disease Registry, 2004. Interaction Profile for: arsenic, cadmium, chromium, and lead. Atlanta: US Department of Health and Human Services. May 2004.

[BEIR IV]. Committee on the Biological Effects of Ionizing Radiations, National Research Council. 1988. Health risks of radon and other internally deposited alpha-emitters. Washington DC: National Academy Press.

[CCAT] Colorado Citizens Against Toxic Waste. 2004-2005 Lincoln Park Health Survey, Cañon City, Colorado 81212.

[CDC] Centers for Disease Control and Prevention. 1998. Estimation of the impact of the former Feed Materials Production Center (FMPC) on lung cancer mortality in the surrounding community. Atlanta: US Department of Health and Human Services Public Health Service; 1998 Dec.

[CDPHE 1975] Colorado Department of Public Health and Environment. 1975. Letter to Fred Matter, Cotter Corporation, from Joe Virgona, CDPHE, concerning the chronological report on Cotter Corporation. July 1975.

[CDPHE 2003] Colorado Department of Public Health and Environment, Laboratory Services Division. 2003. Results of Sampling for Plutonium, Uranium, Lead and Molybdenum in the Cañon City Vicinity. July 2003.

[CDPHE 2005] Colorado Department of Public Health and Environment. 2005. Cotter Cañon City Uranium Mill 1988 Remedial Action Plan, Summary and Status – August 2005. Available at: http://www.cdphe.state.co.us/hm/cotter/rapsummary050826.pdf.

[CDPHE 2007a] Colorado Department of Public Health and Environment. 2007a. Letter to Mr. John Hamrick, Cotter Corporation, from Steve Tarlton, CDPHE, concerning the Cotter Corporation Cañon City Mill Impoundments evaluation. June 14, 2007.

[CDPHE 2007b] Colorado Department of Public Health and Environment. 2007b. Cotter Mill Site Monitoring Database: data through September 25, 2007.

[CDPHE 2008] Colorado Department of Public Health and Environment. 2008. Cotter Corporation Uranium Mill Site Description. Available at: http://www.cdphe.state.co.us/hm/cotter/sitedescript.htm.

[CDPHE 2001] Colorado Department of Public Health and the Environment. 2001. 6 CCR 1007-1, Part 18, State Board of Health Licensing Requirements for Uranium and Thorium Processing. Hazardous Materials and Waste Management Division, Radiation Control, November 2001.

[CDPHE 2005b] Colorado Department of Public Health and the Environment. 2005. Cotter Cañon City Uranium Mill 1988 Remedial Action Plan Summary and Status – August 2005b.

[CDPHE 2005c] Colorado Department of Public Health and the Environment. 2005. 6 CCR 1007-1, Part 3, Licensing of Radioactive Material. Hazardous Materials and Waste Management Division, State Board of Health Rules and Regulations Pertaining to Radiation Control, July 2005.

[CDPHE 2009] Colorado Department of Public Health and the Environment. 2009. Radioactive Materials License 369-01, Amendment 50, February 2009.

Chen J, Meyerhof DP, Tracy BL. 2004. Model results of kidney burdens from uranium intakes. Health Phys 86(1):3-11 (2004).

Cotter. 2000. Sand Creek Project Cleanup Report. June 2000.

[Cotter 2007] Environmental and occupational performance report, ALARA review and annual report on remedial action plan activities. Calendar year 2006. Cañon City Milling Facility. June 29, 2007. Available at: http://www.cdphe.state.co.us/hm/cotter/LetterFromCotter/2006perfrpt/.

Cotter. 2008. Operational unit 2 (OU2) Lincoln Park water use survey. April 7, 2008. Available at: http://www.cdphe.state.co.us/hm/cotter/08cotterdocs.htm.

[Cotter 2004a] Cotter Corporation, Cañon City Milling Facility. 2004. Procedure: Environmental Air Particulate Sampling, #EV-020, Revision 5. July 2004.

[Cotter 2004b] Cotter Corporation, Cañon City Milling Facility. 2004. Procedure: Radon-222/220 Air Surveys, #EV-030, Revision 2. July 2004.

[Cotter 2008b] Cotter Corporation, Cañon City Milling Facility. 2008. Environmental and Occupational Performance Report, ALARA Review, and Annual Report on Remedial Action Plan Activities for Calendar Year 2008.

[Cotter 2009b] Cotter Corporation, Cañon City Milling Facility. 2009. Quality Assurance Program Plan for Environmental and Occupational Sampling and Monitoring Studies for the Cotter Corporation, Cañon City Milling Facility and Lincoln Park, Colorado Superfund Site. Prepared by Environmental Alternatives, Inc., May 2009.

Diamond GL. 1989. Biological consequences of exposure to soluble forms of natural uranium. Rad Protect Dosim 26: 23-33.

[DOE] United States Department of Energy. 2003. Fiscal year 2003 status report, Reimbursements to licensees of active uranium and thorium processing sites. Title X of the Energy Policy Act of 1992. September 2003.

[DOE 1993] U.S. Department of Energy. 1993. Order 5400.5 Change 2. Radiation Protection of the Public and the Environment. Office of Environment, Safety, and Health, January, 1993.

[EA] Environmental Alternatives, Inc. 2007. Report on Semi-Annual Review of Well Permits. March 20, 2007. Available at: http://www.cdphe.state.co.us/hm/cotter/LetterFromCotter/wellpermitreview070329.pdf.

[EIA] Energy Information Administration, 2001, Web site: U.S. Department of Energy, http://www.eia.doe.gov/.

Eisenbud M, Quigley JA. 1955. Industrial hygiene of uranium processing. AMA Archives of Industrial Health. p. 12–22.

[EPA] Environmental Protection Agency, Environmental Response Team. 1995. Superfund Program, Representative Sampling Guidance, Volume 1: Soil. Interim Final. Available at: http://www.clu-in.org/download/char/SF_Rep_Samp_Guid_soil.pdf.

[EPA] Environmental Protection Agency. 2002. Record of Decision: Lincoln Park Study Area Surface Soils, Lincoln Park Superfund Site, Cañon City, Colorado. Available at: http://www.epa.gov/region08/superfund/co/lincolnpark/LincolnPkROD.pdf.

[EPA] Environmental Protection Agency, Superfund Technical Assessment and Response Team 2 - Region 8. 2004. Cañon City Lead Data Compilation Report, Cañon City, Fremont County, Colorado. March 24, 2004. Available at: http://www.epa.gov/region8/superfund/co/lincolnpark/.

[EPA] Environmental Protection Agency, Region 8. 2007. Final First 5-year review report for Lincoln Park Superfund site, Operable Unit 2. September 2007. Available at: http://www.epa.gov/region08/superfund/co/lincolnpark/LincolnPark5YrRvw07.pdf.

[EPA] Environmental Protection Agency, Region 8. 2008. Superfund Program: Lincoln Park. Available at: http://www.epa.gov/region8/superfund/co/lincolnpark/.

[EPA] Environmental Protection Agency, Integrated Risk Information System (IRIS). Cincinnati, OH: Office of Health and Environmental Assessment, Environmental Criteria and Assessment. Accessed June 16, 2009 at http://www.epa.gov/ncea/iris/subst/0425.htm.

[FNB] Food and Nutrition Board, Institute of Medicine. 2001. Molybdenum. In: Dietary reference intakes for vitamin A, vitamin K, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium, and zinc. Washington, D.C.: National Academy Press. p. 420–41.

[FDA] US Food and Drug Administration. 2008. Total Diet Study - Summary of Toxic and Nutritional Elements Found in TDS Foods. Accessed August 4, 2009 at . http://www.fda.gov/downloads/Food/FoodSafety/FoodContaminantsAdulteration/TotalDietStudy/UCM184301.pdf.

Galant, M.M., Linnert, T., and J. Dalton. 2007. Community involvement plan: Lincoln Park Superfund site and associated activities at the Cotter Corporation uranium mill. March 2007. Available at: http://www.cdphe.state.co.us/hm/cotter/lincolnparkcottercip.pdf.

[GeoTrans] GeoTrans, Inc. 1986. Remedial Investigation: Cotter Corporation Uranium Mill Site. February 1986.

[HRAP] Health Risk Assessment Panel, Cotter Uranium Mill Site. 1991. Health Risk Assessment of the Cotter Uranium Mill Site, Cañon City, Colorado. Prepared with the assistance of ENVIRON Corporation, Radiation Surveillance Associates, Radiant Energy Management, and Western Radiation Consultants. October 29, 1991.

Hodge HC. 1953. Resume of chapters 18 to 28. In: Voegtlin C and Hodge HC, eds. Pharmacology and toxicology of uranium compounds. National Nuclear Energy Series, Division VI, Vol 1, Part IV. New York: McGraw-Hill.

[IMS] IMS Inc. 1989. Lincoln Park Water Use Survey. Submitted to Cotter Corporation, Lakewood, Colorado. June 28, 1989.

[IPCS] International Programme on Chemical Safety. 2001.Environmental Health Criteria for Arsenic and Arsenic compounds. EHC 224, Chapter 1: Summary, section 4.

Juhasz, Albert L., Euan Smith, John Weber, Matthew Rees, Allan Rofe, Tim Kuchel, Lloyd Sansom, Ravi Naidu, Application of an In Vivo Swine Model for the Determination of Arsenic Bioavailability in Contaminated Vegetables. Chemosphere. Feb 7, 2008.

Killough GG, Case MJ, Meyer KR, et al. 1998. Fernald Dosimetry Reconstruction Project, Task 6—radiation doses and risk to residents from FMPC Operations from 1951-1988. Vol I and II (final report). Radiological Assessments Corporation Report No. CDC-1. Neeses, SC: 1998 Sep

[Koval'skiy] Koval'skiy, V.V., G.A. Yarovaya and D.M. Shmavonyan. 1961. Changes of purine metabolism in man and animals under conditions of molybdenum biogeochemical provinces. Zh. Obshch. Biol. 22: 179-191.

[Kurttio et al] Päivi Kurttio, Anssi Auvinen, Laina Salonen, Heikki Saha, Juha Pekkanen, Ilona Mäkeläinen, Sari B. Väisänen, Ilkka M. Penttilä, and Hannu Komulainen. Renal Effects of Uranium in Drinking Water. Environmental Health Perspectives Volume 110, Number 4, April 2002.

Laizu Jahanara. 2007. Speciation of arsenic in vegetables and their correlation with inorganic phosphate level. Bangladesh J Pharmacol 2007; 2:88-94.

Leggett RW. 1989. The behavior and chemical toxicity of U in the kidney: a reassessment. Health Phys 57(3): 365-383.

Leggett RW. 1994. Basis for ICRP's age-specific biokinetic model for uranium. Health Phys 67: 589-601.

[MFG] MFG, Inc. 2005. Assessment of potential dose to members of the public from materials along roads near the Cotter Corporation, Cañon City Milling Facility. May 2005. Available at: http://www.cdphe.state.co.us/hm/cotter/potentialdoseassessment.pdf.

Madsden KM, Nielsen S, Tisher CC. 2007. Chapter 2 – Anatomy of the Kidney from Brenner: Brenner and Rector's The Kidney, 8th ed. Oxford: Elsevier Science Ltd.

Maynard EA, Hodge HC. 1949. Studies of the toxicity of various uranium compounds when fed to experimental animals. In: Voegtlin IC, Hodge HC, eds. Pharmacology and toxicology of uranium compounds. National Nuclear Energy Series (VI). New York: McGraw-Hill; 309-376.

McDonald-Taylor CK, Singh A, Gilman A. 1997. Uranyl nitrate-induced tubule alterations in rabbits: a quantitative analysis. Toxicol Pathol 25(4): 381-389.

Morris SC, Meinhold AF. 1995. Probabilistic risk assessment of nephrotoxic effect of uranium in drinking water. Health Phys 69: 897-908.

[ODEQ] State of Oregon Department of Environmental Quality. 2003. Memorandum, Red Rock Road Project File, Evaluation Potential for Arsenic and Mercury Uptake into Garden Vegetables. September 22, 2003.

[NHANES] National Health and Nutrition Examination Survey. Third National Report on Human Exposure to Environmental Chemicals, Dept of Health and Human Services, Centers for Disease Control and Prevention. Atlanta, GA. July 2005.

Plasket, BJ. 2002. Cotter at the Crossroads: On the Hot Seat. The Daily Record News Group. Available at: http://www.timescall.com/cotter/cotter24.htm.

Spear JW. Trace mineral bioavailability in ruminants. J. Nutr. 2003; 133: 1506S—1509S.

Spoor NL, Hursh JB. 1973. Protection criteria. In: Hodge HC, Stannard JN, Hursh JB, eds. Handbook of experimental pharmacology. Berlin: Springer-Verlag; 241-270.

Stokinger HE, Baxter RC, Dygent HP, et al. 1953. In: Voegtlin C, Hodge HC, eds. Toxicity following inhalation for 1 and 2 years. National Nuclear Energy Series: Manhattan Project Technical Section, Div VI, Vol 1. New York: McGraw-Hill.

Turnlund JR. Molybdenum metabolism and requirements in humans. Met. Ions Bio. Syst. 2002; 39:727—739.

[USGS] United States Geological Survey. 1999a. Migration and Geochemical Evolution of Ground Water Affected by Uranium-Mill Effluent near Cañon City, Colorado. Water-Resources Investigations Report 98-4228. DT Chafin and ER Banta.

[USGS] United States Geological Survey. 1999b. Ground-Water Hydrology and Simulation of Five Remediation Alternatives for an Area Affected by Uranium-Mill Effluent near Cañon City, Colorado. ER Banta and DT Chafin.

[USNRC 1980] U.S. Nuclear Regulatory Commission. 1980. Regulatory Guide 4.14 Radiological Effluent and Environmental Monitoring at Uranium Mills, Revision 1. Office of Standards Development, April 1980.

[USNRC 1996] U.S. Nuclear Regulatory Commission. 1996. Regulatory Guide 4.20 Constraint on Releases of Airborne Radioactive Materials to the Environment for Licensees other than Power Reactors. Office of Nuclear Regulatory Research, December 1996.

Vousta D, Grimanis A, Samara C. 1996. Trace elements in vegetables grown in an industrial area in relation to soil and air particulate matter. Environ Pollution 94(3):325–35.

[Weston] Roy F. Weston, Inc. 1996. Supplemental Human Health Risk Assessment. Lincoln Park Superfund Site. Cañon City, Colorado. Phase II Evaluation. Baseline Human Health Risks in 1988. Final Report. Prepared for CDPHE. November 19, 1996.

[Weston] Roy F. Weston, Inc. 1998. Supplemental Human Health Risk Assessment, Lincoln Park Superfund Site, Cañon City, Colorado: Phase III Evaluation, Baseline Human Health Risks in 1994-1996. January 1998.

Wilder, RJ, DJ Goode, P Huidobro, MO Kozik, DR Cogley, NH Krusell, ME Connolly, EJ Limberakis, and AW Levin. 1983. Assessment of data concerning ground water contamination in the Lincoln Park section of Cañon City, Colorado. Final report prepared for EPA by GCA Corporation. May 1983.

[WHO] World Health Organization. 2003. Molydbenum in Drinking water: Background document for development of WHO *Guidelines for Drinking-water Quality*.

Zhao LS, Zhao SF. 1990. Nephrotoxic limit and annual limit on intake for natural U. Health Phys 58: 619-623.

Appendix A - Tables

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Table 14. Well Use in Lincoln Park, 1989

Well Number	Description	Reported Well Use				
		Personal Consumption	Irrigating Fruit	Irrigating Vegetable Gardens	Watering Livestock	Watering Lawns
117	Logan (LPWUS)		✓			✓
119	Birch (LPWUS)			✓		✓
122	Elm (LPWUS)					✓
123	Cedar (LPWUS)					✓
124	Elm (LPWUS)			✓		✓
129	Elm (LPWUS)		✓	✓		✓
130	Poplar (LPWUS)		✓			✓
138	Field well, Cedar (LPWUS)					✓
139	House well, Cedar (LPWUS)					✓
140	C. R. Ransom house well, Cedar (LPWUS)		✓	✓		✓
144	Cedar (LPWUS)		✓	✓	✓	✓
165	Spring, Elm (LPWUS)	✓		✓		✓
166	Willow (LPWUS)				✓	✓
168	Grand (house well) (LPWUS)	✓			✓	✓
173	Beulah (LPWUS)		✓			✓
174	Chestnut (LPWUS)		✓		✓	✓
189	Hickory (LPWUS)	✓				
198	Grand (LPWUS)	✓	✓	✓	✓	✓
206	Grand (field well) (LPWUS)				✓	
212	Cedar (LPWUS)		✓	✓		✓
219	Locust (LPWUS)	✓				
221	Elm (LPWUS)					✓
222	Elm (LPWUS)					✓

Well Number	Description	Reported Well Use				
		Personal Consumption	Irrigating Fruit	Irrigating Vegetable Gardens	Watering Livestock	Watering Lawns
223	Elm (LPWUS)				✓	
224	Elm (LPWUS)		✓			✓
226	Chestnut (LPWUS)					✓
229	Grand (LPWUS)				✓	✓
230	Birch (LPWUS)		✓			✓
231	Birch (LPWUS)		✓	✓		
235	Elm (LPWUS)				✓	
237	Elm (LPWUS)				✓	
239	Grand (LPWUS)		✓	✓	✓	✓
241	Grand (LPWUS)				✓	
243	Chestnut (LPWUS)					✓
245	Elm (LPWUS)				✓	
246	Elm (LPWUS)		✓			✓
252	Poplar (cistern* in barn) (LPWUS)					✓
255	Riley Dr. (LPWUS)	✓	✓			✓
261	Elm (LPWUS)		✓	✓		✓
262	Cedar (LPWUS)		✓	✓		✓
263	Willow (LPWUS)					✓
264	Chestnut (LPWUS)		✓	✓		✓
266	Willow (LPWUS)		✓	✓		✓
267	Willow (spring) (LPWUS)		✓	✓	✓	✓
269	Birch			✓		✓
273	Willow (cistern #1) (LPWUS)			✓		✓
274	Grand (LPWUS)		✓	✓		✓
278	Cedar (LPWUS)					✓

Well Number	Description	Reported Well Use				
		Personal Consumption	Irrigating Fruit	Irrigating Vegetable Gardens	Watering Livestock	Watering Lawns
280	Grand (LPWUS)				✓	
284	Spring - Grand St. (LPWUS)				✓	
285	Grand (LPWUS)				✓	
286	Willow (cistern #2) (LPWUS)				✓	
287	Willow (LPWUS)			✓		✓
288	Poplar (cistern* on porch)					✓
293	Cedar (LPWUS)		✓	✓	✓	✓
	Totals	6	22	20	19	42

Source: IMS 1989

*Modified from the original spelling: “cystern”
Street numbers have been excluded for privacy reasons.

LPWUS – Lincoln Park Water Use Survey

Table 15. Groundwater sampling data (chemicals) from wells used for personal consumption

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Location of Maximum	Date of Maximum	CV (mg/L)	Wells Sampled	Years Sampled
Chloride	N/T*	11/11	4.5	8.8	14	Spring, Elm [165]	13-Mar-84	250 (Secondary MCL)	165, 168	1984, 2005–2007
Iron	D	2/12	0.04	0.06	0.1	Grand (house well) [168]	19-Aug-05	26 (RBC)	165, 168	1984, 2004–2007
Manganese	D	2/12	0.002	0.008	0.01	Grand (house well) [168]	13-Dec-04	0.5 (RMEG, child)	165, 168	1984, 2004–2007
Molybdenum	D	52/59	0.007	**0.082**	**0.28**	Hickory [189]	19-Jan-89	0.035 (SS); 0.05 (RMEG, child)	165, 168, 189, 198, 219, 255	1984, 1988–1991, 1995, 2000–2007
Nitrate	T	8/8	0.5	2.9	7.7	Grand (house well) [168]	19-Mar-07	10 (MCL)	168	2005–2007
Selenium	D	0/2	ND	ND	ND	--	--	0.05 (c-EMEG, child)	165, 168	1984
Sulfate	N/T*	11/11	15	62	214	Grand (house well) [168]	19-Aug-05	250 (Secondary MCL)	165, 168	1984, 2005–2007
Total Dissolved Solids	N/T*	11/11	240	330	410	Spring, Elm [165]	13-Mar-84	500 (Secondary MCL)	165, 168	1984, 2005–2007
Uranium	D	56/57	0.001	0.028	**0.067**	Hickory [189]	15-Dec-06	0.03 (MCL)	165, 168, 189, 198, 219, 255	1984, 1988–1991, 1995, 2001–2007

Source: CDPHE 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
The source of water used for personal consumption at 1935 Elm [165] was a spring.

* For chloride, sulfate, and total dissolved solids, 1984 data were designated “N” and 2005–2007 data were designated “T”.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
D – dissolved
LTHA – lifetime health advisory for drinking water
MCL – maximum contaminant level
mg/L – milligrams per liter
N – not defined in the CDPHE database
ND – not detected
RBC – risk based concentration for drinking water
RMEG – reference dose media evaluation guide
SS – Colorado state groundwater standard
T – total

Table 16. Groundwater sampling data (chemicals) from background wells

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Date of Maximum	CV (mg/L)	Years Sampled
Aluminum	D	0/25	ND	ND	ND	--	10 (c-EMEG, child)	1981, 1988–1994
Ammonia	N	3/45	0.02	0.4	4.2	26-Jan-90	30 (LTHA)	1988–1994
Ammonium	T	0/3	ND	ND	ND	--	NA	1995
Chloride	N/T*	168/168	3	12	110.3	07-Jan-80	250 (Secondary MCL)	1975, 1976, 1978–2007
Iron	D	24/79	0.02	0.03	0.3	16-May-89	26 (RBC)	1981–2007
Manganese	D	13/79	0.005	0.007	0.05	16-Mar-99	0.5 (RMEG, child)	1981–2007
Molybdenum	D	116/193	0.005	0.023	**0.3**	09-Nov-82, 09-Jun-76	0.035 (SS); 0.05 (RMEG, child)	1975, 1976, 1979–2007
Nitrate	N/T*	70/79	0.4	2.5	**50.4****	10-Feb-89	10 (MCL)	1988–2007
Selenium	D	10/103	0.001	0.003	0.015	15-Apr-80	0.05 (c-EMEG, child)	1975, 1977–1988, 1996–2000
Sulfate	N/T*	171/171	10	61	**434**[§]	18-Aug-80	250 (Secondary MCL)	1975–2007
Total Dissolved Solids	N/T*	171/171	286	429	**1,580**[†]	18-Aug-80	500 (Secondary MCL)	1980–2007
Uranium	D	155/193	0.004	0.021	**0.29**	07-Aug-79	0.03 (MCL)	1975–1977, 1979–2007

Source: CDPHE 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
The USGS identified Well 10 (1220 So. 12th St.) and Well 114 (1408 Pine) as representative of background for the Lincoln Park area (Weston 1998).

* For chloride, nitrate, sulfate, and total dissolved solids, pre-1995 data were designated “N” and post-1995 data were designated “T”.
** Only two of 79 samples were above the CV.

[§] Only one of 171 samples was above the CV.
[†] The maximum concentration appears to be an outlier. The next highest concentration is 590 mg/L.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
D – dissolved
LTHA – lifetime health advisory for drinking water
MCL – maximum contaminant level
mg/L – milligrams per liter
N – not defined in the CDPHE database
NA – not available
ND – not detected
RBC – risk based concentration for drinking water
RMEG – reference dose media evaluation guide
SS – Colorado state groundwater standard
T – total

Table 17. Groundwater sampling data (chemicals) from the Grand Avenue Well

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Date of Maximum	CV (mg/L)	Years Sampled
Chloride	N/T*	10/10	4.5	8.250	11	20-Jun-84, 20-Jun-05	250 (Secondary MCL)	1984, 2005–2007
Iron	D	2/11	0.04	0.06	0.1	19-Aug-05	26 (RBC)	1984, 2004–2007
Manganese	D	2/11	0.002	0.009	0.01	13-Dec-04	0.5 (RMEG, child)	1984, 2004–2007
Molybdenum	D	15/20	0.008	0.01	0.015	21-Jun-04	0.035 (SS); 0.05 (RMEG, child)	1984, 1988–1991, 2004–2007
Nitrate	T	8/8	0.5	2.9	7.7	19-Mar-07	10 (MCL)	2005–2007
Selenium	D	0/1	ND	ND	ND	--	0.05 (c-EMEG, child)	1984
Sulfate	N/T*	10/10	15	58	214	19-Aug-05	250 (Secondary MCL)	1984, 2005–2007
Total Dissolved Solids	N/T*	10/10	240	322	402	19-Mar-07	500 (Secondary MCL)	1984, 2005–2007
Uranium	D	20/20	0.001	0.013	0.0218	28-Mar-05	0.03 (MCL)	1984, 1988–1991, 2004–2007

Source: CDPHE 2007b

Averages were calculated using ½ the reporting detection limit for non-detects.
* For chloride, sulfate, and total dissolved solids, 1984 data were designated “N” and 2005–2007 data were designated “T”.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
D – dissolved
MCL – maximum contaminant level
mg/L – milligrams per liter
N – not defined in the CDPHE database

ND – not detected
RBC – risk based concentration for drinking water
RMEG – reference dose media evaluation guide
SS – Colorado state groundwater standard
T – total

Table 18. Groundwater sampling data (chemicals) from wells used to irrigate fruit and vegetable gardens

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Location of Maximum	Date of Maximum	CV (mg/L)	Wells Sampled	Years Sampled
Aluminum	D	3/120	0.01	0.186*	0.02	Elm [124] & Elm [129]	15-Mar-95	10 (c-EMEG, child)	117, 119, 124, 129, 130, 140, 144	1981, 1988–1995
Ammonia	N	10/53	0.01	0.3	0.6	house well, Cedar [140]	23-Aug-88	30 (LTHA)	119, 124, 129, 130, 140, 144	1988–1995
Ammonium	T	0/3	ND	ND	ND	--	--	NA	119, 140, 144	1995
Cadmium	D	0/3	ND	ND	ND	--	--	0.002 (c-EMEG, child)	119, 140, 144	1995
Chloride	N/T**	784/793	2.5	19.6	232	house well, Cedar [140]	05-Apr-79	250 (Secondary MCL)	117, 119, 124, 129, 130, 140, 144, 165, 174, 224	1970, 1975, 1976, 1978–2007
Copper	D	0/3	ND	ND	ND	--	--	0.1 (i-EMEG, child)	119, 140, 144	1995
Iron	D	114/398	0.011	0.029	0.31	Elm [129]	21-Apr-03	26 (RBC)	117, 119, 124, 129, 130, 140, 144, 165, 174, 224	1970, 1981–2007
Manganese	D	69/397	0.0007	0.008	0.13	house well, Cedar [140]	09-Sep-94	0.5 (RMEG, child)	117, 119, 124, 129, 130, 140, 144, 165, 174, 224	1981–2007
Molybdenum	D	1,052/1,077	0.004	0.99	42	house well, Cedar [140]	12-May-73	0.035 (SS); 0.05 (RMEG, child)	All 28 wells (see Table 14)	1968–2007
Nickel	D	0/3	ND	ND	ND	--	--	0.2 (RMEG, child)	119, 140, 144	1995

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Location of Maximum	Date of Maximum	CV (mg/L)	Wells Sampled	Years Sampled
Nitrate	N/T**	159/185	0.1	1.7	9.8	Cedar [144]	14-May-70	10 (MCL)	119, 124, 129, 130, 140, 144, 174, 224	1970, 1988–2007
Selenium	D	115/626	0.001	0.003	**0.082**[†]	house well, Cedar [140]	21-Apr-78	0.05 (c-EMEG, child)	117, 119, 124, 129, 130, 140, 144, 165, 174, 224, 264	1974–1988, 1995–2000
Sulfate	N/T**	798/800	8	214	**25,460**[‡]	house well, Cedar [140]	07-May-79	250 (Secondary MCL)	117, 119, 124, 129, 130, 140, 144, 165, 174, 224	1970, 1975–2007
Total Dissolved Solids	N/T**	767/767	31	**550**	**3,438**	house well, Cedar [140]	20-Apr-81	500 (Secondary MCL)	117, 119, 124, 129, 130, 140, 144, 165, 174, 224	1970, 1980–2007
Uranium	D	1,048/1,088	0.0003	**0.13**	**2.54**	house well, Cedar [140]	05-Jan-79	0.03 (MCL)	All 28 wells (see Table 14)	1962–1964, 1967, 1968, 1971, 1974–2007
	S	1/20	0.081	0.005[§]	**0.081**	house well, Cedar [140]	27-May-97		140, 174, 224	1995–2000
Vanadium	D	0/3	ND	ND	ND	--	--	0.03 (i-EMEG, child)	119, 140, 144	1995
Zinc	D	2/3	0.005	0.01	0.022	Birch [119]	25-Aug-95	3 (c-EMEG, child)	119, 140, 144	1995

Source: CDPHE 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
The source of water used to water fruits and vegetable gardens at 1935 Elm [165] was a spring.

* The calculated average is higher than the maximum detected concentration due to including ½ the detection limit in the calculation.
** For chloride, nitrate, sulfate, and total dissolved solids, pre-1995 data were designated “N” and post-1995 data were designated “T”.
[†] Only two of 626 samples were above the CV.
[‡] The maximum concentration appears to be an outlier. The next highest concentration is 1,948 mg/L from the same well [140] in 1981.
[§] The calculated average is lower than the minimum detected concentration due to including ½ the detection limit in the calculation.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
D – dissolved
i-EMEG – intermediate environmental media evaluation guide
LTHA – lifetime health advisory for drinking water
MCL – maximum contaminant level
mg/L – milligrams per liter
N – not defined in the CDPHE database
NA – not available
ND – not detected
RBC – risk based concentration for drinking water
RMEG – reference dose media evaluation guide
S – suspended
SS – Colorado state groundwater standard
T – total

Table 19. Groundwater sampling data (radionuclides) from wells used to irrigate fruit and vegetable gardens

Radionuclide	Type	Frequency of Detection	Minimum (pCi/L)	Average (pCi/L)	Maximum (pCi/L)	Location of Maximum	Date of Maximum	CV (pCi/L)	Wells Sampled	Years Sampled
Lead-210	D	29/29	-0.2	0.22	1.5	Birch [119]	21-Jun-95	NA	119, 140, 144, 174, 224	1995–2000
	S	20/20	-0.1	0.15	0.6	house well, Cedar [140]	22-Feb-96, 05-May-99		140, 174, 224	1995–2000
Polonium-210	D	29/29	-0.1	0.13	0.6	Cedar [144]	08-Mar-95, 21-Jun-95,	NA	119, 140, 144, 174, 224	1995–2000
	S	20/20	0	0.12	0.6	house well, Cedar [140]	22-Feb-96, 05-Dec-96		140, 174, 224	1995–2000
Radium-226	D	29/29	0	0.12	0.5	house well, Cedar [140]	12-May-95	5 (MCL radium-226/228)	119, 140, 144, 174, 224	1995–2000
	S	19/19*	0	0	0	--	--		140, 174, 224	1995–2000
Thorium-230	D	28/28	-0.1	0.08	0.3	Birch [119] house well, Cedar [140]	25-Aug-95 21-Feb-95	NA	119, 140, 144, 174, 224	1995–2000
	S	17/17	0	0.08	0.3	house well, Cedar [140]	05-May-99		140, 174, 224	1995–2000

Source: CDPHE 2007b

Averages were calculated using ½ the reporting detection limit for non-detects.
Negative and zero result values were included in the summary statistics.
*The detect flag is "Y" for all 19 samples, however, the result value is zero for all 19 samples.

CV – comparison value
D – dissolved
MCL – maximum contaminant level
NA – not available
pCi/L – picocuries per liter
S – suspended

Table 20. Groundwater sampling data (chemicals) from wells used to water livestock

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Location of Maximum	Date of Maximum	CV (mg/L)	Wells Sampled	Years Sampled
Aluminum	D	0/19	ND	ND	ND	--	--	10 (c-EMEG, child)	144	1981, 1988–1995
Ammonia	N	0/10	ND	ND	ND	--	--	30 (LTHA)	144	1988–1995
Ammonium	T	0/1	ND	ND	ND	--	--	NA	144	1995
Cadmium	D	0/1	ND	ND	ND	--	--	0.002 (c-EMEG, child)	144	1995
Chloride	N/T*	160/160	2.5	14	185	Cedar [144]	24-Aug-83	250 (Secondary MCL)	144, 166, 168, 174	1970, 1975, 1976, 1979–1989, 1991–2007
Copper	D	0/1	ND	ND	ND	--	--	0.1 (i-EMEG, child)	144	1995
Iron	D	27/97	0.03	0.04	0.19	Cedar [144]	18-Oct-01	26 (RBC)	144, 166, 168, 174	1970, 1981–2007
Manganese	D	14/96	0.0007	0.007	0.02	Cedar [144]	13-Jul-81, 13-Sep-83, 17-May-01, 06-Jun-02, 23-Oct-03	0.5 (RMEG, child)	144, 166, 168, 174	1981–2007
Molybdenum	D	271/286	0.006	0.212	1	Cedar [144]	12-May-71	0.035 (SS); 0.05 (RMEG, child)	All 19 wells (see Table 14)	1968–1971, 1975–1977, 1979–2007
Nickel	D	0/1	ND	ND	ND	--	--	0.2 (RMEG, child)	144	1995

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Location of Maximum	Date of Maximum	CV (mg/L)	Wells Sampled	Years Sampled
Nitrate	N/T*	55/58	0.1	1.8	9.8	Cedar [144]	14-May-70	10 (MCL)	144, 168, 174	1970, 1988–2007
Selenium	D	10/119	0.001	0.003	0.011	Cedar [144]	19-Mar-80	0.05 (c-EMEG, child)	144, 166, 168, 174	1975–1977, 1979–1988, 1995–2000
Sulfate	N/T*	162/162	10	95	**1,650****	Cedar [144]	18-Aug-80	250 (Secondary MCL)	144, 166, 168, 174	1970, 1975–1977, 1979–1989, 1991–2007
Total Dissolved Solids	N/T*	162/162	195	465	**860**	Cedar [144]	18-Aug-80	500 (Secondary MCL)	144, 166, 168, 174	1970, 1980–2007
Uranium	D	283/302	0.001	**0.034**	**0.46**	Cedar [144]	28-Jun-68	0.03 (MCL)	All 19 wells (see Table 14)	1962–1964, 1967, 1968, 1971, 1975–1977, 1979–2007
	S	0/1	ND	ND	ND	--	--		174	1996
Vanadium	D	0/1	ND	ND	ND	--	--	0.03 (i-EMEG, child)	144	1995
Zinc	D	0/1	ND	ND	ND	--	--	3 (c-EMEG, child)	144	1995

Source: CDPHE 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
* For chloride, nitrate, sulfate, and total dissolved solids, pre-1995 data were designated “N” and post-1995 data were designated “T”.
** The maximum concentration appears to be an outlier. The next highest concentration is 340 mg/L from the same well [144] in 1984.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
D – dissolved
i-EMEG – intermediate environmental media evaluation guide
LTHA – lifetime health advisory for drinking water
MCL – maximum contaminant level
mg/L – milligrams per liter
N – not defined in the CDPHE database
ND – not detected
RBC – risk based concentration for drinking water
RMEG – reference dose media evaluation guide
S – suspended
SS – Colorado state groundwater standard
T – total

Table 21. Groundwater sampling data (radionuclides) from wells used to water livestock

Radionuclide	Type	Frequency of Detection	Minimum (pCi/L)	Average (pCi/L)	Maximum (pCi/L)	Location of Maximum	Date of Maximum	CV (pCi/L)	Wells Sampled	Years Sampled
Lead-210	D	4/4	-0.1	0.1	0.3	Cedar [144]	08-Mar-95	NA	144, 174	1995, 1996
	S	1/1	0.2	0.2	0.2	Chestnut [174]	19-Sep-96		174	1996
Polonium-210	D	4/4	-0.1	0.3	0.6	Cedar [144]	08-Mar-95, 21-Jun-95	NA	144, 174	1995, 1996
	S	1/1*	0	0	0	Chestnut [174]	19-Sep-96		174	1996
Radium-226	D	4/4	0.1	0.1	0.1	--**	--**	5 (MCL radium-226/228)	144, 174	1995, 1996
	S	1/1*	0	0	0	Chestnut [174]	19-Sep-96		174	1996
Thorium-230	D	4/4	0	0.05	0.1	Cedar [144] Chestnut [174]	20-Sep-95 19-Sep-96	NA	144, 174	1995, 1996
	S	1/1*	0	0	0	Chestnut [174]	19-Sep-96		174	1996

Source: CDPHE 2007b

Averages were calculated using ½ the reporting detection limit for non-detects.
Negative and zero result values were included in the summary statistics.
* The detect flag is “Y” for the one sample, however, the result value is zero.
** All four result values were 0.1 pCi/L.

CV – comparison value
D – dissolved
MCL – maximum contaminant level
NA – not available
pCi/L – picocuries per liter
S – suspended

Table 22. Groundwater sampling data (chemicals) from wells used to water lawns

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Location of Maximum	Date of Maximum	CV (mg/L)	Wells Sampled	Years Sampled
Aluminum	D	11/239	0.01	0.19*	0.13	Field well, Cedar [138]	18-Dec-90	10 (c-EMEG, child)	117, 119, 122, 123, 124, 129, 130, 138, 139, 140, 144	1981, 1988–1995
Ammonia	N	21/112	0.01	0.3	0.9	Field well, Cedar [138]	23-Aug-88	30 (LTHA)	119, 122, 123, 124, 129, 130, 138, 139, 140, 144	1988–1995
Ammonium	T	0/5	ND	ND	ND	--	--	NA	119, 138, 139, 140, 144	1995
Cadmium	D	0/5	ND	ND	ND	--	--	0.002 (c-EMEG, child)	119, 138, 139, 140, 144	1995
Chloride	N/T**	1,362/1,372	2.5	30	450	Field well, Cedar [138]	12-Aug-80	250 (Secondary MCL)	117, 119, 122, 123, 124, 129, 130, 138, 139, 140, 144, 165, 166, 168, 174, 224	1970, 1975, 1976, 1978–2007
Copper	D	0/5	ND	ND	ND	--	--	0.1 (i-EMEG, child)	119, 138, 139, 140, 144	1995
Iron	D	205/683	0.005	0.031	0.31	Field well, Cedar [138] Elm [129]	09-Mar-95 21-Apr-03	26 (RBC)	117, 119, 122, 123, 124, 129, 130, 138, 139, 140, 144, 165, 166, 168, 174, 224	1970, 1981–2007

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Location of Maximum	Date of Maximum	CV (mg/L)	Wells Sampled	Years Sampled
Manganese	D	134/683	0.0005	0.008	0.13	house well, Cedar [140]	09-Sep-94	0.5 (RMEG, child)	117, 119, 122, 123, 124, 129, 130, 138, 139, 140, 144, 165, 166, 168, 174, 224	1979, 1981–2007
Molybdenum	D	1,755/1,790	0.004	**2.2**	**56.7**	Field well, Cedar [138]	11-Aug-72	0.035 (SS); 0.05 (RMEG, child)	All 42 wells (see Table 14)	1968–2007
Nickel	D	0/5	ND	ND	ND	--	--	0.2 (RMEG, child)	119, 138, 139, 140, 144	1995
Nitrate	N/T**	277/314	0.1	1.8	9.8	Cedar [144]	14-May-70	10 (MCL)	119, 122, 123, 124, 129, 130, 138, 139, 140, 144, 168, 174, 224	1970, 1988–2007
Selenium	D	320/1,105	0.001	0.005	**0.134**	Field well, Cedar [138]	13-Jul-81	0.05 (c-EMEG, child)	117, 119, 122, 123, 124, 129, 130, 138, 139, 140, 144, 165, 166, 168, 174, 224, 264	1974–1976, 1978–1988, 1995–2000
Sulfate	N/T**	1,382/1,384	8	**351**	**25,460**[†]	house well, Cedar [140]	07-May-79	250 (Secondary MCL)	117, 119, 122, 123, 124, 129, 130, 138, 139, 140, 144, 165, 166, 168, 174, 224	1970, 1975–2007

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Location of Maximum	Date of Maximum	CV (mg/L)	Wells Sampled	Years Sampled
Total Dissolved Solids	N/T**	1,311/1,311	31	**746**	**4,373**	Field well, Cedar [138]	06-Mar-81	500 (Secondary MCL)	117, 119, 122, 123, 124, 129, 130, 138, 139, 140, 144, 165, 166, 168, 174, 224	1970, 1980–2007
Uranium	D	1,733/1,789	0.0003	**0.233**	**5.161**	Field well, Cedar [138]	01-Aug-68	0.03 (MCL)	All 42 wells (see Table 14)	1962–1964, 1967, 1968, 1971, 1974–2007
	S	4/38	0.0067	0.010	**0.26**	Field well, Cedar [138]	27-May-97		138, 140, 174, 224	1995–2000
Vanadium	D	0/5	ND	ND	ND	--	--	0.03 (i-EMEG, child)	119, 138, 139, 140, 144	1995
Zinc	D	3/5	0.005	0.007	0.022	Birch [119]	25-Aug-95	3 (c-EMEG, child)	119, 138, 139, 140, 144	1995

Source: CDPHE 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
* The calculated average is higher than the maximum detected concentration due to including ½ the detection limit in the calculation.
** For chloride, nitrate, sulfate, and total dissolved solids, pre-1995 data were designated "N" and post-1995 data were designated "T".
† The maximum concentration and the second highest concentration (23,200 mg/L from Well 138 in 1978) appear to be outliers. The third highest concentration is 3,360 mg/L from Well 138 in 1979.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
D – dissolved
i-EMEG – intermediate environmental media evaluation guide
LTHA – lifetime health advisory for drinking water
MCL – maximum contaminant level
mg/L – milligrams per liter
N – not defined in the CDPHE database
ND – not detected
RBC – risk based concentration for drinking water
RMEG – reference dose media evaluation guide
S – suspended
SS – Colorado state groundwater standard
T – total

Table 23. Groundwater sampling data (radionuclides) from wells used to water lawns

Radionuclide	Type	Frequency of Detection	Minimum (pCi/L)	Average (pCi/L)	Maximum (pCi/L)	Location of Maximum	Date of Maximum	CV (pCi/L)	Wells Sampled	Years Sampled
Lead-210	D	53/53	-0.2	0.2	1.5	Birch [119]	21-Jun-95	NA	119, 138, 139, 140, 144, 174, 224	1995–2000
	S	38/38	-0.1	0.1	0.6	house well, Cedar [140]	22-Feb-96, 05-May-99		138, 140, 174, 224	1995–2000
	T	1/1*	0	0	0	Field well, Cedar [138]	06-Sep-96		138	1996
Polonium-210	D	53/53	-0.1	0.2	0.9	Field well, Cedar [138]	04-May-99	NA	119, 138, 139, 140, 144, 174, 224	1995–2000
	S	38/38	0	0.1	0.6	house well, Cedar [140]	22-Feb-96, 05-Dec-96		138, 140, 174, 224	1995–2000
	T	1/1	0.5	0.5	0.5	Field well, Cedar [138]	06-Sep-96		138	1996
Radium-226	D	51/51	0	0.1	0.5	house well, Cedar [140]	12-May-95	5 (MCL radium-226/228)	119, 138, 139, 140, 144, 174, 224	1995–2000
	S	37/37**	0	0.003	0.1	Field well, Cedar [138]	30-Oct-95		138, 140, 174, 224	1995–2000
	T	2/2	0	0.05	0.1	Field well, Cedar [138]	06-Sep-96		138	1995–1996
Thorium-230	D	51/51	-0.1	0.08	0.4	Field well, Cedar [138]	06-Aug-98	NA	119, 138, 139, 140, 144, 174, 224	1995–2000
	S	34/34	0	0.06	0.3	house well, Cedar [140]	05-May-99		138, 140, 174, 224	1995–2000
	T	1/1	0.1	0.1	0.1	Field well, Cedar [138]	06-Sep-96		138	1996

Source: CDPHE 2007b
Averages were calculated using ½ the reporting detection limit for non-detects.
Negative and zero result values were included in the summary statistics.
* The detect flag is “Y” for the one sample, however, the result value is zero.
** For all but one sample, the result value is zero.

CV – comparison value
D – dissolved
MCL – maximum contaminant level
NA – not available
pCi/L – picocuries per liter
S – suspended
T – total

Table 24. Groundwater sampling data (chemicals) from Well 138

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Date of Maximum	CV (mg/L)	Years Sampled
Aluminum	D	8/57	0.05	0.23*	0.13	18-Dec-90	10 (c-EMEG, child)	1981, 1988–1995
Ammonia	N	10/42	0.02	0.29	0.9	23-Aug-88	30 (LTHA)	1988–1995
Ammonium	T	0/1	ND	ND	ND	--	NA	1995
Cadmium	D	0/1	ND	ND	ND	--	0.002 (c-EMEG, child)	1995
Chloride	N/T**	199/199	5.5	70	450	12-Aug-80	250 (Secondary MCL)	1975, 1976, 1978–2000
Copper	D	0/1	ND	ND	ND	--	0.1 (i-EMEG, child)	1995
Iron	D	21/106	0.01	0.025	0.31	09-Mar-95	26 (RBC)	1981–2000
Manganese	D	21/107	0.01	0.008§	0.06	11-Jun-91	0.5 (RMEG, child)	1979, 1981–2000
Molybdenum	D	253/253	1.1	8.0	56.7	11-Aug-72	0.035 (SS); 0.05 (RMEG, child)	1968–1973, 1975, 1976, 1978–2000
Nickel	D	0/1	ND	ND	ND	--	0.2 (RMEG, child)	1995
Nitrate	N/T**	59/62	0.7	2.3	4.1	11-Jun-91	10 (MCL)	1988–2000
Selenium	D	102/151	0.001	0.011	0.134†	13-Jul-81	0.05 (c-EMEG, child)	1974–1976, 1978–1988, 1995–2000
Sulfate	N/T**	200/200	71	1,059	23,200‡	01-Nov-78	250 (Secondary MCL)	1975, 1976, 1978–2000
Total Dissolved Solids	N/T**	202/202	290	1,530	4,373	06-Mar-81	500 (Secondary MCL)	1980–2000

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Date of Maximum	CV (mg/L)	Years Sampled
Uranium	D	253/253	0.0005	**0.73**	**5.161**	01-Aug-68	0.03 (MCL)	1968, 1974–1976, 1978–2000
	S	3/18	0.007	0.016	**0.26**	27-May-97		1995–2000
Vanadium	D	0/1	ND	ND	ND	--	0.03 (i-EMEG, child)	1995
Zinc	D	0/1	ND	ND	ND	--	3 (c-EMEG, child)	1995

Source: CDPHE 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
* The calculated average is higher than the maximum detected concentration due to including ½ the detection limit in the calculation.
** For chloride, nitrate, sulfate, and total dissolved solids, pre-1995 data were designated “N” and post-1995 data were designated “T”.
[§] The calculated average is lower than the minimum detected concentration due to including ½ the detection limit in the calculation.
[†] Only three of 151 samples were above the CV.
[‡] The maximum concentration appears to be an outlier. The next highest concentration is 3,360 mg/L in 1979.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
D – dissolved
i-EMEG – intermediate environmental media evaluation guide
LTHA – lifetime health advisory for drinking water
MCL – maximum contaminant level
mg/L – milligrams per liter
N – not defined in the CDPHE database
NA – not available
ND – not detected
RBC – risk based concentration for drinking water
RMEG – reference dose media evaluation guide
S – suspended
SS – Colorado state groundwater standard
T – total

Table 25. Groundwater sampling data (radionuclides) from Well 138

Radionuclide	Type	Frequency of Detection	Minimum (pCi/L)	Average (pCi/L)	Maximum (pCi/L)	Date of Maximum	CV (pCi/L)	Years Sampled
Lead-210	D	21/21	-0.2	0.22	1.1	03-Aug-95	NA	1995–2000
	S	18/18	0	0.08	0.2	27-May-97, 06-Feb-98, 29-Jul-99, 19-Oct-99		1995–2000
	T	1/1*	0	0	0	06-Sep-96		1996
Polonium-210	D	21/21	0	0.28	0.9	04-May-99	NA	1995–2000
	S	18/18	0	0.11	0.4	28-Aug-00		1995–2000
	T	1/1	0.5	0.5	0.5	06-Sep-96		1996
Radium-226	D	19/19	0	0.13	0.4	21-Mar-96	5 (MCL radium-226/228)	1995–2000
	S	18/18	0	0.006	0.1	30-Oct-95		1995–2000
	T	2/2	0	0.05	0.1	06-Sep-96		1995, 1996
Thorium-230	D	20/20	0	0.07	0.4	06-Aug-98	NA	1995–2000
	S	17/17	0	0.04	0.2	04-May-99, 29-Jul-99		1995–2000
	T	1/1	0.1	0.1	0.1	06-Sep-96		1996

Source: CDPHE 2007b

Averages were calculated using ½ the reporting detection limit for non-detects.
Negative and zero result values were included in the summary statistics.
*The detect flag is "Y" even though the result value is zero.

CV – comparison value
D – dissolved
MCL – maximum contaminant level
NA – not available
pCi/L – picocuries per liter
S – suspended
T – total

Table 26. Surface soil sampling data (chemicals) from eight zones around the Cotter Mill and from Lincoln Park

Chemical		Zone A	Zone B	Zone C	Zone D	Zone E	Zone F	Zone G	Zone H	Lincoln Park	CV (ppm)
Arsenic	Range (ppm)	**33–69**	**19–39**	**14–42**	**10–40**	**16–38**	**17–60**	**17–33**	**19–86**	**13–50**	0.5 (CREG), 20 (c-EMEG, child)
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	73/73	
	Average (ppm)	**45**	**30**	**25**	**26**	**28**	**35**	**26**	**42**	**31**	
Beryllium	Range (ppm)	0.5–1.6	0.5–0.9	0.6–1	0.5–1.2	0.6–1.7	0.5–0.7	0.6–0.7	0.5–0.9	0.5–1.7	100 (c-EMEG, child)
	Frequency of Detection	9/10	11/12	9/12	10/10	6/8	8/8	4/4	7/8	72/73	
	Average (ppm)	0.8	0.7	0.7	0.6	0.7	0.6	0.7	0.6	0.7	
Cadmium	Range (ppm)	**1.2–15**	**2.1–13**	**2.2–16**	2.5–6.8	**5.3–18**	**8.9–110**	**1.6–20**	**4.4–51**	0.5–5	10 (c-EMEG, child)
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	68/73	
	Average (ppm)	6.9	6.4	6.4	4.1	9.8	**36.5**	7.9	**21.1**	1.4	
Lead	Range (ppm)	43–270	45–240	46–260	47–130	100–280	**68–800**	**37–450**	**61–1,400**	17–270	400 (SSL)
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	73/73	
	Average (ppm)	132	104	113	74	173	380	201	**445**	120	
Manganese	Range (ppm)	180–480	320–630	200–500	110–750	150–420	140–400	200–370	210–770	290–640	3,000 (RMEG , child)
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	73/73	
	Average (ppm)	336	422	356	391	298	268	290	439	424	
Selenium	Range (ppm)	5–7	39	7–16	5	ND	ND	ND	7	5–44	300 (c-EMEG, child)
	Frequency of Detection	5/10	1/12	2/12	1/10	0/8	0/8	0/4	1/8	7/73	
	Average (ppm)	4.2*	5.5*	4*	2.8*	ND	ND	ND	3.1*	3.5*	

Source: Weston 1998

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.

Each sample is a composite of four subsamples collected from the corners of a 10x10 square established near the center of the grid.
The dates the samples were collected were not specified in the report. It is assumed to be in the 1994–1996 timeframe.
See Figure for a map of the sampling zones.

* The calculated averages are lower than the minimum detected concentrations due to including ½ the detection limit in the calculation.

c-EMEG – chronic environmental media evaluation guide
CREG – cancer risk evaluation guide
CV – comparison value
ND – not detected
ppm – parts per million
RMEG – reference dose media evaluation guide
SSL – EPA’s soil screening level for residential areas

Table 27. Surface soil sampling data (radionuclides) from eight zones around the Cotter Mill and from Lincoln Park

Radionuclide		Zone A	Zone B	Zone C	Zone D	Zone E	Zone F	Zone G	Zone H	Lincoln Park	CV (pCi/g)
Lead-210	Range (pCi/g)	1.6–9.7	3.0–14.4	2.5–6.0	2.3–4.5	2.6–6.1	2.7–4.9	1.2–4.4	1.5–4.7	0.7–4.2	NA
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	58/58	
	Average (pCi/g)	6.3	8.2	4.1	3.4	4.4	3.9	2.9	2.6	2.1	
Radium-226	Range (pCi/g)	2.4–10.7	3.6–16.5	1.3–5.7	1.4–2.3	2.5–5.6	1.9–3.0	1.4–1.9	1.2–2.2	1.1–2.2	5 (UMTRCA, surface)
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	58/58	
	Average (pCi/g)	6.6	9.2	2.6	1.8	3.9	2.5	1.7	1.5	1.5	
Thorium-230	Range (pCi/g)	3.6–35.3	5.8–40.1	1.6–21.7	1.8–4.4	4.3–12.1	3.6–8.3	1.7–2.8	1.6–11.9	1.0–4.2	NA
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	58/58	
	Average (pCi/g)	17.7	20.9	5.9	2.5	7.7	5.2	2.4	3.3	1.7	
Uranium, natural	Range (pCi/g)	0.871–4.288	1.541–5.427	0.737–5.628	0.737–1.64	1.005–2.412	0.6432–1.943	0.5561–1.005	0.536–1.206	0.6566–3.417	NA
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	73/73	
	Average (pCi/g)	2.45	3.29	1.98	1.17	1.52	1.21	0.83	0.73	1.215	
Uranium-234	Range (pCi/g)	0.436–2.14	0.771–2.71	0.369–2.81	0.369–0.82	0.503–1.21	0.322–0.972	0.278–0.503	0.268–0.603	0.328–1.709	NA
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	73/73	
	Average (pCi/g)	1.23	1.65	0.991	0.584	0.758	0.606	0.413	0.366	0.607	

Radionuclide		Zone A	Zone B	Zone C	Zone D	Zone E	Zone F	Zone G	Zone H	Lincoln Park	CV (pCi/g)
Uranium-238	Range (pCi/g)	0.436–2.14	0.771–2.71	0.369–2.81	0.369–0.82	0.503–1.21	0.322–0.972	0.278–0.503	0.268–0.603	0.328–1.709	NA
	Frequency of Detection	10/10	12/12	12/12	10/10	8/8	8/8	4/4	8/8	73/73	
	Average (pCi/g)	1.23	1.65	0.991	0.584	0.758	0.606	0.413	0.366	0.607	

Source: Weston 1998

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that radionuclide.
The dates the samples were collected were not specified in the report. It is assumed to be in the 1994–1996 timeframe.
Each sample is a composite of four subsamples collected from the corners of a 10x10 square established near the center of the grid.
See Figure for a map of the sampling zones.

CV – comparison value
NA – not available
pCi/g – picocuries per gram
UMTRCA – 1978 Uranium Mill Tailings Radiation Control Act

Table 28. Surface soil sampling data (radionuclides) from the county road and the Cotter Uranium Mill access road

Radionuclide		Samples from background areas	Samples along the county road	Samples along the access road*	CV
Radium-226	Range (pCi/g)	0.8–2.1	3.8–14	2.7–**351**	5 pCi/g (UMTRCA, surface)
	Frequency of Detection	5/5	5/5	6/6	
	Average (pCi/g)	1.42	7.7	**65**	
Thorium-230	Range (pCi/g)	0.2–2.4	9.7–25	10–395	NA
	Frequency of Detection	3/5	5/5	6/6	
	Average (pCi/g)	1.53	20	87	
Uranium, natural	Range (ppm)	1.18–3.05	5.28–29.2	4.31–**922**	100 ppm (i-EMEG, child for highly soluble salts)
	Frequency of Detection	5/5	5/5	6/6	
	Average (ppm)	1.87	13.6	**161**	
Uranium-238**	Range (pCi/g)	0.39–1.01	1.74–9.64	1.42–304	NA
	Frequency of Detection	5/5	5/5	6/6	
	Average (pCi/g)	0.62	4.5	53	
Gamma Exposure Rates	Range (µR/hr)	NA	13.8–55.3	18.6–893	NA
	Frequency of Detection	NA	NA	NA	
	Average (µR/hr)	15.7	25.8	73.7	

Source: MFG 2005

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value.
Each sample consists of 10 aliquots taken from 0–6 inches within a 100 m^2 area.
See Figure for a map of the sampling locations.

*There is limited potential for exposure to contaminants along the access road since access to the Cotter Mill is restricted and soils along the access road were remediated in 2007 and 2008.
**Uranium-238 concentrations were calculated by multiplying the natural uranium concentrations by 0.33.

CV – comparison value
i-EMEG – intermediate environmental media evaluation guide
µR/hr – microroentgen per hour
NA – not available
pCi/g – picocuries per gram
ppm – parts per million
UMTRCA – 1978 Uranium Mill Tailings Radiation Control Act

Table 29. Soil data (chemicals) from samples taken by CDPHE, January 2003

Chemical	Frequency of Detection	Minimum (ppm)	Average (ppm)	Maximum (ppm)	Location of Maximum	CV (ppm)
Lead	20/20	23	410	3,651*	Private barn in Lincoln Park (dust sample)	400 (SSL)
Molybdenum	0/20	ND**	ND**	ND**	--	300 (RMEG , child)
Uranium	20/20	1.2	6.0	31	Mill Entrance Road	100 (i-EMEG, child for highly soluble salts)

Source: CDPHE 2003, 2007b

Concentrations from the Background Location§

Lead	36 ppm
Molybdenum	ND
Uranium	1.3 ppm

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
See Figure for a map of the sampling locations.
The sampling event was intentionally biased toward finding the highest amounts of contamination possible (CDPHE 2003).

*The second highest lead concentration is 908 ppm from a location northwest of the Cotter Mill.
**The molybdenum detection limit was 25 ppm.
§ Concentrations from the background location on the corner of Orchard Avenue and High Street were not included in the table.

CV – comparison value
i-EMEG – intermediate environmental media evaluation guide
ND – not detected
ppm – parts per million
RMEG – reference dose media evaluation guide
SSL – EPA’s soil screening level for residential areas

Table 30. Soil data (radionuclides) from samples taken by CDPHE, January 2003

Radionuclide	Frequency of Detection	Minimum (pCi/g)	Average (pCi/g)	Maximum (pCi/g)	Location of Maximum	CV (pCi/g)
Cesium-137	20/20	0	0.64	1.33	Private residence in Lincoln Park (dust sample)	NA
Lead-210	20/20	1.9	9.7	22.8	East of the Cotter Mill	NA
Plutonium-239, 240	9/20	0.03	0.03*	0.06	East of the Cotter Mill & a private residence in Lincoln Park (dust sample)	NA
Potassium-40	20/20	17.6	22.6	31.9	East of the Cotter Mill	NA
Radium-226	20/20	1.4	7.8	21.2	East of the Cotter Mill	15 (UMTRCA, subsurface)
Radium-228	20/20	0.6	1.0	1.3	Private barn in Lincoln Park (dust sample), private residence in Lincoln Park (dust sample), Pine St near Elm Ave in Lincoln Park (sediment sample), Northwest of the Cotter Mill	15 (UMTRCA, subsurface)

Source: CDPHE 2003, 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that radionuclide.
Averages were calculated using ½ the reporting detection limit for non-detects.
See Figure for a map of the sampling locations.
The sampling event was intentionally biased toward finding the highest amounts of contamination possible (CDPHE 2003).

* The calculated average is the same as the minimum detected concentration due to including ½ the detection limit in the calculation.
** Concentrations from the background location on the corner of Orchard Avenue and High Street were not included in the table.

CV – comparison value
NA – not available
pCi/g – picocuries per gram
UMTRCA – 1978 Uranium Mill Tailings Radiation Control Act

<u>Concentrations from the Background Location</u>**

Cesium-137	0.2 pCi/g
Lead-210	3.2 pCi/g
Plutonium-239, 240	ND
Potassium-40	19.5 pCi/g
Radium-226	1.9 pCi/g
Radium-228	1.0 pCi/g

Table 31. Surface soil sampling data from 10 air monitoring locations

Chemical	**Frequency of Detection**	**Minimum (ppm)**	**Average (ppm)**	**Maximum (ppm)**	**Location of Maximum**	**Date of Maximum**	**Years Sampled**	**CV (ppm)**
Molybdenum	106/134	0.6	15.1	251.3	AS-204 (West Boundary)	2002	1992–2006*	300 (RMEG, child)
Radionuclide	**Frequency of Detection**	**Minimum (pCi/g)**	**Average (pCi/g)**	**Maximum (pCi/g)**	**Location of Maximum**	**Date of Maximum**	**Years Sampled**	**CV (pCi/g)**
Radium-224**	10/10	-5.7	-2.9	0.3	Lincoln Park	2006	2006	5 (UMTRCA, surface)
Radium-226	246/251	<0.5	3.9	**53.5**	AS-209 (Mill Entrance Road)	2002	1979–2006†	5 (UMTRCA, surface)
Thorium-230	107/107	0.4	22.2	354	AS-209 (Mill Entrance Road)	2002	1996–2006	NA
Thorium-232	60/60	0.5	1.4	7.9	AS-209 (Mill Entrance Road)	2002	2001–2006	NA
Uranium	258/262	<0.001	4.6	73.6	AS-209 (Mill Entrance Road)	2002	1979–2006	NA

Source: Cotter 2007; GeoTrans 1986

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value.
Uranium and radium-226 were also tested in soil from two additional off-site locations (Oro Verde #1 and Oro Verde #2) in 1983 and 1984.
See Figure for a map of the air monitoring locations.

*Data from 2006 are unavailable.
**Data are blank corrected.
†Results from 2005 were not reported based on quality assurance analysis (Cotter 2007).

CV – comparison value
NA – not available
pCi/g – picocuries per gram
ppm – parts per million
RMEG – reference dose media evaluation guide
UMTRCA – 1978 Uranium Mill Tailings Radiation Control Act

Table 32. Soil sampling data (chemicals) from location AS-212 (the Nearest Resident)

Chemical	Frequency of Detection	Minimum (ppm)	Average (ppm)	Maximum (ppm)	Date of Maximum	Years Sampled	CV (ppm)
Lead	1/1	199	199	199	15-Jan-03	2003	400 (SSL)
Molybdenum	7/8	1.6	11.3	42.4	2005	1999–2005	300 (RMEG , child)
Uranium	1/1	4.9	4.9	4.9	15-Jan-03	2003	100 (i-EMEG, child for highly soluble salts)

Source: CDPHE 2007b, Cotter 2007

Averages were calculated using ½ the reporting detection limit for non-detects.
See Figure for the location of AS-212, the nearest resident.

CV – comparison value
i-EMEG – intermediate environmental media evaluation guide
ppm – parts per million
RMEG – reference dose media evaluation guide
SSL – EPA’s soil screening level for residential areas

Table 33. Soil sampling data (radionuclides) from location AS-212 (the Nearest Resident)

Radionuclide	Frequency of Detection	Minimum (pCi/g)	Average (pCi/g)	Maximum (pCi/g)	Date of Maximum	Years Sampled	CV (pCi/g)
Cesium-137	1/1	0.61	0.61	0.61	15-Jan-03	2003	NA
Lead-210	1/1	8	8	8	15-Jan-03	2003	NA
Plutonium-239, 240	1/1	0.03	0.03	0.03	15-Jan-03	2003	NA
Potassium-40	1/1	17.7	17.7	17.7	15-Jan-03	2003	NA
Radium-224*	1/1	-3.6	-3.6	-3.6	2006	2006	5 (UMTRCA, surface)
Radium-226	8/8	1.4	3.3	7.5	2004	1999–2004, 2006	5 (UMTRCA, surface)
Radium-228	1/1	0.9	0.9	0.9	15-Jan-03	2003	5 (UMTRCA, surface)
Thorium-230	8/8	3.3	10.1	20	2004	1999–2006	NA
Thorium-232	6/6	0.7	1.0	1.1	2001, 2002	2001–2006	NA
Uranium	8/8	2.0	5.2	13	2004	1999–2006	NA

Source: CDPHE 2007b, Cotter 2007

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that radionuclide.
See Figure for the location of AS-212, the nearest resident.

*Data are blank corrected.

CV – comparison value
NA – not available
pCi/g – picocuries per gram
UMTRCA – 1978 Uranium Mill Tailings Radiation Control Act

Table 34. Surface soil sampling data (chemicals) from lawns and gardens in Lincoln Park

Chemical	Frequency of Detection	Minimum (ppm)	Average (ppm)	Maximum (ppm)	Location of Maximum	Years Sampled	CV (ppm)
Arsenic	15/15	31	44	50	garden soil	1996	0.5 (CREG), 20 (c-EMEG, child)
Beryllium	14/15	0.5	0.7	1.1	lawn soil	1996	100 (c-EMEG, child)
Cadmium	14/15	0.5	1.2	1.9	lawn soil	1996	10 (c-EMEG, child)
Manganese	15/15	290	428	640	lawn soil	1996	3,000 (RMEG , child)
Selenium	1/32	18	1.7*	18	garden soil	1990, 1996	300 (c-EMEG, child)

Source: Weston 1996 (some or all of these data may also be included in Table)

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.

* The calculated average is lower than the minimum detected concentration due to including ½ the detection limit in the calculation.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
ppm – parts per million
RMEG – reference dose media evaluation guide

Table 35. Surface soil sampling data (radionuclides) from yards, gardens, and air monitoring locations in Lincoln Park

Radionuclide	Frequency of Detection	Minimum (pCi/g)	Average (pCi/g)	Maximum (pCi/g)	Source of Maximum	Years Sampled	CV (pCi/g)
Lead-210	17/17	0.4	1.6	2.5	0–2” garden sample	1990	NA
Polonium-210	17/17	1.1	1.7	2.6	0–2” garden sample	1990	NA
Radium-226	19/19	0.8	1.5	2.0	0–2” garden sample	1987, 1988, 1990	5 (UMTRCA, surface)
Thorium-228	17/17	1.0	1.4	1.8	0–2” garden sample	1990	NA
Thorium-230	17/17	1.0	1.5	2.3	0–2” garden sample	1990	NA
Uranium-234	29/29	0.355	1.23	1.95	Soil from the yard of a participant in the LPWUS	1987–1990	NA
Uranium-235	0/17	ND*	ND*	ND*	--	1990	NA
Uranium-238	29/29	0.355	1.21	1.95	Soil from the yard of a participant in the LPWUS	1987–1990	NA

Source: Weston 1996

*The uranium-235 detection limit was 0.2 pCi/g.

CV – comparison value
LPWUS – Lincoln Park Water Use Survey
NA – not available
ND – not detected
pCi/g – picocuries per gram
UMTRCA – 1978 Uranium Mill Tailings Radiation Control Act

Table 36. Surface soil data (chemicals) from lawns and gardens in Lincoln Park

Chemical		Samples from locations irrigated with contaminated well water	Samples from locations not irrigated with contaminated well water	CV (ppm)
Arsenic	Range (ppm)	**14–50**	**13–38**	0.5 (CREG), 20 (c-EMEG, child)
	Frequency of Detection	26/26	47/47	
	Average (ppm)	**36***	**28***	
Beryllium	Range (ppm)	0.5–1.1	0.6–1.7	100 (c-EMEG, child)
	Frequency of Detection	25/26	47/47	
	Average (ppm)	0.7	0.8	
Cadmium	Range (ppm)	0.6–1.9	0.5–5	10 (c-EMEG, child)
	Frequency of Detection	23/26	45/47	
	Average (ppm)	1.2	1.5**	
Lead	Range (ppm)	17–270†		400 (SSL)
	Frequency of Detection	73/73†		
	Average (ppm)	122	121	
Manganese	Range (ppm)	290–640	320–580	3,000 (RMEG , child)
	Frequency of Detection	26/26	47/47	
	Average (ppm)	430	421**	
Molybdenum	Range (ppm)	*Data not available*§	*Data not available*§	300 (RMEG , child)
	Frequency of Detection	*Data not available*§	*Data not available*§	
	Average (ppm)	1.7*	0.5*	
Selenium	Range (ppm)	18	5–44	300 (c-EMEG, child)
	Frequency of Detection	1/26	6/47	
	Average (ppm)	3.1	3.8	
Uranium	Range (ppm)	*Data not available*§	*Data not available*§	100 (i-EMEG, child for highly soluble salts)
	Frequency of Detection	*Data not available*§	*Data not available*§	
	Average (ppm)	2.3*	1.6*	

Source: Weston 1998

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
The dates the samples were collected were not specified in the report. It is assumed to be in the 1994–1996 timeframe.

*The concentrations were statistically higher in irrigated soil samples.
**The calculated averages for cadmium and manganese differ slightly from the reported mean concentrations in Table 3-3.
†The raw data for lead are not presented by whether the samples were taken from locations irrigated with contaminated well water. However, Table 3-3 presents the mean concentrations by manner of irrigation.
§The raw data for molybdenum and uranium are not presented in the report. Therefore, the range and frequency of detection could not be determined. Table 3-3 presents the mean concentrations.

c-EMEG – chronic environmental media evaluation guide
CREG – cancer risk evaluation guide
CV – comparison value
i-EMEG – intermediate environmental media evaluation guide
ppm – parts per million
RMEG – reference dose media evaluation guide
SSL – EPA's soil screening level for residential areas

Table 37. Surface soil data (radionuclides) from lawns and gardens in Lincoln Park

Radionuclide		Samples from locations irrigated with contaminated well water	Samples from locations not irrigated with contaminated well water	CV (pCi/g)
Lead-210	Range (pCi/g)	0.8–3.0	0.7–4.2	NA
	Frequency of Detection	11/11	47/47	
	Average (pCi/g)	2.2	2.1*	
Radium-226	Range (pCi/g)	1.3–1.7	1.1–2.2	5 (UMTRCA, surface)
	Frequency of Detection	11/11	47/47	
	Average (pCi/g)	1.4	1.5	
Thorium-230	Range (pCi/g)	1.1–2.2	1.0–4.2	NA
	Frequency of Detection	11/11	47/47	
	Average (pCi/g)	1.6*	1.7	
Uranium, natural	Range (pCi/g)	0.871–3.417	0.6566–2.077	NA
	Frequency of Detection	26/26	47/47	
	Average (pCi/g)	1.514	1.05	
Uranium-234	Range (pCi/g)	0.436–1.709	0.328–1.039	NA
	Frequency of Detection	26/26	47/47	
	Average (pCi/g)	0.755	0.525	
Uranium-238	Range (pCi/g)	0.436–1.709	0.328–1.039	NA
	Frequency of Detection	26/26	47/47	
	Average (pCi/g)	0.755	0.525	

Source: Weston 1998

The dates the samples were collected were not specified in the report. It is assumed to be in the 1994–1996 timeframe.

*The calculated averages for lead-210 and thorium-230 differ slightly from the reported mean concentrations in Table 3-3.

CV – comparison value
NA – not available
pCi/g – picocuries per gram
UMTRCA – 1978 Uranium Mill Tailings Radiation Control Act

Table 38. Sediment sampling data (chemicals) from Sand Creek

Chemical	Location Concentration (ppm)						CV (ppm)
	SD01	SD02*	SD04			SD05	
			1	2	3		
Arsenic	NA	13.7	13	NA	17	<5	20 (c-EMEG, child)
Cadmium	NA	3.9	7.2	NA	7.6	1.5	10 (c-EMEG, child)
Cobalt	NA	11.3	43	NA	21	10	500 (i-EMEG, child)
Copper	19	52.3	46	NA	38	19	500 (i-EMEG, child)
Lead	27	106	93	NA	130	22	400 (SSL)
Molybdenum	4.4	2.6	8	NA	7.9	9.4	300 (RMEG , child)
Nickel	NA	17	63	NA	28	18	1,000 (RMEG, child)
Zinc	NA	343	540	NA	580	106	20,000 (c-EMEG, child)

Source: GeoTrans 1986

SD01 – mouth near the Arkansas River
SD02 – near spring where flow begins (reflects migration of contaminants in the groundwater)
SD04 – below the SCS Dam in
(1) an abandoned stock watering pond (formed by diversion of runoff water into a depression adjacent to Sand Creek)
(2) in drainage (reflects historical picture of uncontrolled emissions)
(3) in drainage above #2 (reflects historical picture of uncontrolled emissions)
SD05 – above the SCS Dam adjacent to the west property edge

Bolded text indicates that the concentration exceeded the comparison value for that chemical.
Samples were collected July 10–20, 1985.

*Values are the mean of three field replicates.

c-EMEG – chronic environmental media evaluation guide
CREG – cancer risk evaluation guide
CV – comparison value
i-EMEG – intermediate environmental media evaluation guide
ppm – parts per million
RMEG – reference dose media evaluation guide
SSL – EPA's soil screening level for residential areas

Table 39. Sediment sampling data (radionuclides) from Sand Creek

Radionuclide	Location Average (pCi/g)						CV
	SD01	SD02	SD04			SD05	
			1	2	3		
Gross Alpha	22±3	47±9	240±40	74±9	39±7	22±5	NA
Gross Beta	29±6	43±8	90±20	34±7	32±7	32±6	NA
Radium-226	1.21±0.06	1.7±1	**12.8±0.6**	3.5±0.2	3.4±0.2	2.3±1	5 (UMTRCA, surface)
Throium-230	4.6±0.3	34±2	82±4	32±2	15.5±0.8	5.2±0.3	NA
Total Uranium	2.4	4.3	11.7	3.4	3.4	3.9	NA

Source: GeoTrans 1986

SD01 – mouth near the Arkansas River
SD02 – near spring where flow begins (reflects migration of contaminants in the groundwater)
SD04 – below the SCS Dam in
  (1) an abandoned stock watering pond (formed by diversion of runoff water into a depression adjacent to Sand Creek)
  (2) in drainage (reflects historical picture of uncontrolled emissions)
  (3) in drainage above #2 (reflects historical picture of uncontrolled emissions)
SD05 – above the SCS Dam adjacent to the west property edge

Bolded text indicates that the concentration exceeded the comparison value for that radionuclide.
Samples were collected July 10–20, 1985.

CV – comparison value
NA – not available
pCi/g – picocuries per gram
UMTRCA – 1978 Uranium Mill Tailings Radiation Control Act

Table 40. Chemical sampling for the Sand Creek Cleanup Project

Chemical	Frequency of Detection	Minimum (ppm)	Average (ppm)	Maximum (ppm)	CV (ppm)
Arsenic	7/7	2.7	3.9	6.9	20 (c-EMEG, child)
Barium	7/7	69	106	160	10,000 (c-EMEG, child)
Beryllium	7/7	0.2	0.3	0.6	100 (c-EMEG, child)
Chromium	7/7	7.4	9.5	12.8	200 (RMEG, child for hexavalent chromium)
Lead	7/7	17	35	75	400 (SSL)
Manganese	7/7	258	343	502	3,000 (RMEG , child)
Molybdenum	7/7	2.1	2.8	3.5	300 (RMEG , child)
Nickel	7/7	8	10.9	16	1,000 (RMEG , child)
Selenium	0/7	ND*	ND*	ND*	300 (c-EMEG, child)
Vanadium	7/7	16.1	20.3	26.1	200 (i-EMEG, child)

Source: Cotter 2000

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Samples were collected in April and May 1998.

*The selenium detection limit was 5 ppm.

c-EMEG – chronic environmental media evaluation guide
CREG – cancer risk evaluation guide
CV – comparison value
i-EMEG – intermediate environmental media evaluation guide
ND – not detected
ppm – parts per million
RMEG – reference dose media evaluation guide
SSL – EPA's soil screening level for residential areas

Table 41. Surface water sampling data (chemicals) from Sand Creek

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Date of Maximum	CV (mg/L)	Years Sampled
Aluminum	D	0/2	ND	ND	ND	--	10 (c-EMEG, child)	1988
Ammonia	N	2/35	0.5	0.43*	0.8	10-Nov-88	30 (LTHA)	1988–1994
Ammonium	T	0/3	ND	ND	ND	--	NA	1995
Chloride	N/T**	92/92	3	8	14	13-May-04	250 (Secondary MCL)	1986–2007
Iron	D	21/55	0.03	0.04	0.26	07-Nov-02	26 (RBC)	1986–1988, 1995–2007
Manganese	D	36/55	0.0084	0.04	**1.3**[†]	19-Nov-01	0.5 (RMEG, child)	1986–1988, 1995–2007
Molybdenum	D	98/104	0.005	0.02	**0.051**[†]	01-Dec-87	0.035 (SS); 0.05 (RMEG, child)	1986–2007
Nitrate	N/T**	75/87	0.5	1.1	4.7	03-May-06	10 (MCL)	1988–2007
Selenium	D	0/8	ND	ND	ND	--	0.05 (c-EMEG, child)	1986–1988
Sulfate	N/T**	94/94	12	65	**310**[†]	11-Oct-96	250 (Secondary MCL)	1986–2007
Total Dissolved Solids	N/T**	99/99	10.7	369	**1,372**[‡]	22-Aug-91	500 (Secondary MCL)	1986–2007
Uranium	D	101/101	0.006	0.012	0.0267	01-Aug-95	0.03 (MCL)	1986–2007
	S	8/48	0.000098	0.001	0.0031	10-Jan-00		1995–2007

Source: CDPHE 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
* The calculated average is lower than the minimum detected concentration due to including ½ the detection limit in the calculation.
** For chloride, nitrate, sulfate, and total dissolved solids, pre-1995 data were designated “N” and post-1995 data were designated “T”.
[†] Only the maximum concentration was above the CV.
[‡] This appears to be an outlier. The next highest concentration is 460 mg/L. Only the maximum concentration was above the CV.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
D – dissolved
LTHA – lifetime health advisory for drinking water
MCL – maximum contaminant level
mg/L – milligrams per liter
N – not defined in the CDPHE database
NA – not available
ND – not detected
RBC – risk based concentration for drinking water
RMEG – reference dose media evaluation guide
S – suspended
SS – Colorado state groundwater standard
T – total

Table 42. Surface water sampling data (radionuclides) from Sand Creek

Radionuclide	Type	Frequency of Detection	Minimum (pCi/L)	Average (pCi/L)	Maximum (pCi/L)	Date of Maximum	CV (pCi/L)	Years Sampled
Lead-210	D	40/49	-0.2	0.39	3.7	06-Aug-07	NA	1995–2007
	S	40/49	-0.1	0.40	4.6	06-Aug-07		1995–2007
Polonium-210	D	41/49	-0.1	0.15	0.6	28-Nov-06	NA	1995–2007
	S	40/49	0	0.13	1.6	09-Nov-99		1995–2007
Radium-226	D	45/49	0	0.12	0.6	03-May-06	5 (MCL radium-226/228)	1995–2007
	S	42/47	0	0.06	0.4	09-Nov-99, 28-Nov-06		1995–2007
Thorium-230	D	44/49	-0.1	0.13	0.8	28-Nov-06	NA	1995–2007
	S	41/46	0	0.16	0.9	06-Aug-07		1995–2007

Source: CDPHE 2007b

Averages were calculated using ½ the reporting detection limit for non-detects.
Negative and zero result values were included in the summary statistics.

CV – comparison value
D – dissolved
MCL – maximum contaminant level
NA – not available
pCi/L – picocuries per liter
S – suspended

Table 43. Surface water sampling data (chemicals) from the DeWeese Dye Ditch

Chemical	Type	Frequency of Detection	Minimum (mg/L)	Average (mg/L)	Maximum (mg/L)	Date of Maximum	CV (mg/L)	Years Sampled
Aluminum	D	1/4	0.02	0.06*	0.02	14-Jun-95	10 (c-EMEG, child)	1981, 1995
Ammonia	N	0/2	ND	ND	ND	--	30 (LTHA)	1989, 1995
Chloride	N/T**	95/102	2	7	18	08-May-01	250 (Secondary MCL)	1981–1989, 1995–2007
Iron	D	22/50	0.029	0.9	**43[†]**	09-Jun-99	26 (RBC)	1981–1987, 1995–2007
Manganese	D	28/50	0.004	0.05	**1.9[‡]**	09-Jun-99	0.5 (RMEG, child)	1981–1987, 1995–2007
Molybdenum	D	10/120	0.001	0.013[§]	0.013	06-Aug-03	0.035 (SS); 0.05 (RMEG, child)	1981–2007
Nitrate	N/T**	7/26	0.1	0.3	0.8	10-May-00, 02-Aug-06	10 (MCL)	1989, 1995–2007
Selenium	D	4/76	0.005	0.003[††]	0.011	22-Jun-87, 25-Apr-88	0.05 (c-EMEG, child)	1981–1988, 1995
Sulfate	N/T**	102/102	6	31	95	28-Apr-82	250 (Secondary MCL)	1981–1989, 1995–2007
Total Dissolved Solids	N/T**	119/119	12.9	231	**1,647[‡‡]**	10-Sep-90	500 (Secondary MCL)	1981–2007
Uranium	D	86/116	0.0004	0.01	**0.11[§§]**	05-May-83	0.03 (MCL)	1981–2007
	S	0/8	ND	ND	ND	--		1996–1999

Source: CDPHE 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.

* The calculated average is higher than the maximum detected concentration due to including ½ the detection limit in the calculation.
** For chloride, nitrate, sulfate, and total dissolved solids, pre-1995 data were designated “N” and post-1995 data were designated “T”.
[†] This appears to be an outlier. The next highest concentration is 0.24 mg/L from the same location in 2003. Only the maximum concentration was above the CV.
[‡] Only the maximum concentration was above the CV.
[§] The calculated average is the same as the maximum detected concentration due to including ½ the detection limit in the calculation.

[††] The calculated average is the lower than the minimum detected concentration due to including ½ the detection limit in the calculation.
[‡‡] This appears to be an outlier. The next highest concentration is 870 mg/L. Only three of the 119 samples were above the CV.
[§§] Only three of the samples were above the CV.

c-EMEG – chronic environmental media evaluation guide
CV – comparison value
D – dissolved
LTHA – lifetime health advisory for drinking water
MCL – maximum contaminant level
mg/L – milligrams per liter
N – not defined in the CDPHE database
ND – not detected
RBC – risk based concentration for drinking water
RMEG – reference dose media evaluation guide
S – suspended
SS – Colorado state groundwater standard
T – total

Table 44. Surface water sampling data (radionuclides) from the DeWeese Dye Ditch

Radionuclide	Type	Frequency of Detection	Minimum (pCi/L)	Average (pCi/L)	Maximum (pCi/L)	Date of Maximum	CV (pCi/L)	Years Sampled
Lead-210	D	8/8	0	0.3	1.2	09-May-96	NA	1996–1999
	S	8/8	0	0.09	0.2	12-May-97		1996–1999
Polonium-210	D	8/8	0	0.1	0.2	09-Jun-99, 02-Sep-99	NA	1996–1999
	S	8/8	0	0.05	0.2	09-Jun-99		1996–1999
Radium-226	D	8/8	0	0.04	0.1	09-May-96, 16-Jul-96, 02-Sep-99	5 (MCL radium-226/228)	1996–1999
	S	7/7	0	0.01	0.1	02-Sep-99		1996–1999
Thorium-230	D	8/8	0	0.025	0.2	12-May-97	NA	1996–1999
	S	7/7	0	0.07	0.2	09-Sep-98		1996–1999

Source: CDPHE 2007b

Averages were calculated using ½ the reporting detection limit for non-detects.
Negative and zero result values were included in the summary statistics.

CV – comparison value
D – dissolved
MCL – maximum contaminant level
NA – not available
pCi/L – picocuries per liter
S – suspended

Table 45. Surface water sampling data (chemicals) from the Arkansas River

Chemical	Type		Upstream of Sand Creek at 1st Street (907)	Downstream of Sand Creek at Mackenzie Ave (904)	CV (mg/L)
Chloride	T	Range (mg/L)	3–60	3–14	250 (Secondary MCL)
		Frequency of Detection	127/130	127/130	
		Average (mg/L)	8	8	
Molybdenum	D	Range (mg/L)	0.0029–**0.046**	0.003–0.029	0.035 (SS); 0.05 (RMEG, child)
		Frequency of Detection	32/142	46/142	
		Average (mg/L)	0.025	0.025	
Molybdenum	S	Range (mg/L)	0.0019–0.022	0.0017–0.016	0.035 (SS); 0.05 (RMEG, child)
		Frequency of Detection	8/135	6/135	
		Average (mg/L)	0.025	0.025	
Molybdenum	T	Range (mg/L)	0.006	0.005	0.035 (SS); 0.05 (RMEG, child)
		Frequency of Detection	1/7	1/7	
		Average (mg/L)	0.003*	0.003*	
Sulfate	T	Range (mg/L)	**10–1,300****	**5–4,200****	250 (Secondary MCL)
		Frequency of Detection	130/130	130/130	
		Average (mg/L)	41	84	
Total Dissolved Solids	T	Range (mg/L)	**45–2,880**†	62–337	500 (Secondary MCL)
		Frequency of Detection	130/130	130/130	
		Average (mg/L)	172	192	
Uranium	D	Range (mg/L)	0.0003– 0.0135	0.0002–0.0155	0.03 (MCL)
		Frequency of Detection	129/130	130/130	
		Average (mg/L)	0.004	0.005	
Uranium	S	Range (mg/L)	0.0002– 0.014	0.0002–0.0043	0.03 (MCL)
		Frequency of Detection	16/121	14/121	
		Average (mg/L)	0.001	0.001	
Uranium	T	Range (mg/L)	0.0033–0.0056	0.0029–0.0054	0.03 (MCL)
		Frequency of Detection	7/7	7/7	
		Average (mg/L)	0.004	0.004	

Source: CDPHE 2007b

Bolded text indicates that the average and/or maximum concentration exceeded the comparison value for that chemical.
Averages were calculated using ½ the reporting detection limit for non-detects.
All samples were collected between 1995 and 2007. The "T" samples for uranium were only collected in 1995.
* The calculated average is lower than the minimum detected concentration due to including ½ the detection limit in the calculation.
** This appears to be an outlier. The next highest concentration is 200 mg/L. Only the maximum concentration was above the CV.
† This appears to be an outlier. The next highest concentration is 405 mg/L. Only the maximum concentration was above the CV.

CV – comparison value
D – dissolved
MCL – maximum contaminant level
mg/L – milligrams per liter
RMEG – reference dose media evaluation guide
S – suspended
SS – Colorado state groundwater standard
T – total

Table 46. Surface water sampling data (radionuclides) from the Arkansas River

Radionuclide	Type		Upstream of Sand Creek at 1st Street (907)	Downstream of Sand Creek at Mackenzie Ave (904)	CV (pCi/L)
Lead-210	D	Range (pCi/L)	ND	3.7	NA
		Frequency of Detection	0/1	1/1	
		Average (pCi/L)	ND	3.7	
Lead-210	S	Range (pCi/L)	ND	0	NA
		Frequency of Detection	0/1	1/2	
		Average (pCi/L)	ND	0.25*	
Polonium-210	D	Range (pCi/L)	ND	ND	NA
		Frequency of Detection	0/1	0/1	
		Average (pCi/L)	ND	ND	
Polonium-210	S	Range (pCi/L)	ND	0.26–3.3	NA
		Frequency of Detection	0/1	2/2	
		Average (pCi/L)	ND	1.8	
Radium-226	D	Range (pCi/L)	0–0.6	0–0.4	5 (MCL radium-226/228)
		Frequency of Detection	119/128	116/127	
		Average (pCi/L)	0.13	0.07	
Radium-226	S	Range (pCi/L)	0–0.8	0–2.3	5 (MCL radium-226/228)
		Frequency of Detection	114/120	112/119	
		Average (pCi/L)	0.08	0.09	
Radium-226	T	Range (pCi/L)	0.1–0.7	0.1–0.7	5 (MCL radium-226/228)
		Frequency of Detection	7/7	7/7	
		Average (pCi/L)	0.3	0.3	
Thorium-230	D	Range (pCi/L)	-0.1–1	-0.1–1.2	NA
		Frequency of Detection	121/127	116/127	
		Average (pCi/L)	0.1	0.1	
Thorium-230	S	Range (pCi/L)	0–2.5	0–2.4	NA
		Frequency of Detection	115/120	113/119	
		Average (pCi/L)	0.2	0.2	
Thorium-230	T	Range (pCi/L)	0.1–0.7	0–0.6	NA
		Frequency of Detection	7/7	7/7	
		Average (pCi/L)	0.3	0.2	

Source: CDPHE 2007b

Averages were calculated using ½ the reporting detection limit for non-detects.
Negative and zero result values were included in the summary statistics.
Radium-226 and thorium-230 “D” and “S” samples were collected between 1995 and 2007. The radium-226 and thorium-230 “T” samples were only collected in 1995. Lead-210 and polonium-210 were sampled upstream (907) in 2005 (“D” and “S”) and downstream (904) in 2005 (“D”) and 2006 (“D” and “S”).

* The calculated average is higher than the detected concentration due to including ½ the detection limit in the calculation.

CV – comparison value
D – dissolved
MCL – maximum contaminant level
NA – not available
ND – not detected
pCi/L – picocuries per liter
S – suspended
T – total

Table 47. Sampling data (chemicals) for local and supermarket foods

Chemical	Food Type	Average (mg/kg)	
		Local	Supermarket
Barium*	Vegetables	4.75	NA
Cadmium*	Vegetables	0.215	NA
Chromium*	Vegetables	0.095	NA
Manganese*	Vegetables	11.25	NA
Molybdenum	Chicken	0.19	0.72
	Fruits	0.079	0.017
	Vegetables	0.667	0.023
Selenium	Chicken	0.31	0.18
	Fruits	0.024	0.017
	Vegetables	0.061	0.020
Strontium*	Vegetables	22	NA
Uranium	Chicken	0.061	0.001
	Fruits	0.0056	0.0013
	Vegetables	0.0043	0.0013
Vanadium*	Vegetables	0.105	NA
Zinc*	Vegetables	7.5	NA

Source: Weston 1996

Averages were calculated using ½ the reporting detection limit for non-detects.
Concentrations are reported on a wet weight basis.
Vegetables were also tested for arsenic, beryllium, cobalt, lead, mercury, nickel, and silver, but none of these chemicals were detected.

*Chicken and fruits were not analyzed for these chemicals.

NA – not available
mg/kg – milligrams per kilogram

Table 48. Sampling data (radionuclides) for local and supermarket foods

Radionuclide	Food Type	Average (pCi/kg)	
		Local	Supermarket
Lead-210	Chicken	1.26	1.70
	Fruits	1.48	1.18
	Vegetables	0.58	0.60
Polonium-210	Chicken	3.79	21.75
	Fruits	2.26	1.30
	Vegetables	1.13	1.56
Radium-226	Chicken	0.64	2.60
	Fruits	1.34	0.05
	Vegetables	1.37	0.07
Thorium-228	Chicken	0.39	ND
	Fruits	0.33	ND
	Vegetables	0.41	1.42
Thorium-230	Chicken	1.01	0.53
	Fruits	1.85	ND
	Vegetables	0.27	0.29
Uranium-234	Chicken	1.10	1.05
	Fruits	1.53	0.34
	Vegetables	0.55	0.76
Uranium-235	Chicken	ND	0.36
	Fruits	0.13	0.13
	Vegetables	0.13	0.14
Uranium-238	Chicken	1.59	0.53
	Fruits	1.41	0.23
	Vegetables	0.44	0.25

Source: Weston 1996

Averages were calculated using ½ the reporting detection limit for non-detects.
Concentrations are reported on a wet weight basis.

ND – not detected
pCi/kg – picocuries per kilogram

Table 49. Sampling data (chemicals) for local produce irrigated with contaminated well water

Chemical		Fruits	Vegetables
Arsenic	Frequency of Detection	2/16	14/43
	Average (mg/kg)	0.051	0.077
	Maximum (mg/kg)	0.2	0.4
Barium	Frequency of Detection	7/16	33/43
	Average (mg/kg)	0.44	1.6
	Maximum (mg/kg)	0.9	15
Cadmium	Frequency of Detection	2/16	18/43
	Average (mg/kg)	0.041	0.034
	Maximum (mg/kg)	0.23	0.14
Chromium	Frequency of Detection	12/16	39/43
	Average (mg/kg)	0.052	0.056
	Maximum (mg/kg)	0.1	0.19
Cobalt	Frequency of Detection	0/16	6/43
	Average (mg/kg)	ND	0.02
	Maximum (mg/kg)	ND	0.07
Lead	Frequency of Detection	3/16	26/43
	Average (mg/kg)	0.13	0.2
	Maximum (mg/kg)	1.2	1.9
Manganese	Frequency of Detection	16/16	43/43
	Average (mg/kg)	0.87	2.4
	Maximum (mg/kg)	1.8	11
Molybdenum	Frequency of Detection	6/16	41/43
	Average (mg/kg)	0.11	0.68
	Maximum (mg/kg)	0.3	9.8
Nickel	Frequency of Detection	0/16	2/43
	Average (mg/kg)	ND	0.075
	Maximum (mg/kg)	ND	0.2
Strontium	Frequency of Detection	16/16	43/43
	Average (mg/kg)	1.6	4.9
	Maximum (mg/kg)	8.5	33
Uranium	Frequency of Detection	3/16	14/43
	Average (mg/kg)	0.0074	0.0071
	Maximum (mg/kg)	0.035	0.041
Vanadium	Frequency of Detection	0/16	16/43
	Average (mg/kg)	ND	0.046
	Maximum (mg/kg)	ND	0.21

Chemical		Fruits	Vegetables
Zinc	Frequency of Detection	16/16	43/43
	Average (mg/kg)	1.4	3.1
	Maximum (mg/kg)	4.0	10

Source: Weston 1998

Averages were calculated using ½ the reporting detection limit for non-detects.
Concentrations are reported on a wet weight basis.
The dates the samples were collected were not specified in the report. It is assumed to be in the 1994–1996 timeframe.

ND – not detected
mg/kg – milligrams per kilogram

Table 50. Sampling data (radionuclides) for local produce irrigated with contaminated well water

Radionuclide		Fruits	Vegetables
Lead-210	Frequency of Detection	3/16	8/43
	Average (pCi/kg)	12	21
	Maximum (pCi/kg)	21	51
Radium-226	Frequency of Detection	1/16	15/43
	Average (pCi/kg)	5.7	6.2
	Maximum (pCi/kg)	18	41
Thorium-230	Frequency of Detection	1/16	8/43
	Average (pCi/kg)	3.9	5.1
	Maximum (pCi/kg)	10	20
Uranium (natural)	Frequency of Detection	3/16	14/43
	Average (pCi/kg)	5.0	4.8
	Maximum (pCi/kg)	23	27

Source: Weston 1998

Averages were calculated using ½ the reporting detection limit for non-detects.
Concentrations are reported on a wet weight basis.
The dates the samples were collected were not specified in the report. It is assumed to be in the 1994–1996 timeframe.
pCi/kg – picocuries per kilogram

Table 51. Characteristics of Cotter Mill's Ambient Air Monitoring Stations

Monitor Code	*Monitor Location*	*Years of Operation*	*Monitor Type*	*Area Description*
AS-202	East Boundary	1979 – present	Perimeter	Eastern perimeter of Cotter Mill facility
AS-203	South Boundary	1979 – present	Perimeter	Southern perimeter of Cotter Mill facility
AS-204	West Boundary	1979 – present	Perimeter	Western perimeter of Cotter Mill facility
AS-206	North Boundary	1981 – present	Perimeter	Northern perimeter of Cotter Mill facility
AS-209	Mill entrance road	1994 – present	Perimeter	Entrance road to Cotter Mill
AS-210	Shadow Hills Estates	1997 – present	Off-site	Near Shadow Hills Golf Club
AS-212	Nearest resident	1999 – present	Off-site	Residential
LP-1/LP-2	Lincoln Park	1980 – present	Off-site	Residential
CC-1/CC-2	Cañon City	1979 – present	Off-site	Residential
OV-3	Oro Verde	1981 – present	Off-site	Remote (1 mile west of AS-204)

Notes: Both the Lincoln Park and Cañon City monitoring stations moved locations in the 1991-1992 time frame. The original station in Lincoln Park (LP-1) operated from 1980 to 1992, and the new station (LP-2) operated from 1991 to the present. The original station in Cañon City (CC-1) operated from 1979 to 1992, and the new station (CC-2) operated from 1991 to the present.

Table 52. Average Annual ^{nat}U Concentrations 1979-2008 (µCi/ml)

Year	Perimeter Monitoring Stations					Off-Site Monitoring Stations				
	AS-202	AS-203	AS-204	AS-206	AS-209	AS-210	AS-212	LP-1/2	CC-1/2	OV-3
1979	6.19E-15	1.50E-15	2.26E-15	--	--	--	--	--	1.00E-15	--
1980	3.71E-15	1.55E-15	2.82E-15	--	--	--	--	8.36E-16	1.40E-15	--
1981	4.07E-15	1.54E-15	5.28E-15	8.30E-15	--	--	--	1.03E-15	1.02E-15	1.37E-15
1982	2.31E-15	1.26E-15	2.48E-14	2.79E-15	--	--	--	5.28E-16	4.79E-16	5.96E-16
1983	1.26E-15	1.43E-15	1.32E-15	1.63E-15	--	--	--	4.77E-16	6.86E-16	5.03E-16
1984	5.50E-16	7.64E-16	8.36E-16	1.52E-15	--	--	--	2.78E-16	3.27E-16	4.01E-16
1985	1.42E-15	1.22E-15	8.96E-16	1.92E-15	--	--	--	4.56E-16	5.77E-16	6.66E-16
1986	6.71E-16	6.56E-16	4.05E-16	9.36E-16	--	--	--	2.95E-16	2.93E-16	4.84E-16
1987	8.08E-16	1.03E-15	1.09E-15	1.05E-15	--	--	--	4.66E-16	5.12E-16	4.60E-16
1988	6.73E-16	6.96E-16	9.03E-16	5.51E-16	--	--	--	1.85E-16	1.95E-16	1.89E-16
1989	9.58E-17	9.95E-17	2.86E-16	3.62E-17	--	--	--	8.37E-17	9.38E-17	6.38E-17
1990	5.59E-17	3.14E-17	1.06E-16	3.10E-17	--	--	--	6.18E-17	1.26E-16	9.09E-17
1991	1.12E-16	9.18E-17	2.65E-16	1.24E-16	--	--	--	1.70E-16	1.73E-16	2.60E-16
1992	6.55E-17	7.84E-17	1.12E-16	6.48E-17	--	--	--	9.71E-17	9.40E-17	8.23E-17
1993	7.13E-17	9.08E-17	1.61E-16	6.30E-17	--	--	--	8.26E-17	1.20E-16	2.55E-16
1994	1.25E-16	4.68E-17	1.00E-16	3.68E-17	1.55E-16	--	--	9.68E-17	8.12E-17	2.54E-16
1995	2.99E-16	5.86E-17	1.53E-16	5.23E-17	2.11E-16	--	--	9.34E-17	1.26E-16	4.83E-16
1996	2.25E-16	1.43E-16	2.26E-16	8.62E-17	2.44E-16	7.89E-17	--	9.73E-17	1.25E-16	5.93E-17
1997	1.23E-16	1.18E-16	2.20E-16	1.19E-16	1.51E-16	1.75E-16	--	1.27E-16	2.00E-16	9.48E-17
1998	1.32E-16	1.02E-16	3.29E-16	1.06E-16	2.27E-15	2.32E-16	--	8.13E-17	7.50E-17	2.43E-16
1999	4.06E-16	1.49E-16	2.91E-16	3.23E-16	1.46E-15	2.82E-16	4.59E-16	1.16E-16	9.41E-17	7.97E-17
2000	4.33E-16	2.04E-16	2.61E-16	1.63E-16	1.49E-15	1.89E-16	4.82E-16	5.39E-17	5.33E-17	5.39E-17
2001	4.96E-16	6.19E-16	4.96E-16	5.29E-16	1.32E-15	2.06E-16	2.88E-16	4.96E-17	3.80E-17	5.18E-17
2002	6.50E-16	4.93E-16	6.21E-16	3.24E-16	9.91E-16	3.69E-16	4.05E-16	2.46E-16	1.59E-16	2.05E-16
2003	3.55E-16	2.19E-16	2.55E-16	2.01E-16	4.91E-16	2.21E-16	2.20E-16	2.11E-16	2.07E-16	2.62E-16
2004	2.51E-16	1.95E-16	2.40E-16	1.99E-16	6.27E-16	1.40E-16	2.30E-16	9.69E-17	9.68E-17	8.61E-17
2005	4.54E-16	2.77E-16	2.87E-16	1.58E-16	3.97E-15	4.85E-16	5.25E-16	1.68E-16	1.29E-16	1.23E-16
2006	5.14E-16	2.68E-16	3.24E-16	2.12E-16	1.72E-15	6.62E-16	3.40E-16	2.20E-16	1.75E-16	1.87E-16
2007	3.56E-16	1.51E-16	2.03E-16	1.39E-16	3.13E-16	1.46E-16	1.33E-16	1.41E-16	1.43E-16	1.27E-16
2008	4.36E-16	8.61E-17	1.72E-16	8.44E-17	2.17E-16	9.77E-17	9.78E-17	9.02E-17	8.97E-17	6.43E-17

Notes: For station LP-1/2, data from 1980-1992 were collected at LP-1, and data from 1993-2008 were collected at LP-2.

For station CC-1/2, data from 1979-1992 were collected at CC-1, and data from 1993-2008 were collected at CC-2.

Shaded cells are the highest annual averages for the calendar year; "--" indicates that no data are available because the station was not yet operating.

Table 53. Average Annual ^{230}Th Concentrations 1979-2008 (µCi/ml)

Year	Perimeter Monitoring Stations					Off-Site Monitoring Stations				
	AS-202	**AS-203**	**AS-204**	**AS-206**	**AS-209**	**AS-210**	**AS-212**	**LP-1/2**	**CC-1/2**	**OV-3**
1979	2.33E-15	1.05E-15	8.08E-15	--	--	--	--	--	3.07E-16	--
1980	2.50E-16	8.76E-16	2.81E-16	--	--	--	--	8.17E-17	1.30E-16	--
1981	2.60E-15	3.50E-15	3.00E-14	6.93E-15	--	--	--	1.42E-16	8.17E-17	3.92E-16
1982	2.12E-14	1.94E-14	8.95E-14	1.26E-14	--	--	--	7.49E-16	9.18E-16	3.15E-15
1983	5.86E-15	9.79E-15	5.64E-15	8.26E-15	--	--	--	3.74E-16	3.12E-16	1.07E-15
1984	1.64E-15	2.98E-15	3.82E-15	6.35E-15	--	--	--	2.69E-16	2.00E-16	2.89E-16
1985	1.84E-15	2.15E-15	4.86E-15	3.73E-15	--	--	--	2.60E-16	2.64E-16	2.84E-16
1986	3.70E-15	5.55E-15	3.13E-15	4.68E-15	--	--	--	3.70E-16	3.08E-16	2.41E-16
1987	1.21E-15	1.29E-15	2.28E-15	1.08E-15	--	--	--	2.06E-16	1.77E-16	9.90E-17
1988	2.58E-15	3.51E-15	5.85E-15	2.05E-15	--	--	--	1.41E-16	1.72E-16	1.70E-16
1989	6.33E-16	3.85E-16	9.17E-16	1.08E-16	--	--	--	8.93E-17	9.03E-17	9.24E-17
1990	7.63E-16	4.00E-16	5.86E-16	1.09E-16	--	--	--	7.40E-17	7.04E-17	7.20E-17
1991	7.25E-16	4.59E-16	8.75E-16	2.83E-16	--	--	--	1.91E-16	1.25E-16	1.33E-16
1992	4.57E-16	2.20E-16	4.71E-16	9.46E-17	--	--	--	6.58E-17	5.98E-17	9.56E-17
1993	4.45E-16	3.03E-16	6.42E-16	9.32E-17	--	--	--	1.06E-16	9.17E-17	2.33E-16
1994	1.18E-15	2.96E-16	1.08E-15	1.24E-16	9.20E-16	--	--	1.54E-16	1.16E-16	2.83E-16
1995	1.65E-15	5.33E-16	1.24E-15	1.18E-16	8.88E-16	--	--	9.80E-17	1.12E-16	3.30E-16
1996	2.21E-15	2.95E-16	8.13E-16	8.85E-17	7.67E-16	2.33E-16	--	7.11E-17	5.08E-17	6.39E-17
1997	7.64E-16	1.31E-16	6.17E-16	6.49E-17	1.99E-15	3.82E-16	--	8.37E-17	7.86E-17	3.24E-17
1998	2.88E-15	2.02E-16	9.34E-16	1.15E-16	2.17E-15	3.32E-16	--	7.70E-17	7.99E-17	7.82E-17
1999	3.76E-15	3.24E-16	1.09E-15	1.84E-16	2.19E-15	4.15E-16	3.02E-16	7.37E-17	9.51E-17	1.11E-16
2000	1.22E-15	2.48E-16	1.01E-15	2.02E-16	4.16E-15	4.71E-16	6.69E-16	1.47E-16	1.57E-16	1.27E-16
2001	8.20E-16	5.19E-16	9.67E-16	2.61E-16	4.15E-15	4.04E-16	4.61E-16	1.56E-16	9.95E-17	1.13E-16
2002	5.84E-16	2.76E-16	5.95E-16	2.57E-16	1.25E-15	2.38E-16	3.13E-16	8.15E-17	8.54E-17	8.55E-17
2003	5.19E-16	2.62E-16	4.90E-16	9.73E-17	1.40E-15	4.11E-16	1.77E-16	8.27E-17	8.91E-17	5.30E-17
2004	2.17E-16	8.26E-17	3.87E-16	8.33E-17	6.57E-16	2.26E-16	1.08E-16	5.36E-17	5.62E-17	6.07E-17
2005	3.17E-16	1.97E-16	3.51E-16	2.64E-16	3.41E-15	4.85E-16	4.81E-16	1.04E-16	1.05E-16	1.08E-16
2006	5.17E-16	2.91E-16	4.74E-16	1.77E-16	1.40E-15	4.73E-16	3.27E-16	2.73E-16	2.04E-16	2.85E-16
2007	6.62E-16	1.90E-16	4.32E-16	1.48E-16	1.05E-15	2.77E-16	2.23E-16	1.68E-16	1.57E-16	1.53E-16
2008	7.21E-16	1.87E-16	5.12E-16	1.32E-16	6.21E-16	2.88E-16	2.05E-16	1.11E-16	1.08E-16	1.16E-16

Notes: For station LP-1/2, data from 1980-1992 were collected at LP-1, and data from 1993-2008 were collected at LP-2. For station CC-1/2, data from 1979-1992 were collected at CC-1, and data from 1993-2008 were collected at CC-2.

Shaded cells are the highest annual averages for the calendar year; "--" indicates that no data are available because the station was not yet operating; bold cells are concentrations above Cotter Mill's regulatory limit

Table 54. Average Annual ^{232}Th Concentrations 2001-2008 (µCi/ml)

Year	Perimeter Monitoring Stations					Off-Site Monitoring Stations				
	AS-202	AS-203	AS-204	AS-206	AS-209	AS-210	AS-212	LP #2	CC #2	OV-3
2001	5.78E-17	7.62E-17	6.97E-17	6.37E-17	8.32E-17	4.58E-17	6.67E-17	6.85E-17	8.33E-17	5.68E-17
2002	4.67E-17	3.81E-17	3.09E-17	4.55E-17	4.34E-17	3.17E-17	3.35E-17	5.36E-17	3.51E-17	4.68E-17
2003	4.57E-17	4.14E-17	4.84E-17	2.06E-17	5.72E-17	4.61E-17	3.71E-17	6.21E-17	4.61E-17	3.96E-17
2004	1.39E-17	2.53E-17	2.53E-17	1.40E-17	1.57E-17	1.99E-17	1.65E-17	3.24E-17	2.28E-17	2.39E-17
2005	2.83E-17	2.40E-17	2.86E-17	3.09E-17	3.36E-17	2.53E-17	3.42E-17	3.99E-17	3.57E-17	3.45E-17
2006	4.11E-17	5.18E-17	4.82E-17	4.29E-17	5.54E-17	4.33E-17	4.79E-17	6.25E-17	4.98E-17	3.65E-17
2007	4.07E-17	3.47E-17	4.60E-17	4.14E-17	4.12E-17	3.99E-17	3.51E-17	5.43E-17	4.48E-17	3.92E-17
2008	1.08E-17	1.63E-17	1.15E-17	9.89E-18	1.57E-17	2.30E-17	1.26E-17	3.13E-17	2.25E-17	2.03E-17

Note: Shaded cells are the highest annual averages for the calendar year; "--" indicates that no data are available because the station was not yet operating

Table 55. Average Annual ^{226}Ra Concentrations 1979-2008 (µCi/ml)

Year	Perimeter Monitoring Stations					Off-Site Monitoring Stations				
	AS-202	AS-203	AS-204	AS-206	AS-209	AS-210	AS-212	LP-1/2	CC-1/2	OV-3
1979	1.55E-15	3.75E-16	7.89E-15	--	--	--	--	--	3.07E-16	--
1980	3.61E-15	7.81E-16	1.62E-15	--	--	--	--	2.78E-16	1.58E-15	--
1981	4.19E-15	2.35E-15	2.94E-15	2.96E-15	--	--	--	3.79E-16	4.59E-16	6.30E-16
1982	6.53E-15	6.92E-15	3.81E-15	3.82E-15	--	--	--	6.07E-16	4.02E-16	1.25E-15
1983	2.00E-15	5.08E-15	4.95E-15	2.85E-15	--	--	--	9.42E-17	1.76E-16	5.30E-16
1984	1.11E-15	1.84E-15	3.63E-15	2.20E-15	--	--	--	1.18E-16	1.67E-16	1.87E-16
1985	9.63E-15	1.11E-15	1.78E-15	1.97E-15	--	--	--	1.69E-16	1.88E-16	1.89E-16
1986	1.47E-15	1.98E-15	1.61E-15	2.60E-15	--	--	--	1.43E-16	3.45E-16	2.22E-16
1987	5.91E-16	7.52E-16	1.19E-15	4.74E-16	--	--	--	1.83E-16	1.15E-16	1.89E-16
1988	1.29E-15	2.05E-15	2.53E-15	3.60E-16	--	--	--	1.24E-16	5.09E-17	1.09E-16
1989	2.72E-16	1.81E-16	3.30E-16	4.79E-17	--	--	--	1.02E-16	8.89E-17	7.77E-17
1990	1.75E-16	1.68E-16	1.92E-16	4.36E-17	--	--	--	6.69E-17	8.36E-17	7.82E-17
1991	1.19E-16	1.25E-16	2.68E-16	6.17E-17	--	--	--	6.85E-17	7.16E-17	1.37E-16
1992	8.46E-17	7.30E-17	1.50E-15	3.71E-17	--	--	--	5.10E-17	5.80E-17	1.17E-16
1993	9.11E-17	1.14E-16	2.49E-16	5.99E-17	--	--	--	6.14E-17	6.72E-17	2.20E-16
1994	1.03E-16	7.57E-17	1.69E-16	4.96E-17	1.55E-16	--	--	7.80E-17	8.68E-17	2.64E-16
1995	1.21E-16	1.14E-16	2.07E-16	7.46E-17	2.06E-16	--	--	6.88E-17	1.05E-16	3.99E-16
1996	1.78E-16	1.02E-16	2.08E-16	5.33E-17	2.11E-16	5.82E-17	--	5.22E-17	6.67E-17	3.59E-17
1997	1.29E-16	7.55E-17	2.01E-16	5.66E-17	9.45E-16	1.06E-16	--	5.09E-17	5.40E-17	4.84E-17
1998	2.89E-16	8.22E-17	2.95E-16	9.43E-17	1.34E-15	1.21E-16	--	6.21E-17	6.71E-17	4.24E-17
1999	4.18E-16	1.29E-16	3.81E-16	1.02E-16	1.26E-15	1.46E-16	2.13E-16	8.27E-17	9.21E-17	5.90E-17
2000	3.37E-16	1.53E-16	4.64E-16	1.40E-16	2.38E-15	2.21E-16	4.60E-16	7.41E-17	4.64E-17	5.10E-17
2001	2.15E-16	2.09E-16	4.36E-16	1.38E-16	1.92E-15	1.51E-16	1.99E-16	7.01E-17	6.82E-17	5.16E-17
2002	1.55E-16	1.17E-16	2.34E-16	7.51E-17	3.83E-16	1.05E-16	1.14E-16	8.41E-17	6.07E-17	6.72E-17
2003	1.45E-16	1.10E-16	1.75E-16	8.02E-17	2.96E-16	1.23E-16	9.65E-17	9.70E-17	8.40E-17	8.93E-17
2004	7.81E-17	7.35E-17	1.41E-16	6.14E-17	3.30E-16	9.05E-17	8.14E-17	5.79E-17	6.26E-17	4.95E-17
2005	1.78E-16	1.56E-16	1.75E-16	1.97E-16	2.29E-15	2.49E-16	2.95E-16	1.08E-16	1.22E-16	9.58E-17
2006	4.10E-16	1.40E-16	2.17E-16	1.34E-16	7.52E-16	1.69E-16	1.42E-16	1.20E-16	1.03E-16	1.15E-16
2007	8.67E-16	1.11E-16	2.07E-16	1.00E-16	2.31E-16	1.16E-16	9.11E-17	1.09E-16	9.66E-17	1.11E-16
2008	7.92E-16	7.36E-17	2.00E-16	5.16E-17	1.78E-16	7.33E-17	5.71E-17	6.21E-17	5.91E-17	3.28E-17

Notes: For station LP-1/2, data from 1980-1992 were collected at LP-1, and data from 1993-2008 were collected at LP-2. For station CC-1/2, data from 1979-1992 were collected at CC-1, and data from 1993-2008 were collected at CC-2. Shaded cells are the highest annual averages for the calendar year; "--" indicates that no data are available because the station was not yet operating.

Table 56. Average Annual ^{210}Pb Concentrations 1979-2008 (µCi/ml)

Year	Perimeter Monitoring Stations					Off-Site Monitoring Stations				
	AS-202	AS-203	AS-204	AS-206	AS-209	AS-210	AS-212	LP-1/2	CC-1/2	OV-3
1979	2.11E-14	1.65E-14	2.08E-14	--	--	--	--	--	2.30E-14	--
1980	1.81E-14	1.69E-14	1.25E-14	--	--	--	--	1.86E-14	1.98E-14	--
1981	2.01E-14	1.72E-14	4.71E-14	2.34E-14	--	--	--	1.57E-14	1.70E-14	2.11E-14
1982	3.87E-14	4.35E-14	9.95E-14	4.07E-14	--	--	--	2.50E-14	3.31E-14	4.05E-14
1983	1.70E-14	1.73E-14	1.82E-14	1.95E-14	--	--	--	1.29E-14	1.79E-14	1.44E-14
1984	1.44E-14	1.46E-14	1.60E-14	1.43E-14	--	--	--	1.26E-14	1.15E-14	1.48E-14
1985	9.12E-15	8.12E-15	8.80E-15	9.30E-15	--	--	--	9.97E-15	1.14E-14	9.90E-15
1986	1.26E-14	1.19E-14	1.12E-14	1.22E-14	--	--	--	1.07E-14	1.22E-14	8.81E-15
1987	1.95E-14	1.92E-14	2.22E-14	2.35E-14	--	--	--	2.17E-14	2.01E-14	1.43E-14
1988	2.15E-14	1.94E-14	2.10E-14	1.93E-14	--	--	--	2.04E-14	2.11E-14	1.76E-14
1989	2.28E-14	2.30E-14	1.98E-14	2.34E-14	--	--	--	2.43E-14	2.35E-14	2.40E-14
1990	2.05E-14	2.10E-14	2.07E-14	2.07E-14	--	--	--	2.24E-14	2.00E-14	1.95E-14
1991	2.40E-14	2.15E-14	2.15E-14	2.13E-14	--	--	--	2.23E-14	2.15E-14	1.07E-14
1992	2.16E-14	2.00E-14	2.20E-14	2.19E-14	--	--	--	1.99E-14	1.61E-14	2.20E-14
1993	2.38E-14	2.35E-14	2.35E-14	2.49E-14	--	--	--	2.22E-14	2.13E-14	2.10E-14
1994	2.21E-14	2.07E-14	2.10E-14	2.24E-14	2.18E-14	--	--	2.33E-14	2.38E-14	2.06E-14
1995	2.07E-14	2.07E-14	2.02E-14	2.01E-14	2.11E-14	--	--	1.97E-14	2.03E-14	1.74E-14
1996	2.02E-14	2.01E-14	2.16E-14	2.21E-14	2.11E-14	--	--	2.08E-14	1.96E-14	1.98E-14
1997	2.21E-14	2.07E-14	2.12E-14	2.20E-14	2.26E-14	2.05E-14	--	2.13E-14	2.00E-14	1.98E-14
1998	2.01E-14	2.07E-14	1.98E-14	2.11E-14	2.01E-14	1.93E-14	--	2.01E-14	2.01E-14	1.93E-14
1999	2.14E-14	1.94E-14	1.83E-14	1.84E-14	2.03E-14	1.94E-14	2.03E-14	2.03E-14	1.94E-14	1.78E-14
2000	2.07E-14	2.05E-14	2.01E-14	2.23E-14	2.37E-14	2.00E-14	2.07E-14	2.16E-14	2.08E-14	2.03E-14
2001	3.10E-14	3.04E-14	2.91E-14	3.11E-14	3.06E-14	2.94E-14	3.12E-14	3.06E-14	2.96E-14	2.79E-14
2002	2.36E-14	2.20E-14	2.28E-14	2.25E-14	2.30E-14	2.37E-14	2.40E-14	2.46E-14	2.33E-14	2.17E-14
2003	2.19E-14	2.11E-14	2.16E-14	2.06E-14	2.28E-14	2.12E-14	2.18E-14	2.11E-14	1.94E-14	2.27E-14
2004	1.72E-14	1.64E-14	1.58E-14	1.60E-14	1.66E-14	1.45E-14	1.79E-14	1.56E-14	1.54E-14	1.59E-14
2005	2.45E-14	2.74E-14	2.82E-14	2.54E-14	3.11E-14	2.91E-14	2.92E-14	3.11E-14	3.15E-14	2.94E-14
2006	2.11E-14	2.31E-14	2.47E-14	2.31E-14	2.09E-14	2.08E-14	1.89E-14	1.98E-14	1.89E-14	2.12E-14
2007	1.88E-14	1.64E-14	1.79E-14	1.82E-14	1.54E-14	1.58E-14	1.49E-14	1.66E-14	1.61E-14	1.72E-14
2008	1.65E-14	1.48E-14	1.64E-14	1.93E-14	1.66E-14	1.73E-14	1.57E-14	1.67E-14	1.61E-14	1.61E-14

Notes: For station LP-1/2, data from 1980-1992 were collected at LP-1, and data from 1993-2008 were collected at LP-2. For station CC-1/2, data from 1979-1992 were collected at CC-1, and data from 1993-2008 were collected at CC-2.

Shaded cells are the highest annual averages for the calendar year; "--" indicates that no data are available because the station was not yet operating.

Table 57. ^{220}Rn/^{222}Rn Concentrations 2002-2008 (pCi/m^3)

Year	Perimeter Monitoring Stations					Off-Site Monitoring Stations				
	AS-202	AS-203	AS-204	AS-206	AS-209	AS-210	AS-212	CC-1	LP-1	OV-3
2002	543	975	1125	693	1475	700	698	875	673	625
2003	700	825	775	900	625	675	700	375	800	567
2004	1500	850	1025	950	1100	850	925	825	875	825
2005	925	1025	850	700	1025	675	775	700	900	800
2006	1250	1275	1275	1450	1400	1125	1275	1075	1375	1200
2007	1000	1100	1175	1100	1250	975	825	925	1175	975
2008	850	900	925	950	1075	950	850	800	925	825

Notes: Data are presented for only those years when measurements quantified combined levels of the two isotopes.
Shaded cells are the highest annual averages for the calendar year.

Table 58. Environmental TLD Measurements, 1979-2008 (μR/hr)

Year	Perimeter Monitoring Stations					Off-Site Monitoring Stations				
	AS-202	AS-203	AS-204	AS-206	AS-209	AS-210	AS-212	CC-1	LP-1	OV-3
1979	14.0	12.6	12.7	--	--	--	--	11.8	11.4	--
1980	13.4	11.7	12.9	--	--	--	--	10.4	11.4	--
1981	14.3	12.8	12.7	--	--	--	--	10.6	12.3	12.3
1982	13.7	12.6	14.7	20.4	--	--	--	9.9	11.2	12.7
1983	13.6	12.6	14.2	15.6	--	--	--	10.6	11.6	12.0
1984	14.5	14.3	14.6	14.8	--	--	--	12.3	11.2	13.2
1985	14.3	13.5	14.5	14.8	--	--	--	10.5	11.2	12.3
1986	13.9	13.7	14.5	14.2	--	--	--	11.0	10.7	11.8
1987	12.9	12.5	12.6	12.6	--	--	--	9.6	9.7	10.4
1988	15.0	13.6	12.8	13.4	--	--	--	9.3	11.6	10.2
1989	14.7	14.9	15.3	15.9	--	--	--	10.6	13.7	11.9
1990	13.2	13.1	14.8	15.2	--	--	--	9.6	11.5	11.7
1991	14.1	13.2	15.7	17.5	--	--	--	10.0	12.9	12.4
1992	13.7	13.2	16.0	18.3	--	--	--	9.6	12.1	11.3
1993	12.5	12.6	14.4	15.6	--	--	--	8.6	10.7	10.9
1994	14.3	13.8	15.9	16.2	27.8	--	--	10.8	12.1	12.3
1995	12.5	13.7	14.0	15.4	23.0	--	--	9.2	10.3	11.3
1996	13.1	13.2	14.5	16.2	27.2	13.0	--	9.7	10.9	11.4
1997	12.6	13.1	13.8	15.7	29.1	12.3	--	9.1	10.2	11.1
1998	12.3	12.0	13.4	15.9	28.0	12.0	--	9.0	10.3	11.5
1999	12.7	12.0	13.8	16.0	29.6	12.2	9.1	9.3	10.6	10.9
2000	12.7	12.6	14.7	16.6	27.7	12.5	9.3	9.5	10.7	11.4
2001	13.7	14.3	15.4	18.6	26.2	13.9	9.7	10.4	12.0	12.2
2002	14.0	14.4	15.9	17.7	30.3	14.3	10.5	10.5	12.3	12.6
2003	12.8	13.3	14.8	15.5	27.7	13.3	10.0	10.0	11.7	11.8
2004	13.6	14.1	15.5	14.7	25.5	14.2	10.9	10.5	12.2	12.5
2005	12.8	13.5	14.8	13.8	22.9	12.9	9.9	10.1	11.5	11.5
2006	12.7	13.4	14.6	14.2	21.5	12.6	9.5	10.1	11.5	11.7
2007	12.9	13.2	14.6	14.1	17.8	12.7	9.5	10.1	11.5	11.6
2008	13.9	13.5	15.5	14.9	18.7	13.3	10.2	10.8	12.2	12.6

Notes: Shaded cells are the highest annual averages for the calendar year; "--" indicates that no data are available because the station was not yet operating.

Table 59. TSP Air Concentrations (µg/m^3) from 1969-1987

Year	Cañon City		Lincoln Park	
	Maximum	Average	Maximum	Average
1969	172	64.2	--	--
1970	200	55.9	--	--
1971	148	58.7	--	--
1972	240	69.9	--	--
1973	229	66.1	--	--
1974	187	58	--	--
1975	419	73.7	--	--
1976	174	56.8	--	--
1977	227	62.7	--	--
1978	313	84.7	--	--
1979	286	72.6	--	--
1980	304	70.4	--	--
1981	180	56.8	61*	8.2*
1982	525	84	228	51.7
1983	187	65.2	106	77.6
1984	571	70.9	--	--
1985	334	64.8	--	--
1986	402	66.3	--	--
1987	385	65.2	--	--

Notes: Data downloaded from EPA's Air Quality System database.
EPA's former annual average National Ambient Air Quality Standard for TSP was 75 µg/m^3.
* The TSP monitoring station in Lincoln Park started operating late in 1981; therefore, the statistics reported are not representative of the entire calendar year.

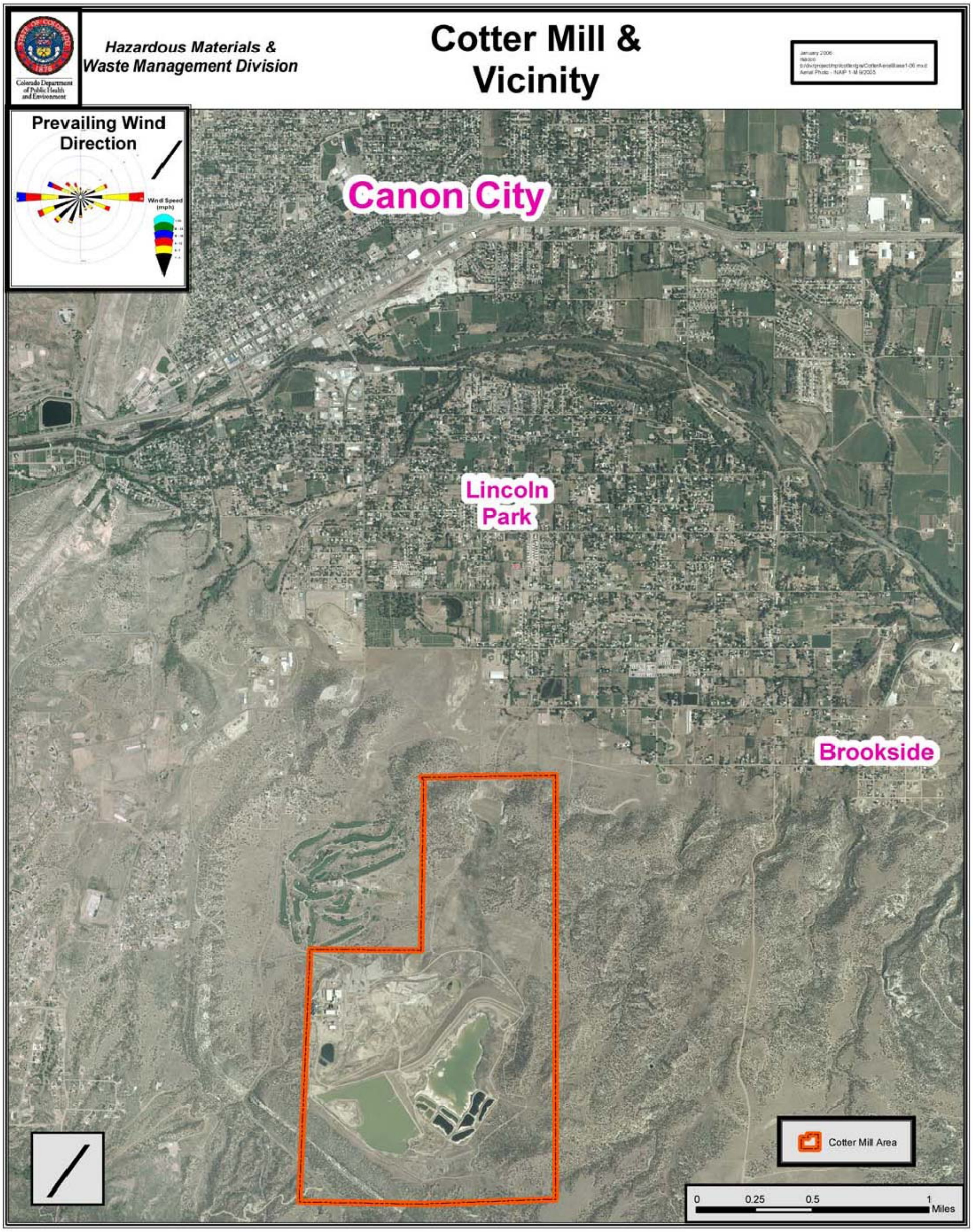
Table 60. Monitoring Data for Constituents in TSP (1978-1987)

Constituent	Location	Years of Data	Concentrations (µg/m^3)	
			Highest 24-Hour Average	Highest Annual Average
Iron	Lincoln Park	1981-1982	1.2	0.8
Lead	Lincoln Park	1981-1982	0.1	0.034
Manganese	Lincoln Park	1981-1982	0.03	0.0185
Nitrate	Cañon City	1978-1987	14.3	2.35
	Lincoln Park	1981-1982	4.7	1.81
Sulfate	Cañon City	1978-1987	18.4	5.99
	Lincoln Park	1981-1982	13	6.48
Zinc	Lincoln Park	1981-1982	0.04	0.0283

Notes Data downloaded from EPA's Air Quality System database.

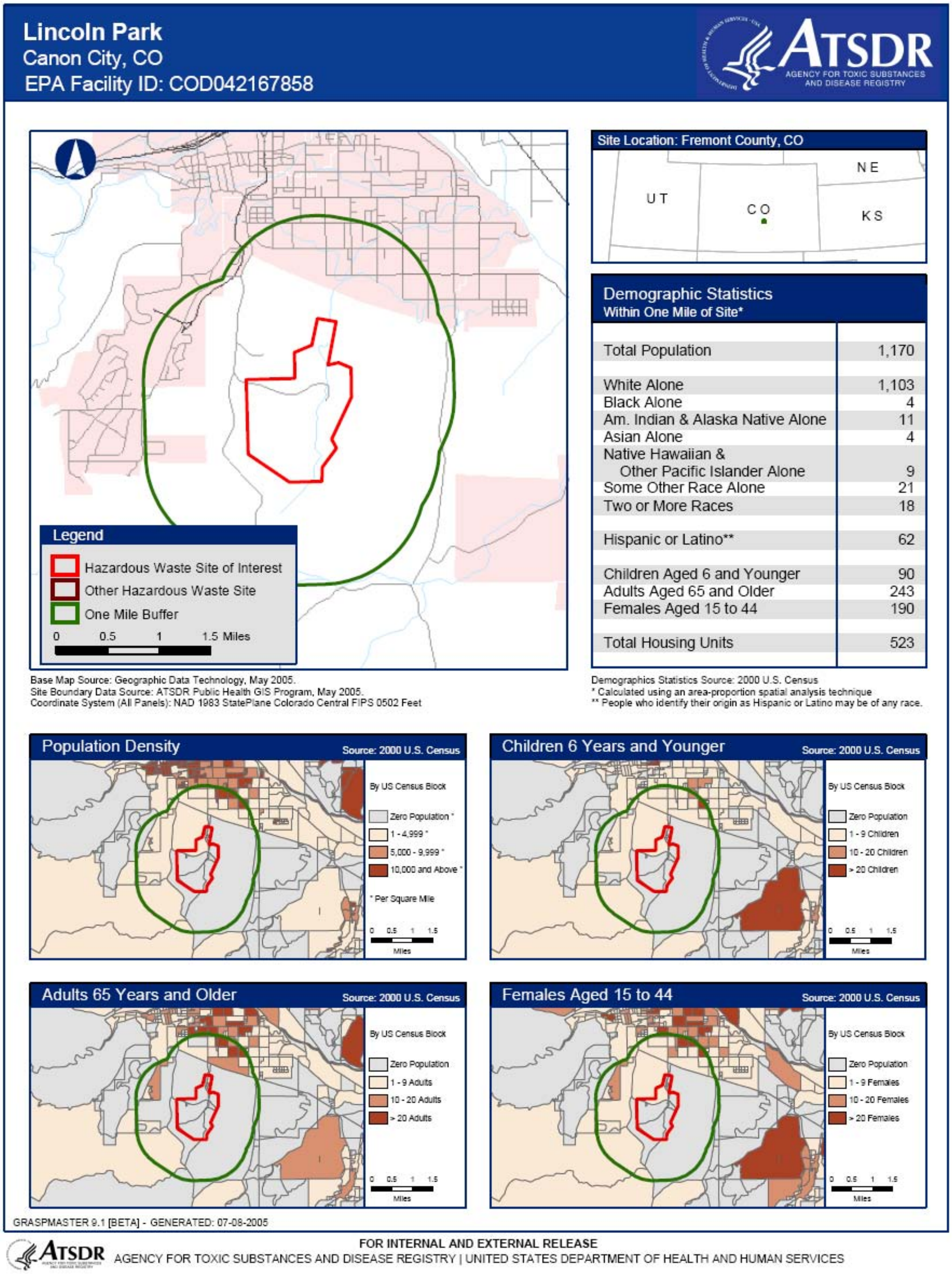
Appendix B - Site Figures

Figure 1. Location of the Cotter Mill, Lincoln Park, and Cañon City



Source: Galant et al. 2007

Figure 2. Demographics within 1 mile of the Cotter Mill property



Lincoln Park
Canon City, CO
EPA Facility ID: COD042167858

Demographic Statistics
Within One Mile of Site*

Total Population	1,170
White Alone	1,103
Black Alone	4
Am. Indian & Alaska Native Alone	11
Asian Alone	4
Native Hawaiian & Other Pacific Islander Alone	9
Some Other Race Alone	21
Two or More Races	18
Hispanic or Latino**	62
Children Aged 6 and Younger	90
Adults Aged 65 and Older	243
Females Aged 15 to 44	190
Total Housing Units	523

Base Map Source: Geographic Data Technology, May 2005.
Site Boundary Data Source: ATSDR Public Health GIS Program, May 2005.
Coordinate System (All Panels): NAD 1983 StatePlane Colorado Central FIPS 0502 Feet

Demographics Statistics Source: 2000 U.S. Census
* Calculated using an area-proportion spatial analysis technique
** People who identify their origin as Hispanic or Latino may be of any race.

Population Density Source: 2000 U.S. Census

Children 6 Years and Younger Source: 2000 U.S. Census

Adults 65 Years and Older Source: 2000 U.S. Census

Females Aged 15 to 44 Source: 2000 U.S. Census

GRASPMASTER 9.1 [BETA] - GENERATED: 07-08-2005

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Figure 3. Wind Rose for Cotter Mill, 2008

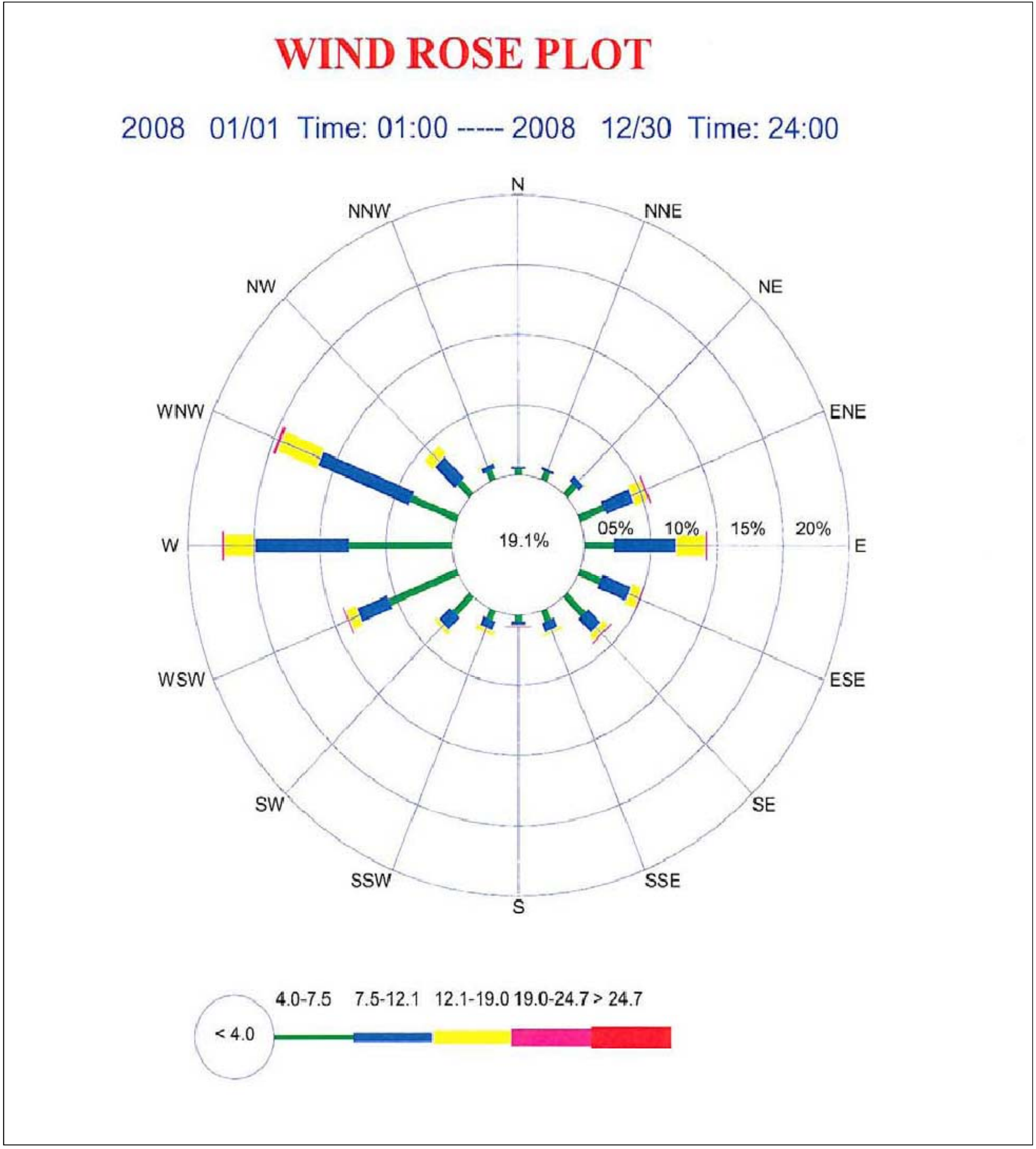
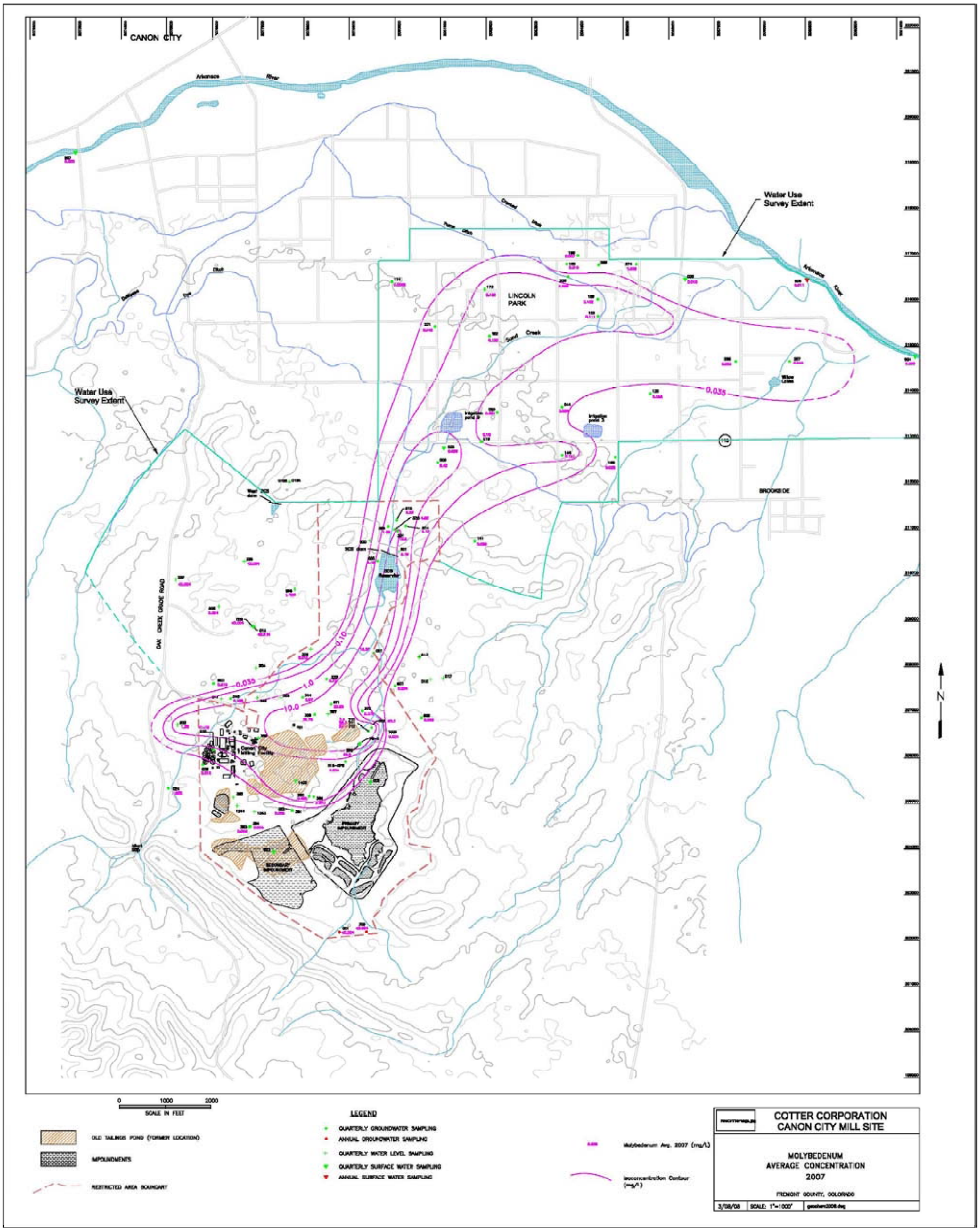
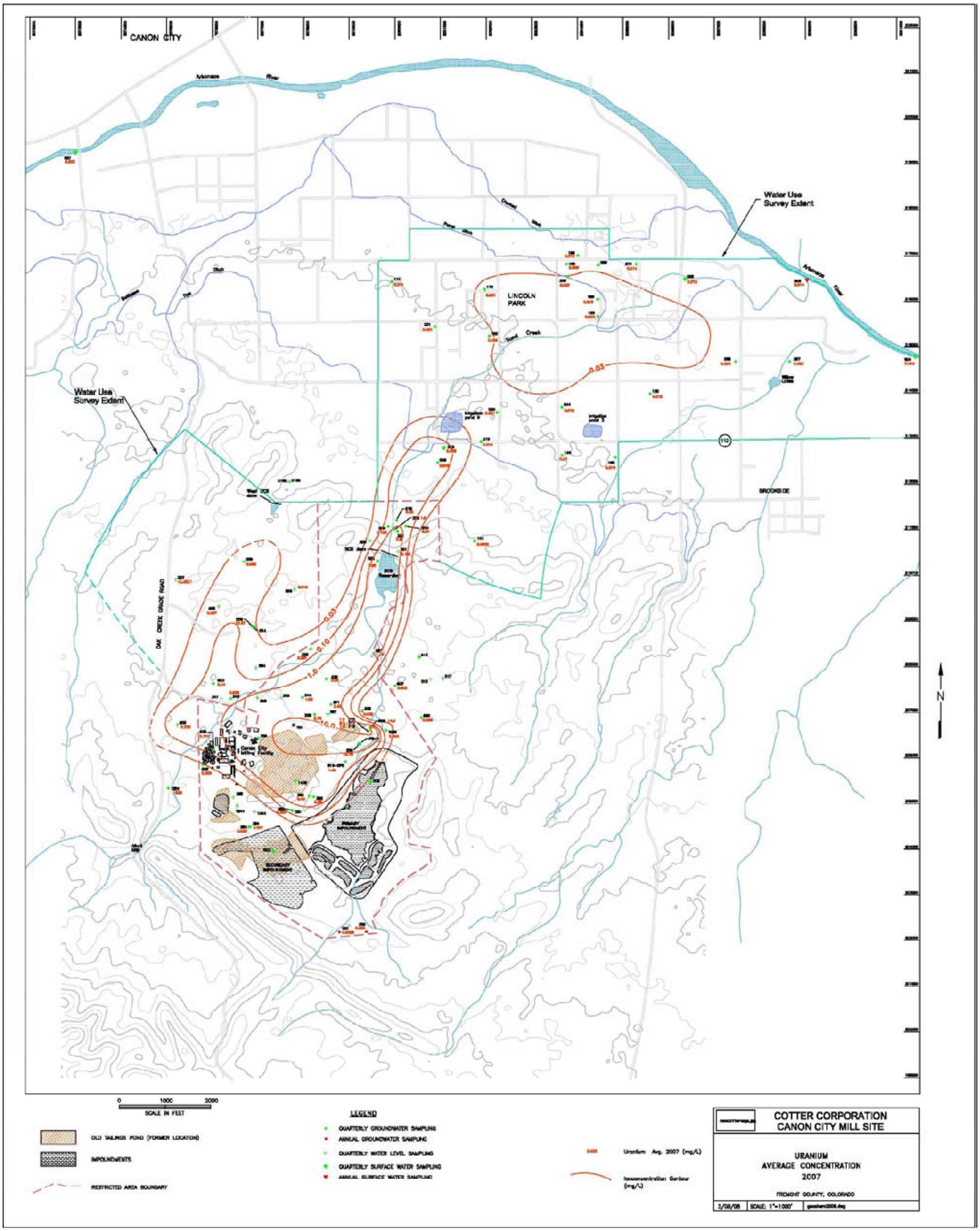


Figure 4. Molybdenum Plume Map



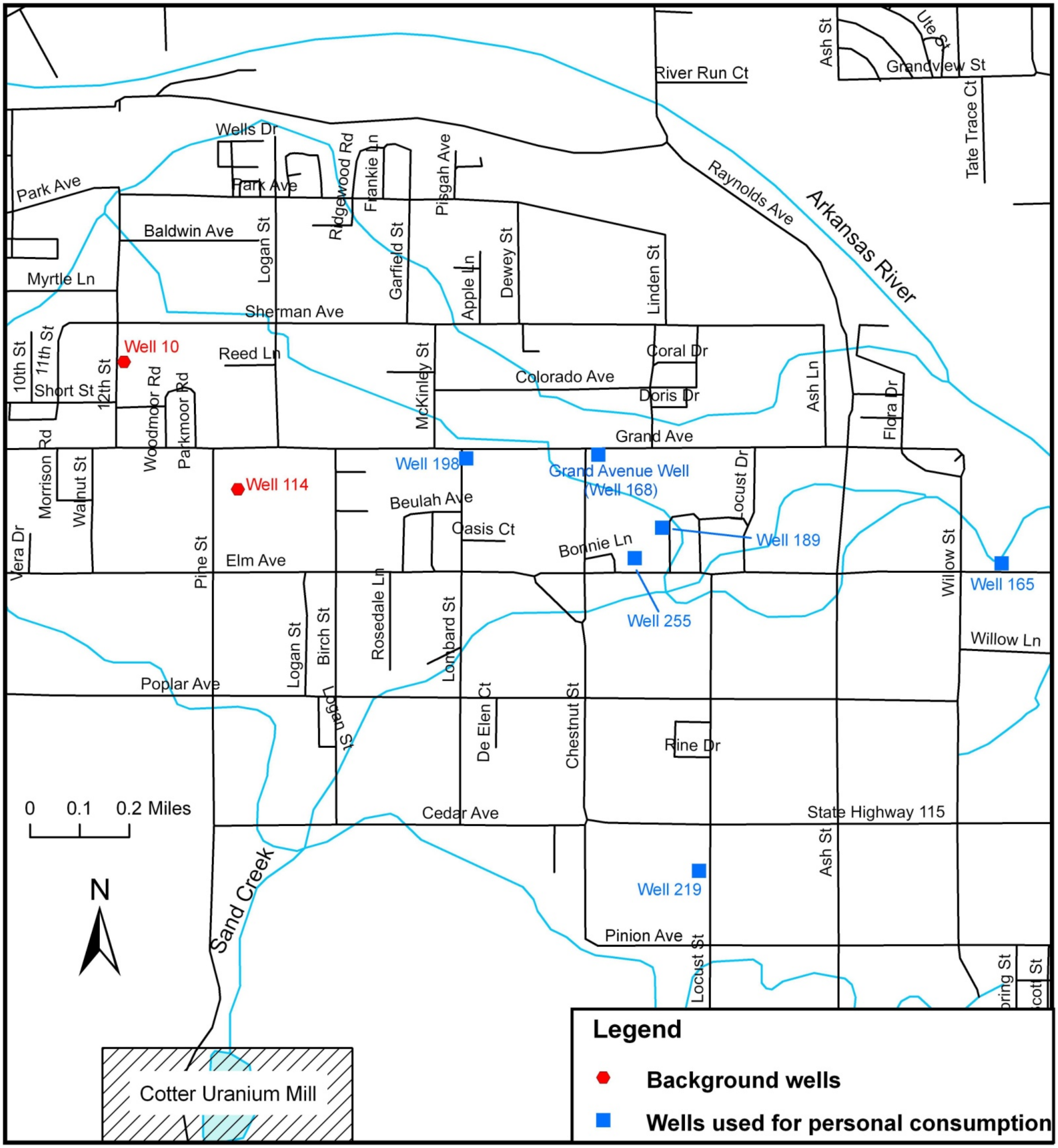
Source: Cotter 2008

Figure 5. Uranium Plume Map



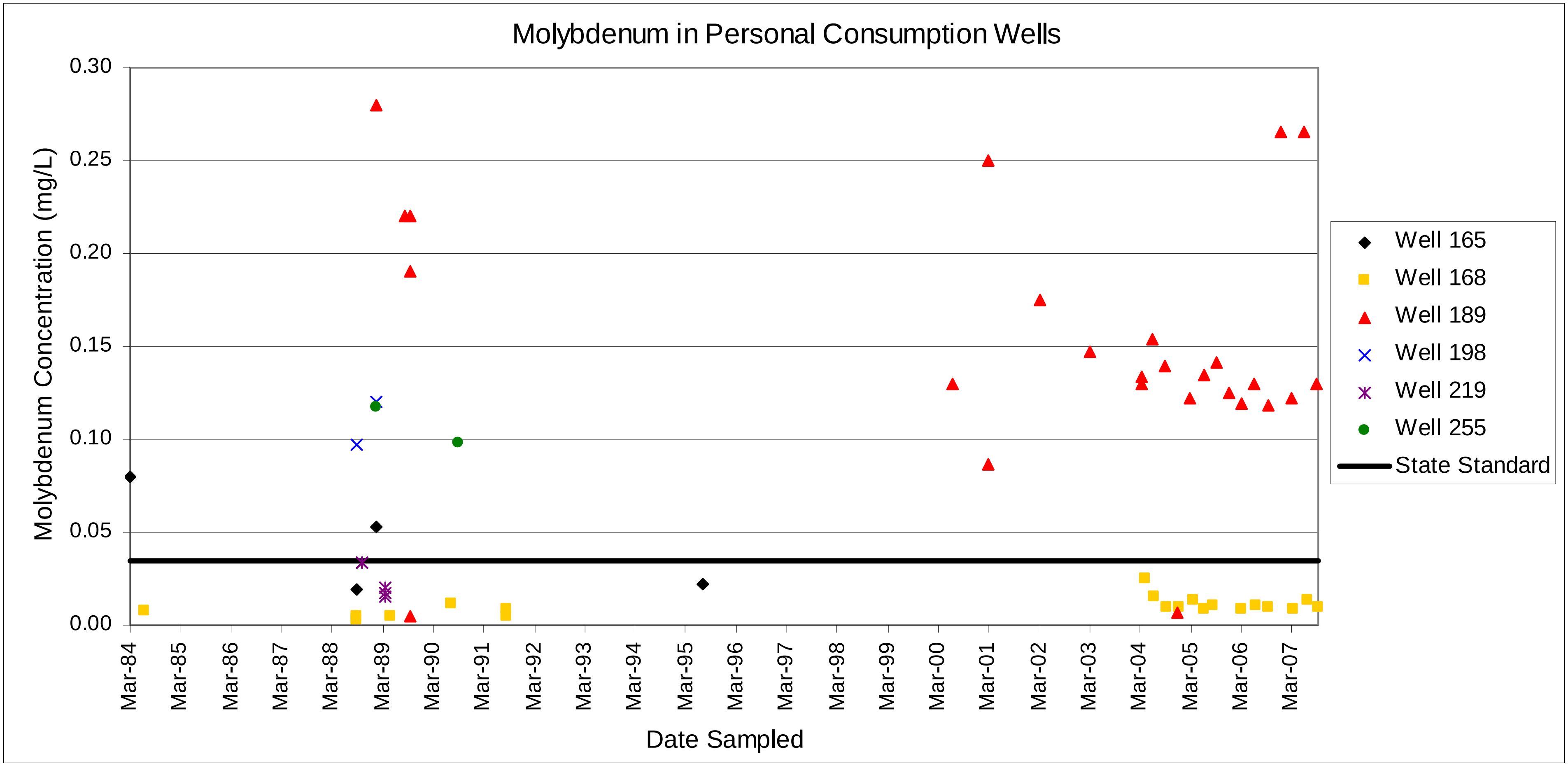
Source: Cotter 2008

Figure 6. Wells in Lincoln Park used for personal consumption



Source: CDPHE 2007b (coordinates)

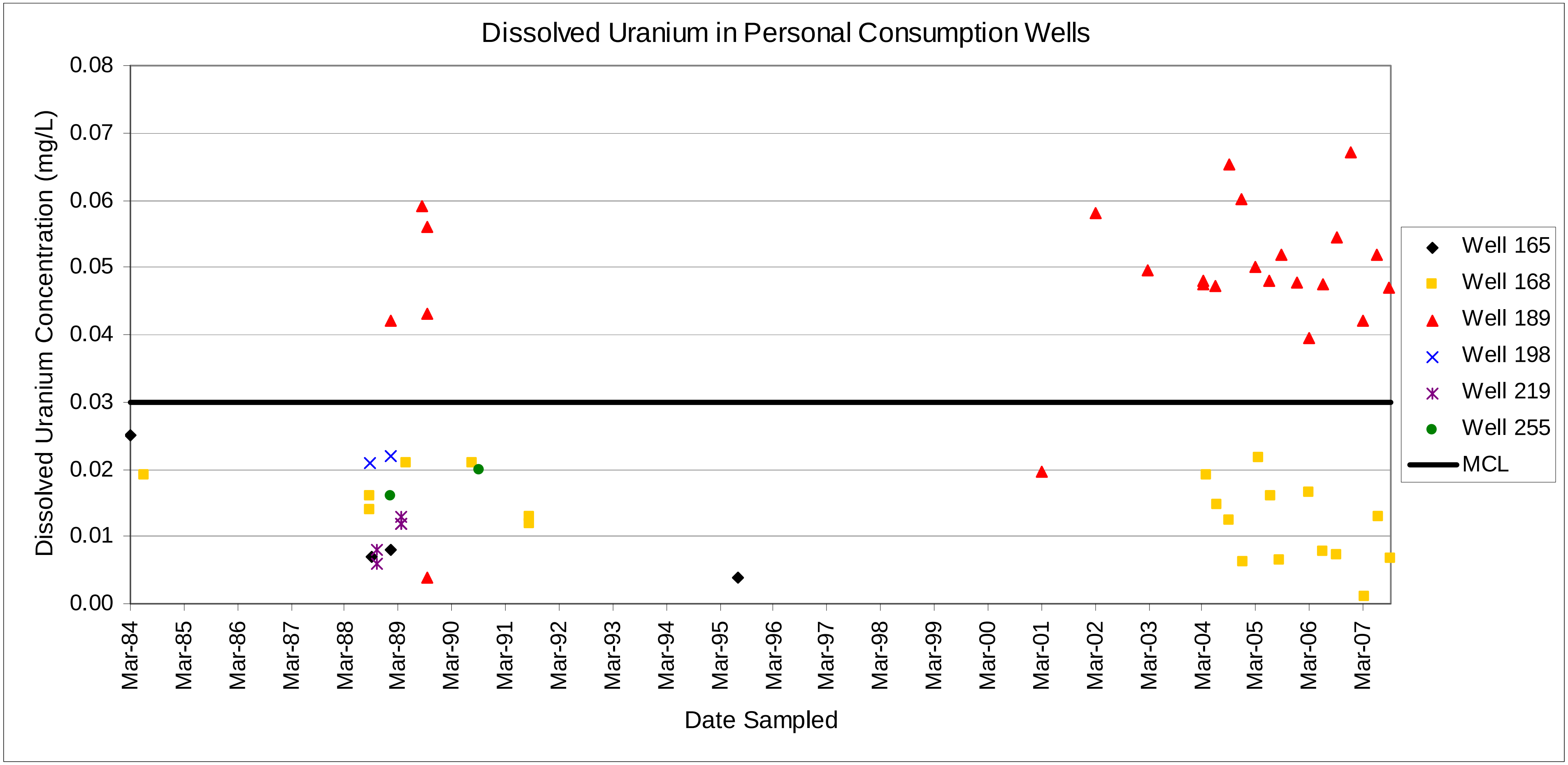
Figure 7. Molybdenum concentrations in wells used for personal consumption



Source: CDPHE 2007b

Non-detected concentrations were plotted as ½ the reporting detection limit.

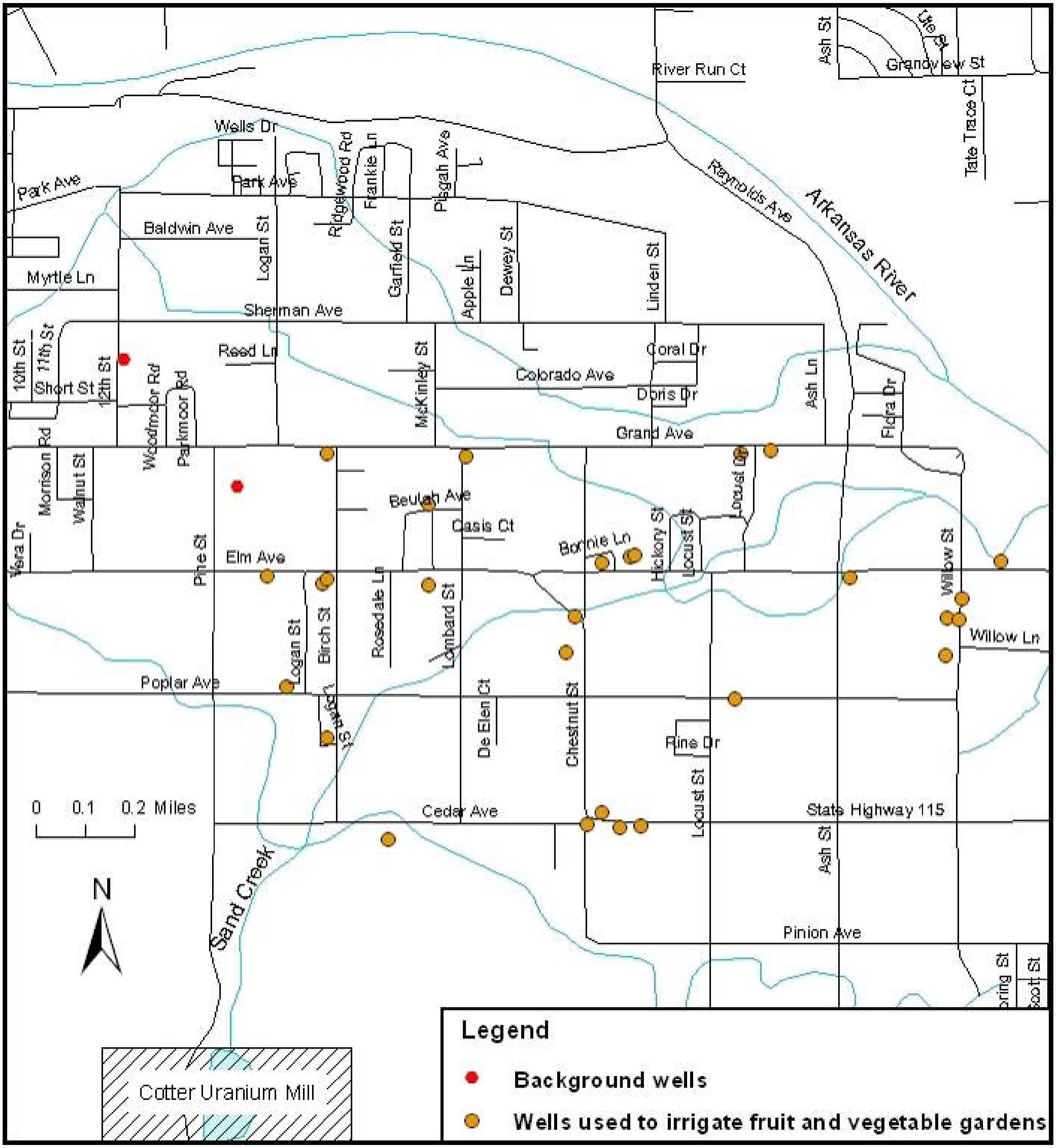
Figure 8. Dissolved uranium concentrations in wells used for personal consumption



Source: CDPHE 2007b

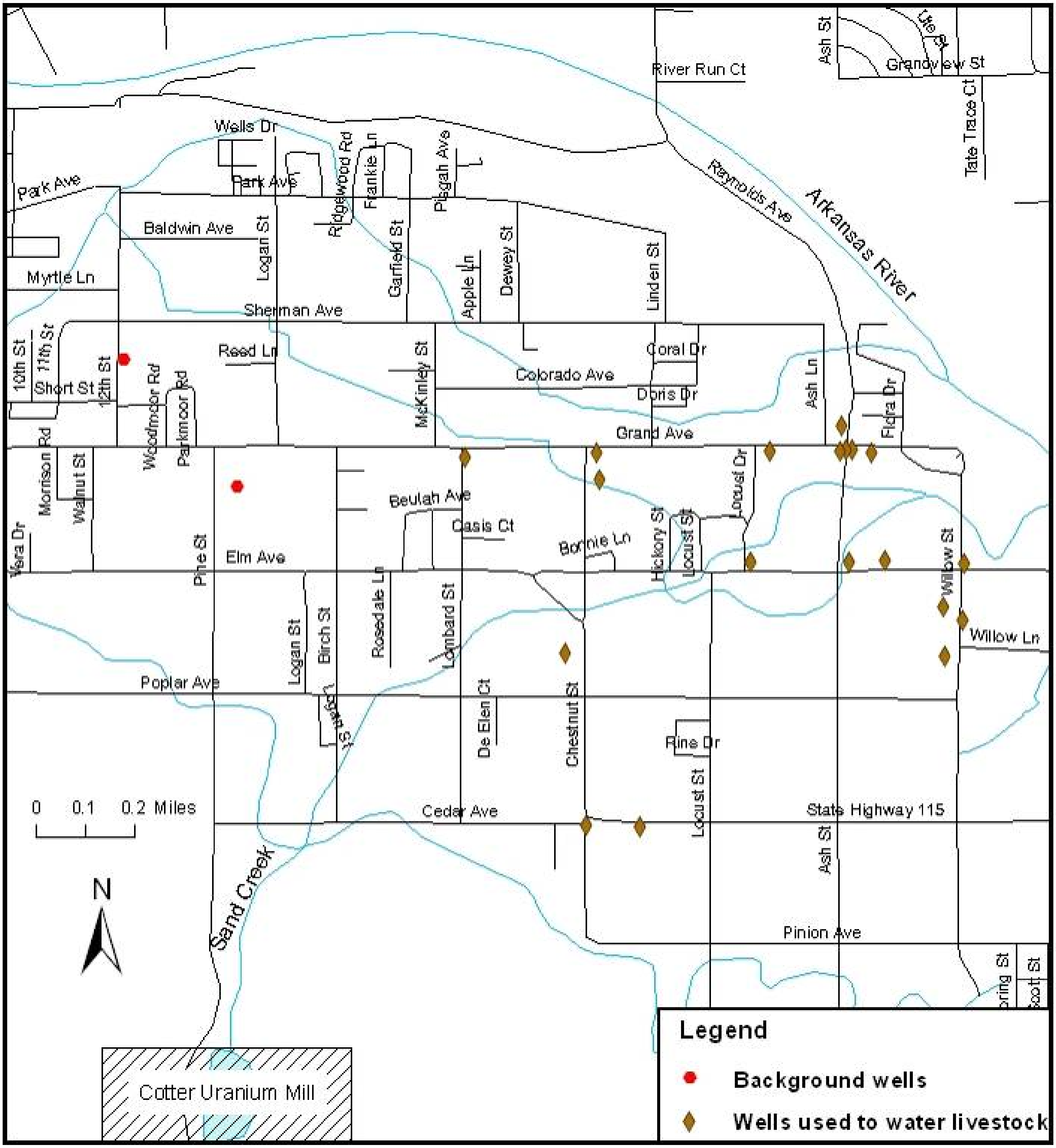
Non-detected concentrations were plotted as ½ the reporting detection limit.

Figure 9. Wells in Lincoln Park used to irrigate fruit and vegetable gardens



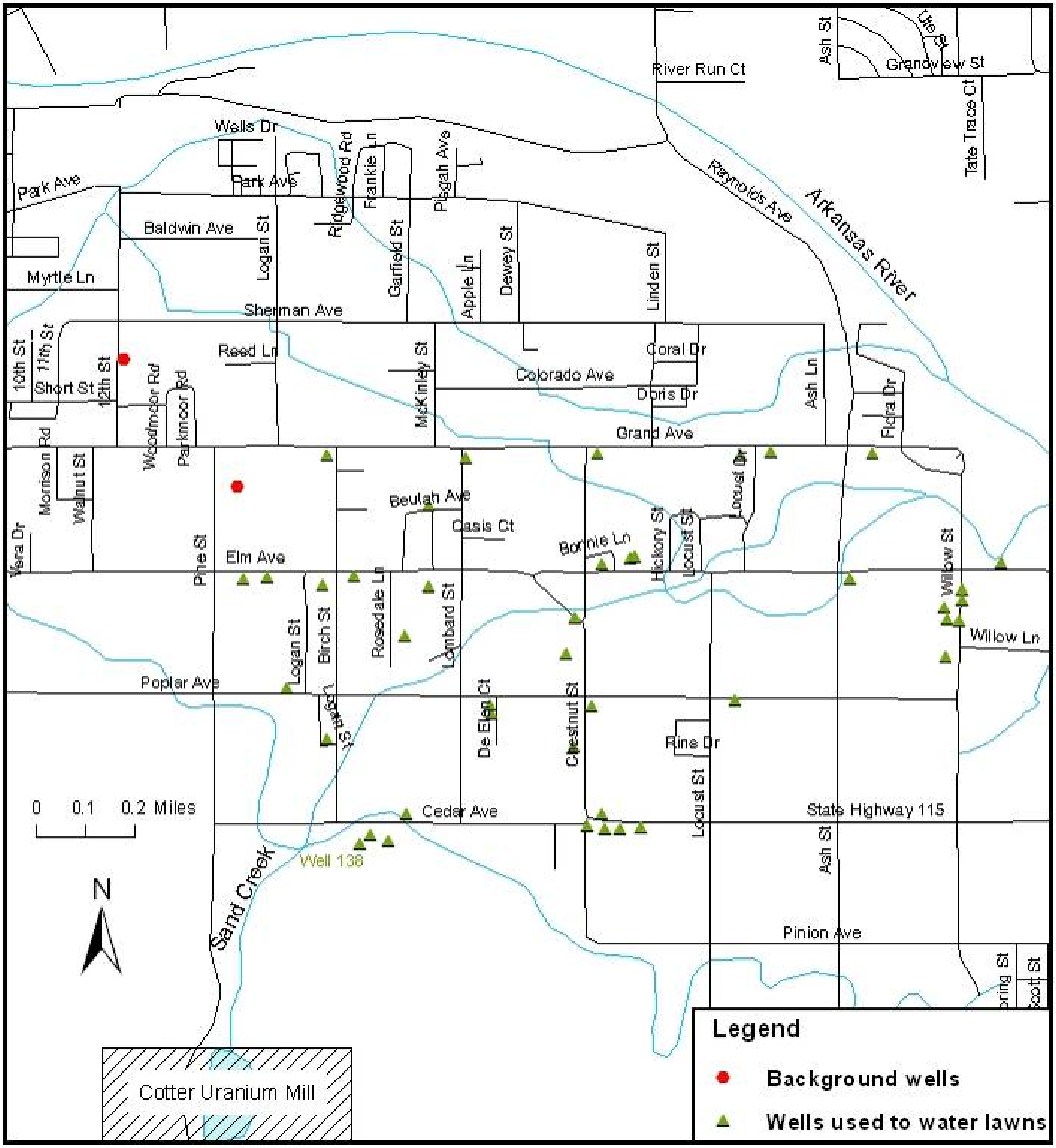
Source: CDPHE 2007b (coordinates)

Figure 10. Wells in Lincoln Park used to water livestock



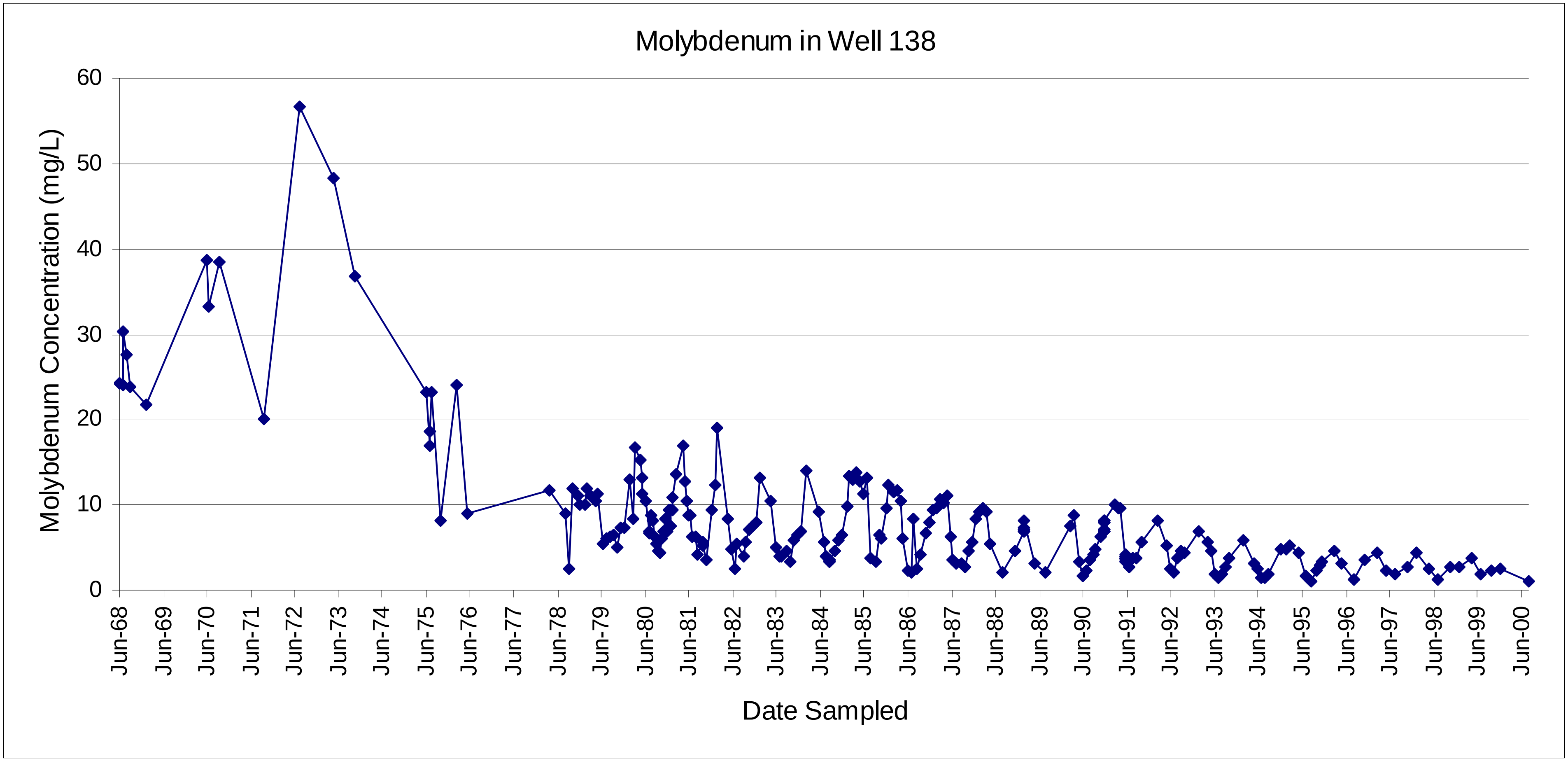
Source: CDPHE 2007b (coordinates)

Figure 11. Wells in Lincoln Park used to water lawns



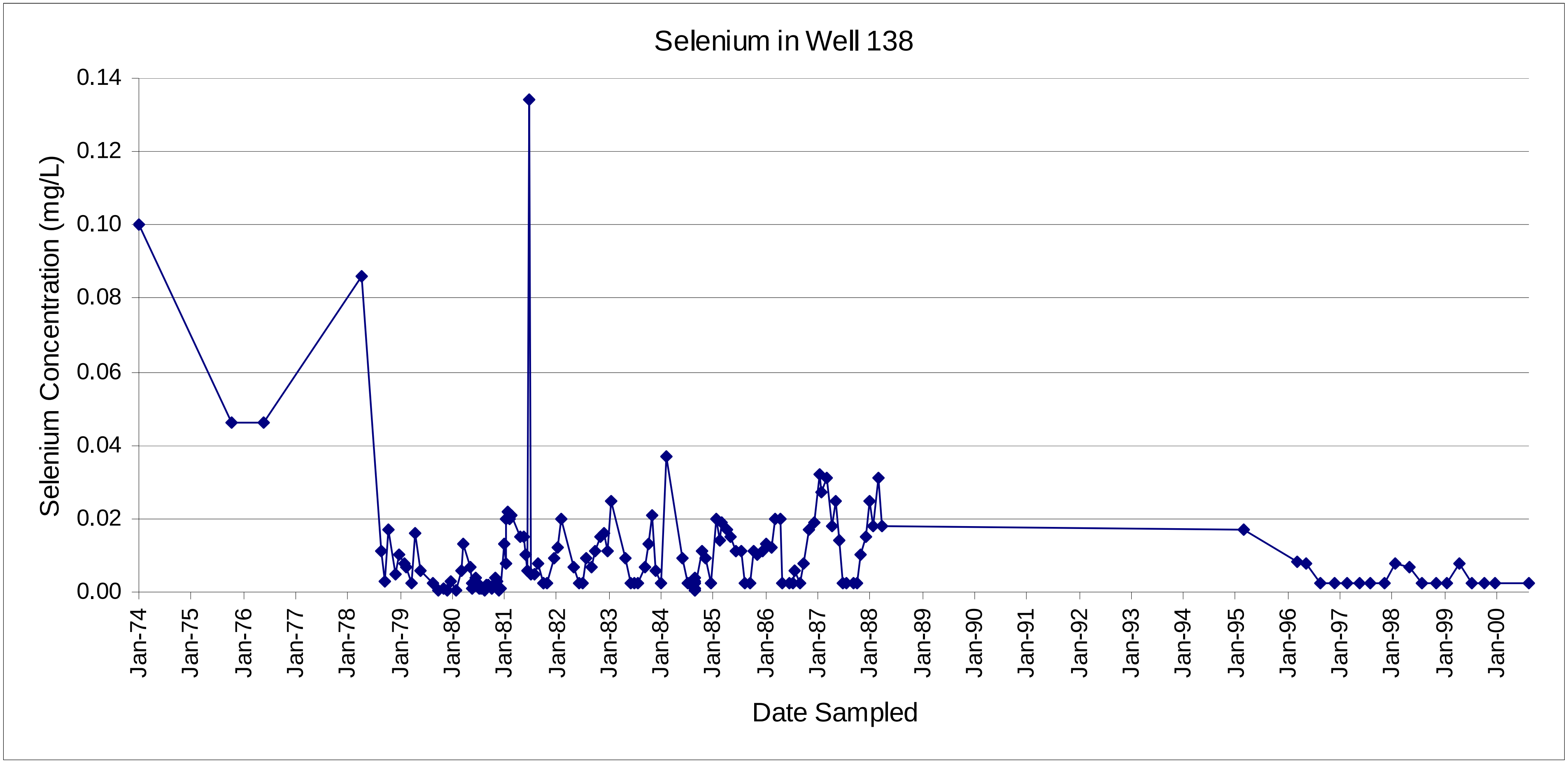
Source: CDPHE 2007b (coordinates)

Figure 12. Molybdenum concentrations in Well 138



Source: CDPHE 2007b

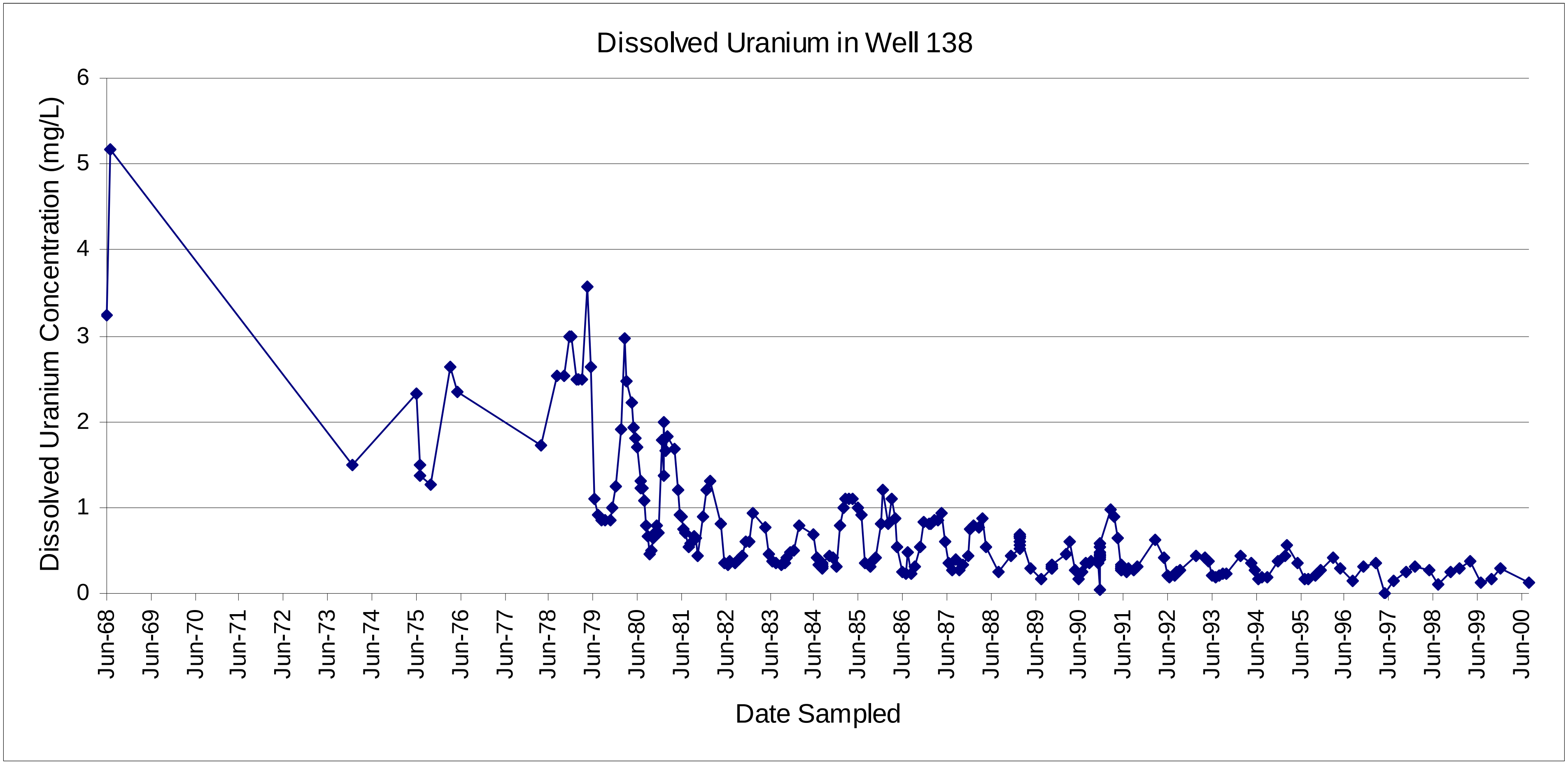
Figure 13. Selenium concentrations in Well 138



Source: CDPHE 2007b

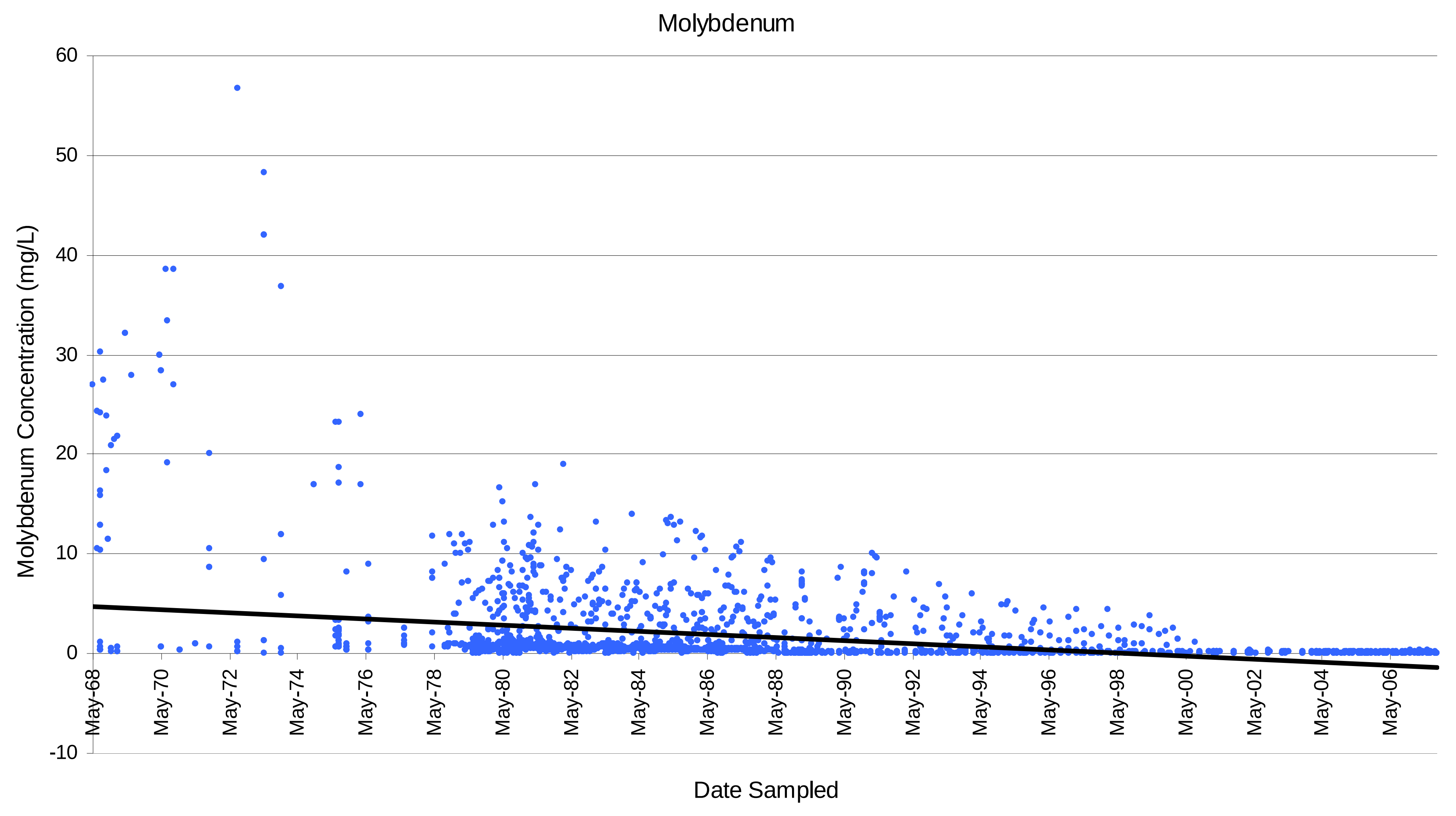
Non-detected concentrations were plotted as ½ the reporting detection limit.

Figure 14. Dissolved uranium concentrations in Well 138



Source: CDPHE 2007b

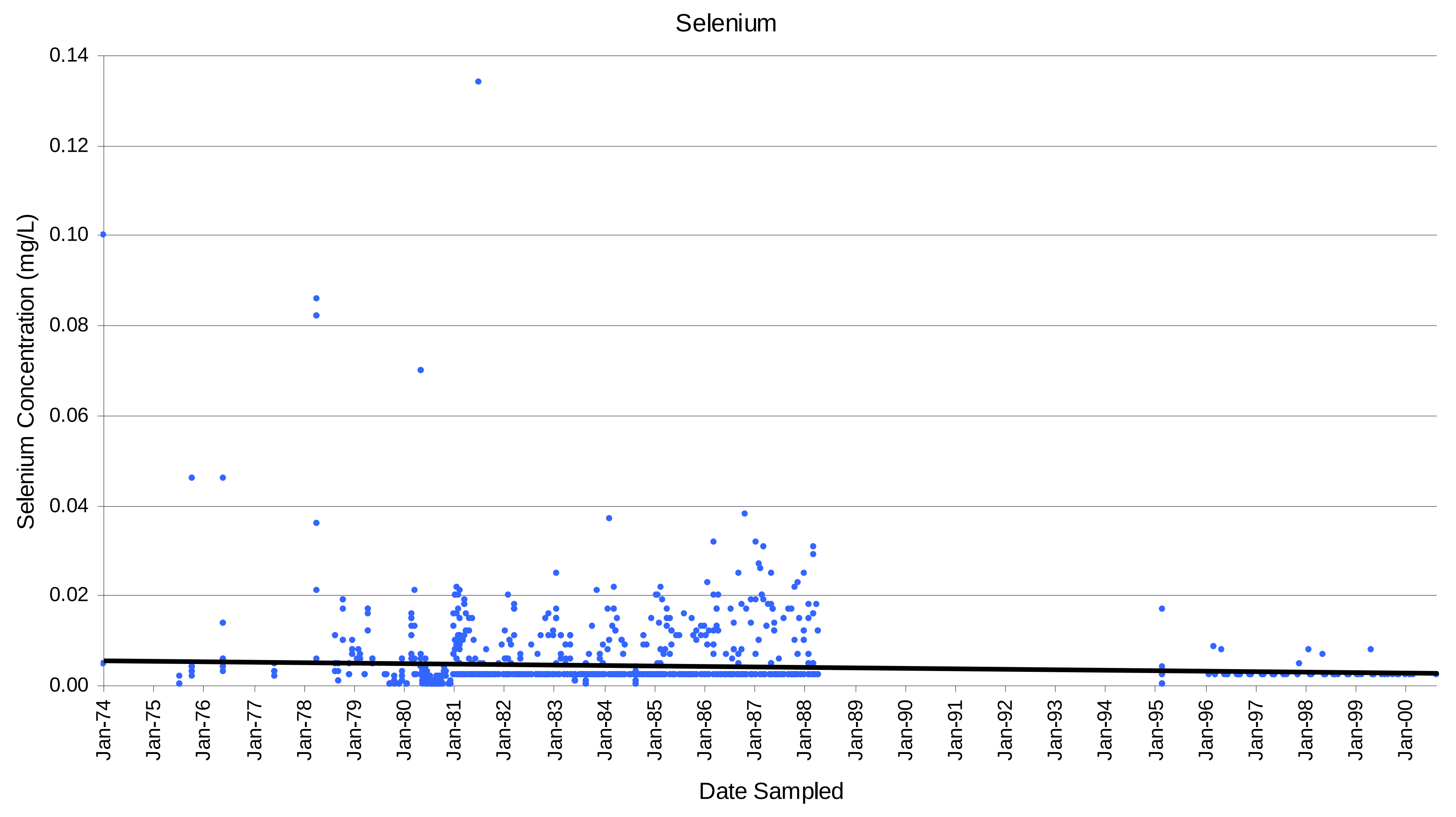
Figure 15. Molybdenum concentrations in all groundwater wells evaluated



Source: CDPHE 2007b

Non-detected concentrations were plotted as ½ the reporting detection limit.

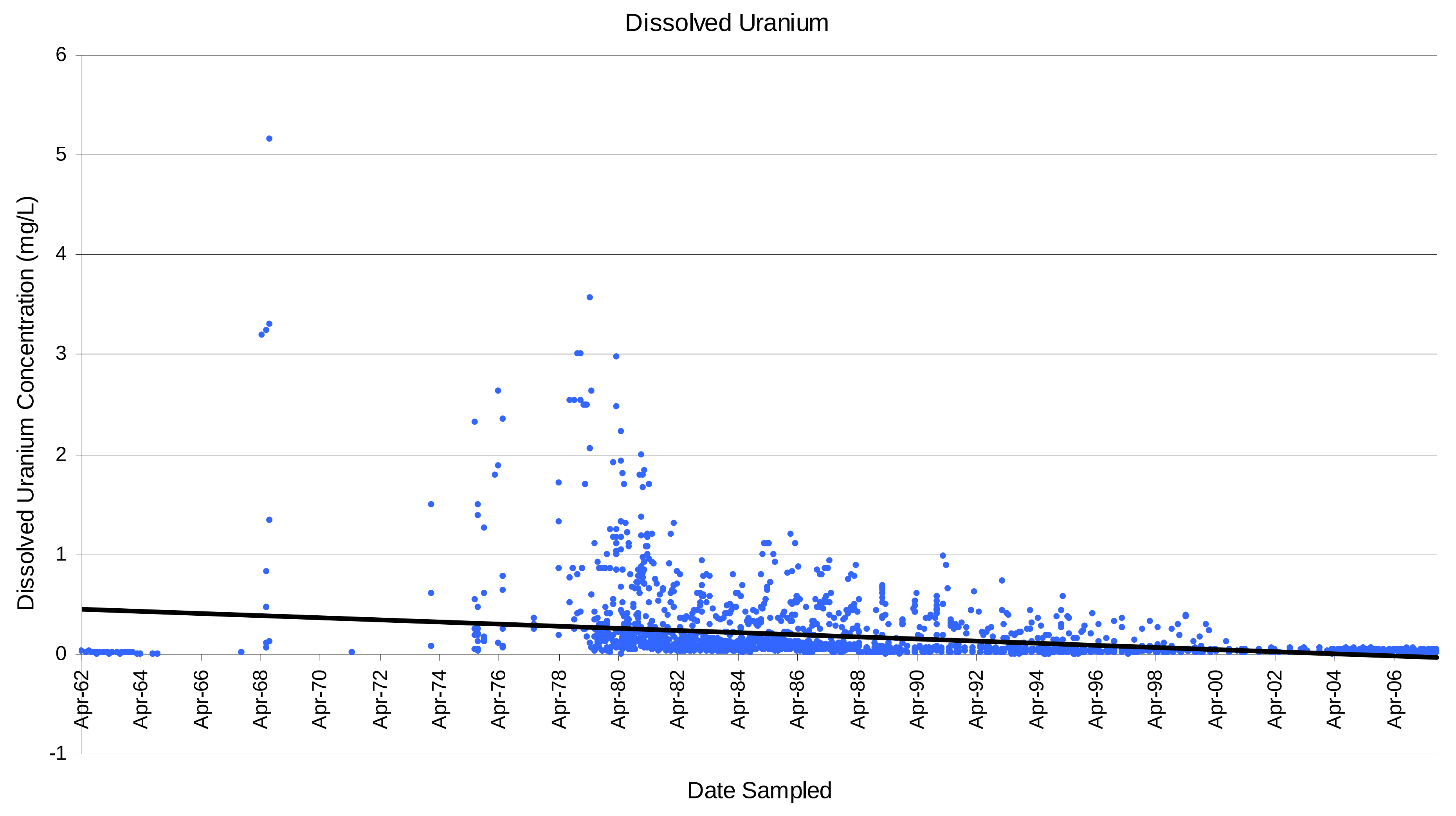
Figure 16. Selenium concentrations in all groundwater wells evaluated



Source: CDPHE 2007b

Non-detected concentrations were plotted as ½ the reporting detection limit.

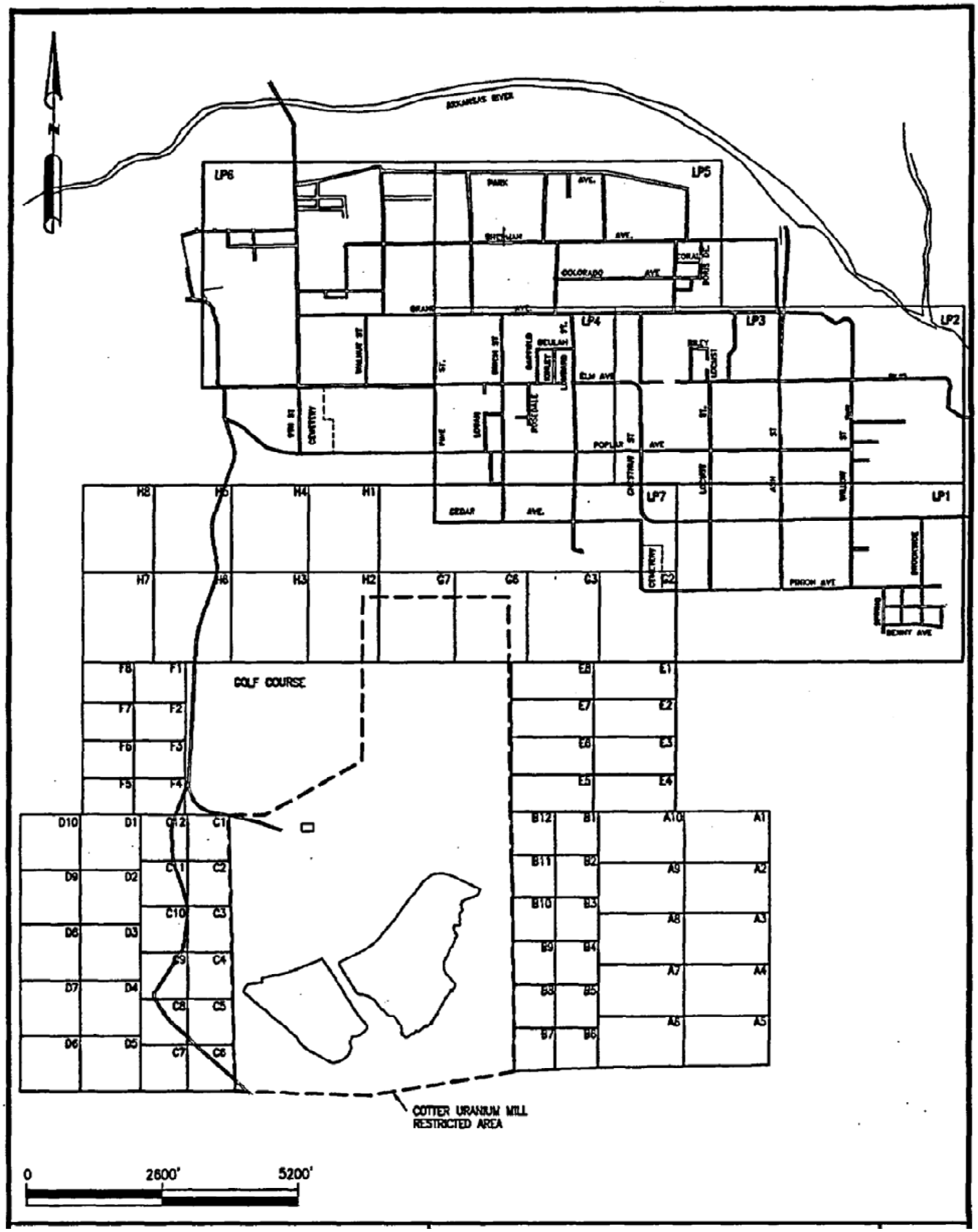
Figure 17. Dissolved uranium concentrations in all groundwater wells evaluated



Source: CDPHE 2007b

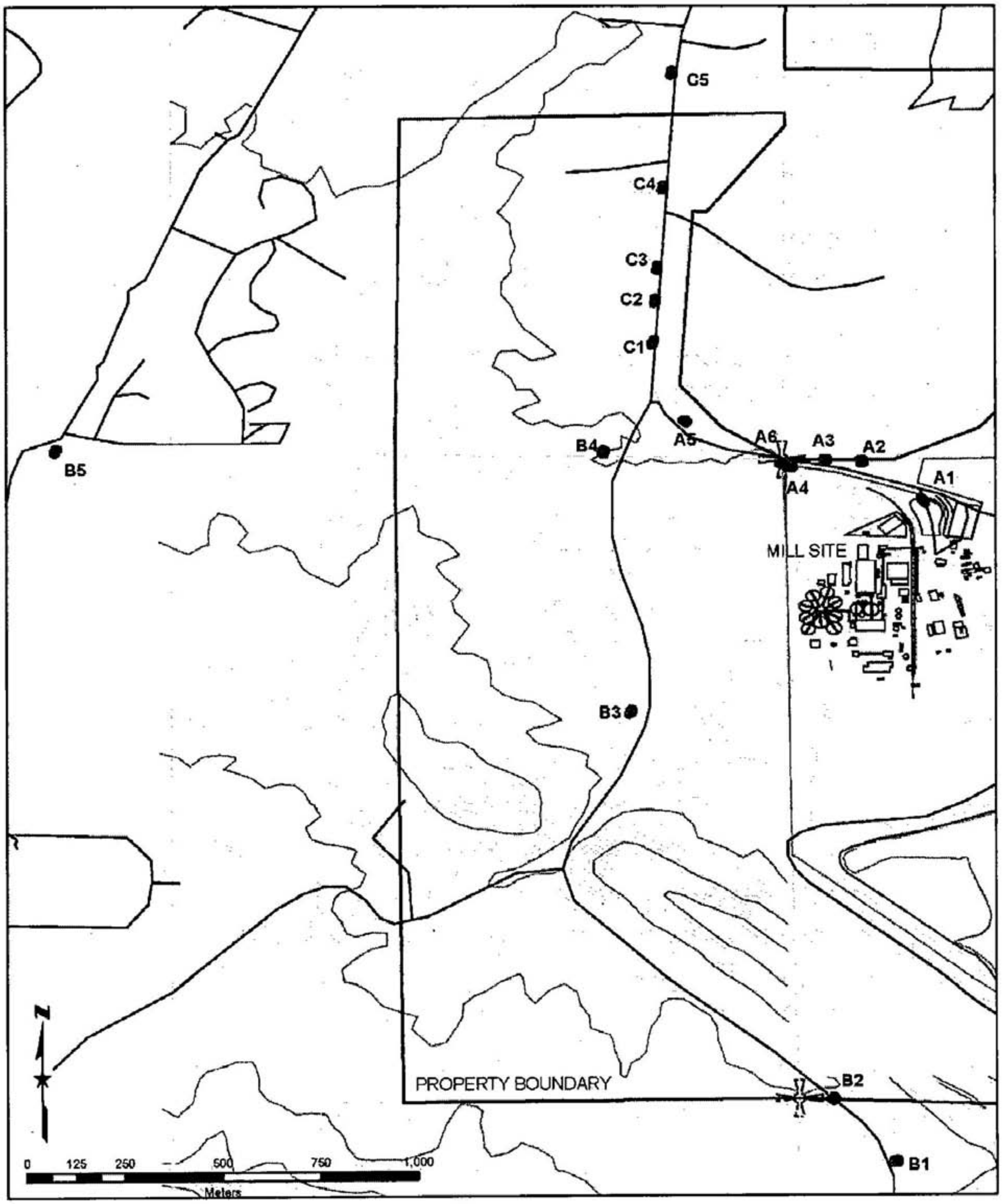
Non-detected concentrations were plotted as ½ the reporting detection limit.

Figure 18. Sampling zones established during the 1998 Supplemental Human Health Risk Assessment



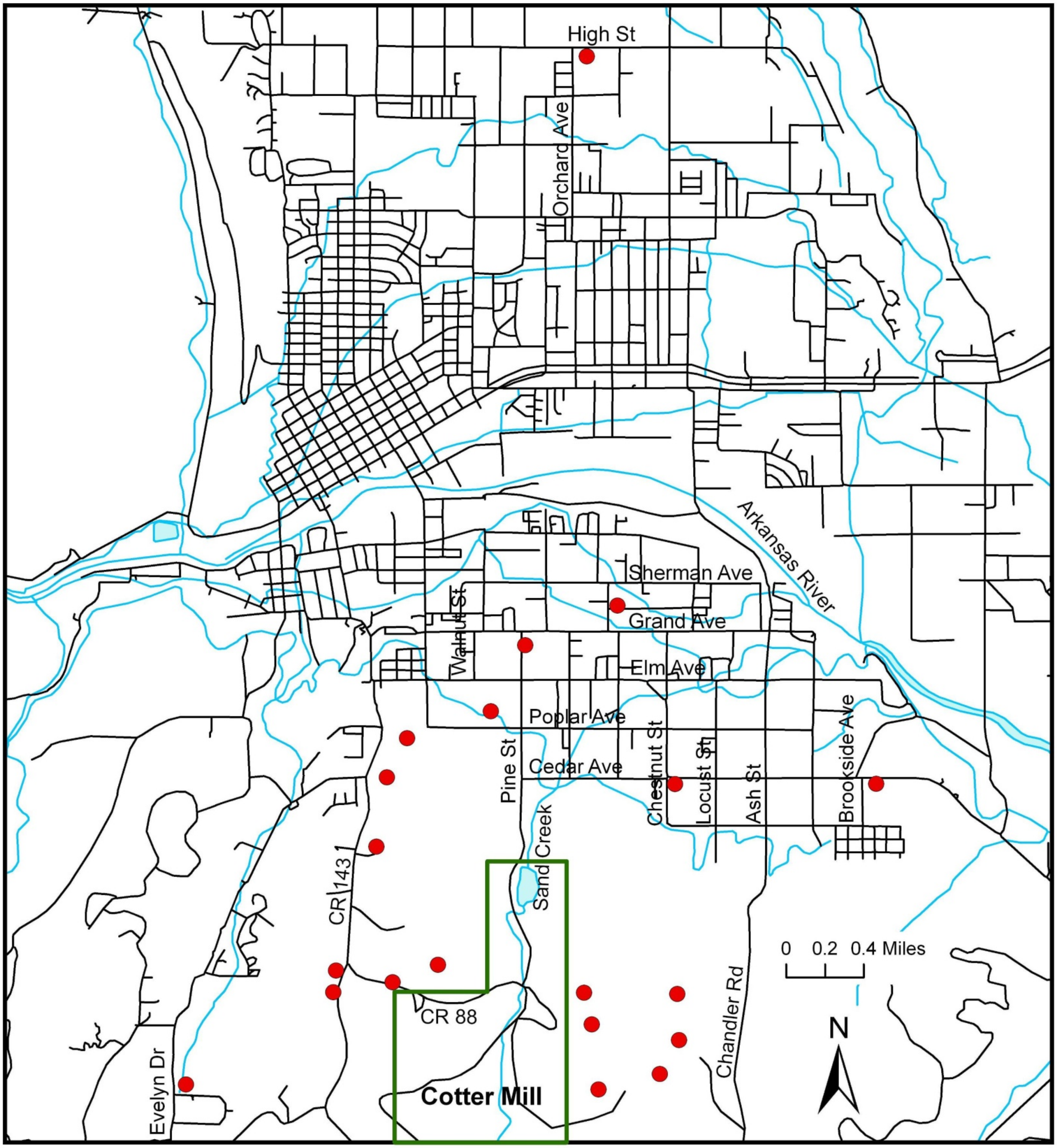
Source: Weston 1998

Figure 19. Locations of soil samples taken along the county road and Cotter Mill's access road



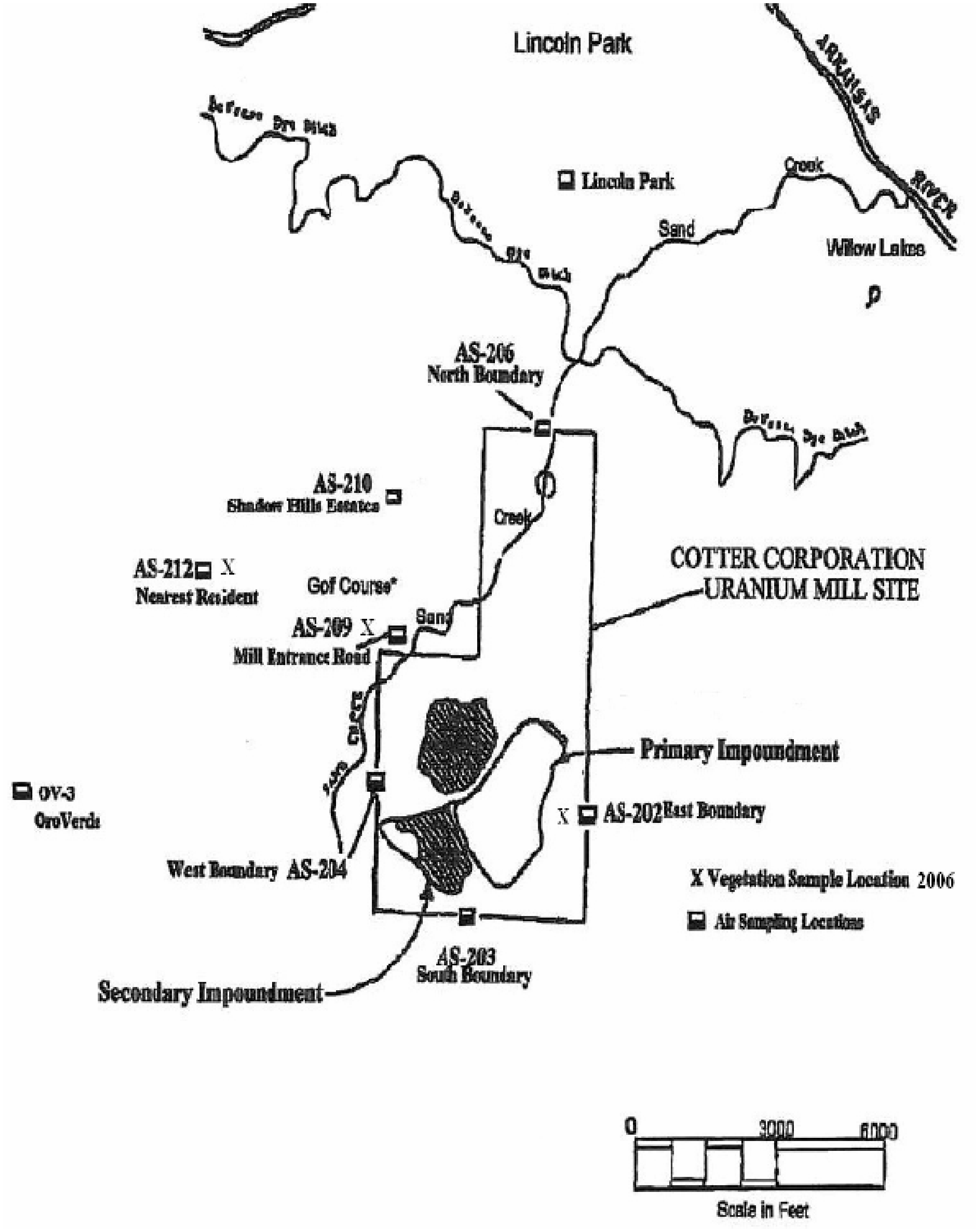
Source: MFG 2005

Figure 20. Locations of soil samples taken by CDPHE in January 2003



Source: CDPHE 2007b (coordinates)

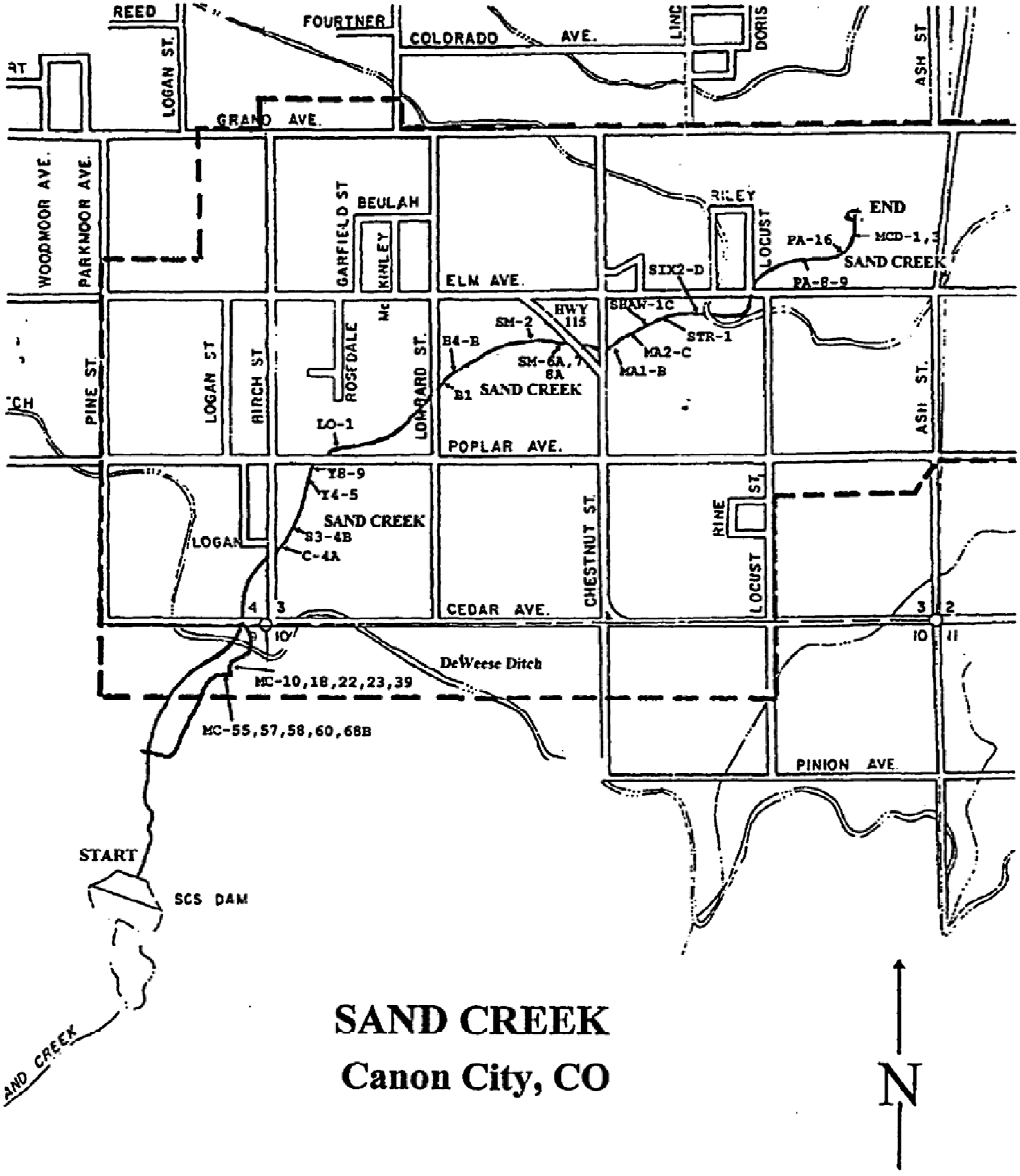
Figure 21. Location of air sampling locations where soil samples are collected



Source: Cotter 2007

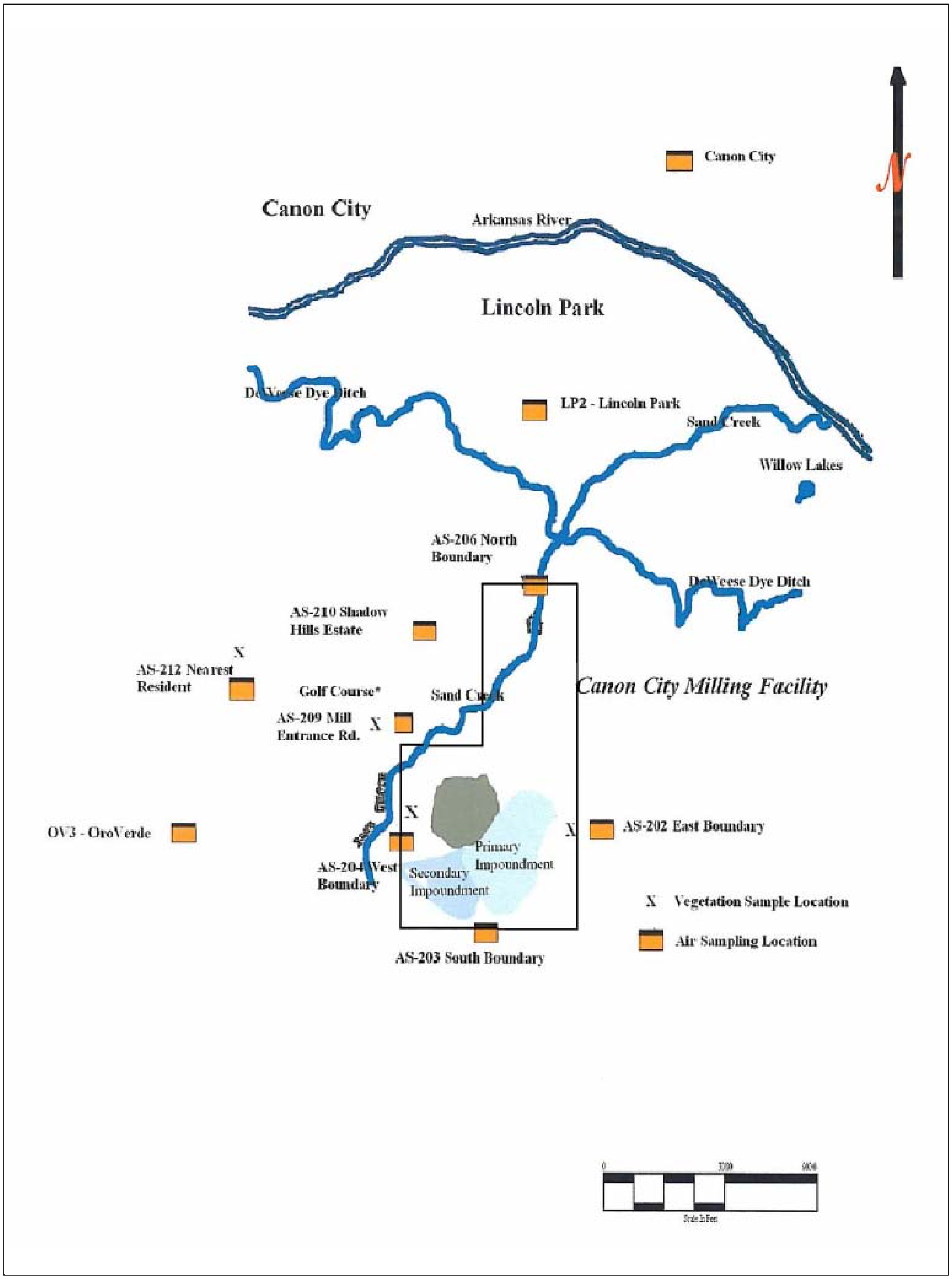
Note: An additional air sampling station is located in Cañon City (not depicted on the figure).

Figure 22. Sand Creek Cleanup Project



Source: Cotter 2000

Figure 23. Approximate Locations of Cotter Mill Monitoring Stations



Notes: Figure reproduced from: Cotter 2008

APPENDIX C:
ATSDR's Evaluation Process
And
Exposure Dose Calculations

ATSDR's Evaluation Process

Step 1 – Comparison Values and the Screening Process

To evaluate the available data, ATSDR used comparison values (CVs) to determine which chemicals to examine more closely. CVs are the contaminant concentrations found in a specific media (for example: air, soil, or water) and are used to select contaminants for further evaluation. CVs incorporate assumptions of daily exposure to the chemical and a standard amount of air, water, or soil that someone may inhale or ingest each day. CVs are generated to be conservative and non-site specific. These values are used only to screen out chemicals that do not need further evaluation; CVs are not intended as environmental clean-up levels or to indicate that health effects occur at concentrations that exceed these values.

CVs can be based on either carcinogenic (cancer-causing) or non-carcinogenic effects. Cancer-based comparison values are calculated from the U.S. Environmental Protection Agency's (EPA) oral cancer slope factor (CSF) or inhalation risk unit. CVs based on cancerous effects account for a lifetime exposure (70 years) with an unacceptable theoretical excess lifetime cancer risk of 1 new case per 1 million exposed people. Non-cancer values are calculated from ATSDR's Minimal Risk Levels (MRLs), EPA's Reference Doses (RfDs), or EPA's Reference Concentrations (RfCs). When a cancer and non-cancer CV exists for the same chemical, the lower of these values is used in the comparison for conservatism.

Step 2 – Evaluation of Public Health Implications

The next step in the evaluation process is to take those contaminants that are above their respective CVs and further identify which chemicals and exposure situations are likely to be a health hazard. Separate child and adult exposure doses (or the amount of a contaminant that gets into a person's body) are calculated for site-specific exposure scenarios, using assumptions regarding an individual's likelihood of accessing the site and contacting contamination. A brief explanation of the calculation of estimated exposure doses is presented below. Calculated doses are reported in units of milligrams per kilograms per day (mg/kg/day). Separate calculations have been performed to account for non-cancer and cancer health effects, if applicable, for each chemical based on the health impacts reported for each chemical. Some chemicals are associated with non-cancer effects while the scientific literature many indicate that cancer-related health impacts are not expected from exposure.

Exposure Dose Factors and Calculations

When chemical concentrations at the site exceed the established CVs, it is necessary for a more thorough evaluation of the chemical to be conducted. In order to evaluate the potential for human exposure to contaminants present at the site and potential health effects from site-specific activities, ATSDR estimates human exposure to the site contaminant from different environmental media by calculating exposure doses.

A discussion of the calculations and assumptions used in this assessment is presented below. The equations are based on the EPA Risk Assessment Guidance for Superfund, Part A (1989), or ATSDR's Public Health Guidance Manual (2005), unless otherwise specified. Assumptions used were based on default values, EPA's Exposure Assessment Handbook (1997) or Child-Specific Exposure Factors Handbook (2008), or professional (site-specific) judgment. When available, site-specific information is used to estimate exposures.

Ingestion of Chemicals in Well Water:

The exposure dose formula used for the ingestion of chemicals in well water is:

$$\text{Exposure Dose (ED)} = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

Where:

***ED** = exposure dose in milligrams per kilogram per day (mg/kg/day)*
***C** = concentration of contaminant in water in milligrams per liter (mg/L)*
***IR** = ingestion rate in liters per day (L/day)*
***EF** = exposure frequency (days/year)*
***ED** = exposure duration (years)*
***BW** = body weight (kg)*
***AT** = averaging time, days (equal to ED for non-carcinogens and 70 year lifetime for carcinogens, i.e., 70 years x 365 days/year)*

Note: In the intake equation, averaging time (AT) for exposure to non-carcinogenic compounds is always equal to ED; whereas, for carcinogens a 70 year AT is still used in order to compare to EPA's cancer slope factors typically based on that value.

This pathway assumes that an adult resident drinks 2 liters (L) of water per day for 350 days per year. In terms of exposure duration (ED), the adult resident is assumed to live in the same home and drink the same well water for 30 years. The drinking water ingestion rate for children was assumed to be 1 L per day for 350 days per year for 6 years. For average body weight, 70 kg and 16 kg were used for adults and children, respectively.

ATSDR used the average chemical concentration in Well 186 to represent a high exposure scenario from a single well. Well 186 was selected because it consistently contained the highest chemical concentrations over time. The average concentration for all private wells was used to represent exposures to a typical well user.

Table C1. Summary of Exposure Factors and Exposure Doses for the Drinking Water Pathway for Chemicals at the Cotter Mill Site

Chemical	**Chemical Concentration (mg/L)**	**Daily Ingestion Rate (L/day)**	**Exposure Frequency (days/yr)**	**Exposure Duration (yrs)**	**Body Weight (kg)**	**Averaging Time (days)**	**Exposure Dose (mg/kg/day)**	**Health Guideline (mg/kg/day)**
Drinking Water Pathway: Ingestion – ADULT and CHILD								
Molybdenum ADULT	0.16 *WELL 189** HIGH EXPOSURE	2	350	30	70	10950	0.004	0.005 Chronic Oral RfD
Molybdenum CHILD		1	350	6	16	2190	**0.010**	
Molybdenum ADULT	0.082 All wells TYPICAL EXPOSURE	2	350	30	70	10950	0.002	
Molybdenum CHILD		1	350	6	16	2190	0.005	
Uranium ADULT	0.048 Well 189* HIGH EXPOSURE	2	350	30	70	10950	0.001	0.002 Intermediate Oral MRL
Uranium CHILD		1	350	6	16	2190	**0.003**	
Uranium ADULT	0.028 All wells TYPICAL EXPOSURE	2	350	30	70	10950	0.0008	
Uranium CHILD		1	350	6	16	2190	0.002	

Bolded type exceeds a comparison value.
* "Well 189" represents a high exposure scenario. This well contained the highest level of chemicals in the sampled group.
"All wells" is used to represent an average exposure scenario for the average private well drinker.

Accidental Ingestion of Chemicals in Soil

The exposure dose formula for incidental ingestion of chemicals soil and/or sediment is:

$$\text{Exposure Dose (ED)} = \frac{C \times IR \times EF \times ED \times CF}{BW \times AT}$$

Where:

ED *= exposure dose in milligrams per kilogram per day (mg/kg/day)*
C *= concentration of contaminant in soil in milligrams per kilogram (mg/kg or ppm)*
IR *= ingestion rate in milligrams per day (mg/day)*
EF *= exposure frequency (days/year)*
ED *= exposure duration (years)*
CF *= conversion factor (10^{-6} kg/mg)*
BW *= body weight (kg)*
AT *= averaging time, days (equal to ED for non-carcinogens and 70 year lifetime for carcinogens, i.e., 70 years x 365 days/year)*

This pathway assumes that the average adolescent (11 to 16 years of age) or adult resident accidentally ingests 100 milligrams of soil per day. Because the area is in a primarily vacant “buffer zone” between the Cotter Mill and residential homes, ATSDR assumed that very young children would not access the area. Adolescent and adults would access the site infrequently. Therefore, exposure duration (ED) for an adolescent and adult resident was assumed to be 2 days per week (or 104 days/year) for 30 years. For average body weight, 57 kg was used for an adolescent and70 kg was used for an adult.

In this evaluation, the bioavailability from incidental ingestion of arsenic in soil was assumed to be 80% because it is protective of health. Cadmium was assumed to be 100% bioavailable, which is also conservative but protective of health.

Direct Skin (Dermal) Contact with Chemicals in Soil

Dermal absorption of chemicals from soil depends on the area of contact with exposed skin, the duration of contact, the chemical and physical attraction between the contaminant and soil, the ability of the chemical to penetrate the skin, and other factors.

The exposure dose formula for dermal absorption of chemicals soil and/or sediment is:

$$\text{Exposure Dose (ED)} = \frac{C \times SA \times AF \times ABS \times EF \times ED \times CF}{BW \times AT}$$

Where:

ED *= exposure dose in milligrams per kilogram per day (mg/kg/day)*
C *= chemical concentration (mg/kg)*
SA *= surface area exposed (square centimeters/day or cm^2/day)*

AF *= soil to skin adherence factor (milligrams per square centimeters or mg/cm^2)*
ABS *= Absorption factor (unitless)*
EF *= exposure frequency (days/year)*
ED *= exposure duration (years)*
CF *= conversion factor (10^{-6} kg/mg)*
BW *= body weight (kg)*
AT *= averaging time (days)*

Note: Absorption factors (ABS) are used to reflect the desorption of the chemical from soil and the absorption of the chemical across the skin and into the bloodstream.

For the dermal contact pathway, ATSDR assumed that the surface area available in an adolescent for direct skin contact is 4,300 cubic centimeters per day (cm^2/day); the surface area available in an adult is 5,000 cm^2/day. An adherence factor of 0.07 milligrams per cubic centimeter (mg/cm^3) was used. An absorption factor of 0.03 was used for arsenic and 0.01 was used for cadmium. Individuals were assumed to weigh 57 kg as an adolescent and 70 kg as an adult, and to be exposed for 6 and 30 years, respectively.

The total soil oral and dermal non-carcinogenic dose was estimated as follows:

Total Dose (TD) = ***ID + DD***

Where:

TD *= total soil ingestion and dermal non-carcinogenic dose*
ID *= Soil ingestion non-carcinogenic dose (mg/kg/day)*
DD*= Soil dermal non-carcinogenic dose (mg/kg/day)*

Cancer Risk Estimates

EPA classifies arsenic as a Class A known human carcinogen by the oral and inhalation routes. Cadmium is classified by EPA as a probable human carcinogen, but only via the inhalation route of exposure. Therefore, only arsenic is evaluated for its carcinogenic risk.

The Lifetime Estimated Cancer Risk for arsenic is estimated as follows:

LECR = ***TDs x CSF x EF***

Where:

LECR *= lifetime estimated cancer risk*
TDs *= total soil oral and dermal non-carcinogenic dose (mg/kg/day)*
CSF *= cancer slope factor ((mg/kg-day)$^{-1}$)*
EF *= Exposure factor (unitless) = exposure duration / lifetime = (30 years) / (70 years) = 0.4*

The cancer slope factor for arsenic is 1.5 mg/kg-day. Therefore, the LECR is 1.2 x 10^{-5}.

Table C2. Summary of Exposure Factors and Exposure Doses for the Soil Exposure Pathway for Chemicals at the Cotter Mill Site

Chemical	**Chemical Concentration (mg/kg)**	**Daily Intake Rate (mg/day)**	**Exposure Frequency (days/yr)**	**Exposure Duration (years)**	**Body Weight (kg)**	**Averaging Time (days)**	**Exposure Dose (mg/kg/day)**	**Health Guideline (mg/kg/day)**
Soil Exposure Pathway: Accidental Ingestion and Direct Skin Contact - ADULT and ADOLESCENT								
Arsenic (ingestion)	45	100	104	30	70	10950	0.00002	0.0003 MRL
Arsenic (dermal)		NA	104	30	70	10950	0.000002	
TOTAL DOSE ARSENIC - Adult							0.00002	*Below Guideline*
Cadmium (ingestion)	37	100	104	30	70	10950	0.00002	0.0001 MRL
Cadmium (dermal)		NA	104	30	70	10950	0.0000005	
TOTAL DOSE CADMIUM -Adult							0.00002	*Below Guideline*
Arsenic (ingestion)	45	100	104	6	54	2190	0.00002	0.0003 MRL
Arsenic (dermal)		NA	104	6	54	2190	0.000002	
TOTAL DOSE ARSENIC - Adolescent							0.00002	*Below Guideline*
Cadmium (ingestion)	37	100	104	6	54	2190	0.00002	0.0001 MRL
Cadmium (dermal)		NA	104	6	54	2190	0.0000006	
TOTAL DOSE CADMIUM - Adolescent							0.00002	*Below Guideline*

Incidental Ingestion of Chemicals in Surface Water

The ATSDR exposure dose formula used for the ingestion of chemicals in surface water while wading or swimming is:

$$\text{Exposure Dose (ED)} = \frac{\mathbf{C \times IR \times ET \times EF \times ED}}{\mathbf{BW \times AT}}$$

Where:

***ED** = exposure dose in milligrams per kilogram per day (mg/kg/day)*
***C** = concentration of contaminant in water in milligrams per liter (mg/L)*
***IR** = ingestion rate in liters per day (L/day); based on contact rate of 50 ml/hr*
***ET** = exposure time (hours/event)*
***EF** = exposure frequency (events/year)*
***ED** = exposure duration (years)*
***BW** = body weight (kg)*
***AT** = averaging time, days (equal to ED for non-carcinogens and 70 year lifetime for carcinogens, i.e., 70 years x 365 days/year)*

This pathway assumes that adult and children residents would accidentally swallow 50 milliliters of water per hour while swimming, wading or recreating in Sand Creek or the DeWeese Dye Ditch. In terms of exposure time and frequency, ATSDR conservatively assumed an adult and child resident would recreate in these waters for 2 hours per day, 2 days per week (or 104 days/year) for 30 years and 6 years, respectively. For average body weight, 70 kg and 16 kg were used for adults and children, respectively.

Direct Skin (Dermal) Contact with Chemicals in Surface Water

ATSDR’s exposure dose formula for dermal absorption of chemicals soil and/or sediment is:

$$\text{Exposure Dose (ED)} = \frac{\mathbf{C \times SA \times PC \times ET \times EF \times ED \times CF}}{\mathbf{BW \times AT}}$$

Where:

***ED** = exposure dose in milligrams per kilogram per day (mg/kg/day)*
***C** = chemical concentration (mg/L)*
***SA** = surface area exposed (cm^2)*
***PC** = chemical-specific dermal permeability constant (cm/hr)*
***ET** = exposure time (hours/day)*
***EF** = exposure frequency (days/year)*
***ED** = exposure duration (years)*
***CF** = volumetric conversion factor for water ($1L/1000\ cm^3$)*
***BW** = body weight (kg)*
***AT** = averaging time (days)*

The dermal contact pathway assumes that the total body surface area available for contact with water is 20,000 cm^2 for adults and 9,300 cm^2 for children. Adults were assumed to weigh 70 kg and to be exposed for 30 years. Children were assumed to weigh 16 kg and to be exposed for 6 years. Adults and children were conservatively assumed to swim in the contaminated water 2 days per week (104 days per year) for 2 hours per recreating event. A dermal permeability constant of 0.001 cm/hr was used for both manganese and molybdenum.

Table C3. Summary of Exposure Factors and Exposure Doses for the Surface Water Pathway for Chemicals at the Cotter Mill Site

Chemical	**Chemical Concentration (mg/L)**	**Daily Ingestion Rate (L/day)**	**Exposure Frequency (days/yr)**	**Exposure Duration (yrs)**	**Body Weight (kg)**	**Averaging Time (days)**	**Exposure Dose (mg/kg/day)**	**Health Guideline (mg/kg/day)**
Surface Water Exposure Pathway: Accidental Ingestion and Direct Skin Contact while Wading or Swimming – ADULT and CHILD								
Manganese* Adult Ingestion	1.9	0.1	104	30	70	10950	3.9×10^{-4}	0.05 Chronic Oral RfD
Manganese Adult Dermal		NA	104	30	70	10950	3.1×10^{-4}	
		TOTAL DOSE MANGANESE – Adult					7×10^{-4}	*Below Guideline*
Manganese Child Ingestion		0.1	104	6	16	2190	1.7×10^{-3}	0.05 Chronic Oral RfD
Manganese Child Dermal		NA	104	6	16	2190	6.3×10^{-4}	
		TOTAL DOSE MANGANESE - Child					2.3×10^{-3}	*Below Guideline*
Molybdenum† Adult Ingestion	0.051	0.1	104	30	70	10950	1.0×10^{-5}	0.005 Chronic Oral RfD
Molybdenum Adult Dermal		NA	104	30	70	10950	8.3×10^{-6}	
		TOTAL DOSE MOLYBDENUM - Adult					1.8×10^{-5}	*Below Guideline*
Molybdenum Child Ingestion		0.1	104	6	16	2190	4.5×10^{-5}	0.005 Chronic Oral RfD
Molybdenum Child Dermal		NA	104	6	16	2190	1.7×10^{-5}	
		TOTAL DOSE MOLYBDENUM - Child					6.2×10^{-5}	*Below Guideline*

*Maximum concentration of manganese in surface water detected in DeWeese Dye Ditch

†Maximum concentration of molybdenum in surface water detected in Sand Creek

Consumption of Homegrown Fruits and Vegetables

The following formula presents the method for calculating an exposure dose for a typical consumer of homegrown fruits and vegetables:

$$\text{Exposure Dose (mg/kg/day)} = \mathbf{C \times IR \times CF}$$

Where:

C *= contaminant concentration (mg/kg)*
IR *= intake rate of fruit or vegetable (g/kg/day)*
CF *= conversion factor (1 x* 10^{-3} *kg/mg)*

Exposure doses for ingestion of garden vegetables were calculated using the average detected concentration of each contaminant measured in fruit and vegetable samples, in mg/kg, multiplied by average consumption rates of homegrown fruits or vegetables in grams per kilogram of body weight per day (g/kg/day). Intake rates were taken from EPA’s Exposure Factors Handbook for adults, and EPA’s Child-Specific Exposure Factors Handbook for children, for the Western United States. The average consumption rate was used to represent a “typical” fruit and vegetable consumer. The 95 percentile consumption rate was used to represent an “above average” consumer of fruits and vegetables. The calculated value was multiplied by a conversion factor of 0.001 kilograms per gram.

Table C4. Summary of Exposure Doses for Local Fruits and Vegetables Irrigated with Contaminated Well Water

Chemical	Chemical Concentration/ Exposure Group	Exposure Dose Fruits (mg/kg/day)	Exposure Dose Vegetables (mg/kg/day)	Health Guideline (mg/kg/day)
Arsenic	Average consumer	0.0001	0.0001	0.0003, Chronic Oral MRL
	Above Average Consumer	0.0006	0.0005	
	Child	0.0002	0.0002	
	Infant	0.0004	0.0004	
Barium	Average consumer	0.001	0.003	0.2 Chronic Oral MRL
	Above Average Consumer	0.005	0.010	
	Child	0.002	0.004	
	Infant	0.004	0.008	
Cadmium	Average consumer	0.0001	0.0001	0.001, RfD
	Above Average Consumer	0.0005	0.0002	
	Child	0.0002	0.0001	
	Infant	0.0004	0.0002	
Chromium	Average consumer	0.0001	0.0001	1.5 RfD
	Above Average Consumer	0.0006	0.0003	
	Child	0.0002	0.0001	
	Infant	0.0005	0.0003	
Cobalt	Average consumer	ND	0.00004	0.01 Intermediate MRL
	Above Average Consumer	ND	0.00012	
	Child	ND	0.00005	
	Infant	ND	0.0001	
Lead	Average consumer	0.0003	0.0004	NA
	Above Average Consumer	0.001	0.001	
	Child	0.0005	0.0005	
	Infant	0.001	0.001	
Manganese	Average consumer	0.002	0.004	0.14 RfD
	Above Average Consumer	0.01	0.02	
	Child	0.004	0.006	
	Infant	0.008	0.01	
Molybdenum	Average consumer	0.0003	0.001	0.005 RfD
	Above Average Consumer	0.001	0.004	

Chemical	Chemical Concentration/ Exposure Group	Exposure Dose Fruits (mg/kg/day)	Exposure Dose Vegetables (mg/kg/day)	Health Guideline (mg/kg/day)
	Child	0.0005	0.002	
	Infant	0.001	0.004	
Nickel	Average consumer	ND	0.0001	0.02 RfD
	Above Average Consumer	ND	0.0005	
	Child	ND	0.0002	
	Infant	ND	0.0004	
Strontium	Average consumer	0.004	0.009	0.6 RfD
	Above Average Consumer	0.02	0.03	
	Child	0.007	0.01	
	Infant	0.01	0.03	
Uranium	Average consumer	0.00002	0.00001	0.002 Intermediate MRL
	Above Average Consumer	0.00008	0.00004	
	Child	0.00003	0.00002	
	Infant	0.00006	0.00004	
Vanadium	Average consumer	ND	0.00008	0.003 Intermediate MRL
	Above Average Consumer	ND	0.0003	
	Child	ND	0.0001	
	Infant	ND	0.0002	
Zinc	Average consumer	0.004	0.006	0.3 Chronic Oral MRL
	Above Average Consumer	0.02	0.02	
	Child	0.006	0.008	
	Infant	0.01	0.02	

Bolded text exceeds a health guideline.
ND = not detected
NA = not available

ATSDR's Evaluation of Cancer and Non-Cancer Health Effects

Non-Cancer Health Effects

The doses calculated for exposure to each individual chemical are compared to an established health guideline, such as a MRL or RfD, in order to assess whether adverse health impacts from exposure are expected. These health guidelines, developed by ATSDR and EPA, are chemical-specific values that are based on the available scientific literature and are considered protective of human health. Non-carcinogenic effects, unlike carcinogenic effects, are believed to have a threshold, that is, a dose below which adverse health effects will not occur. As a result, the current practice for deriving health guidelines is to identify, usually from animal toxicology experiments, a No Observed Adverse Effect Level (or NOAEL), which indicates that no effects are observed at a particular exposure level. This is the experimental exposure level in animals (and sometimes humans) at which no adverse toxic effect is observed. The NOAEL is then modified with an uncertainty (or safety) factor, which reflects the degree of uncertainty that exists when experimental animal data are extrapolated to the general human population. The magnitude of the uncertainty factor considers various factors such as sensitive subpopulations (for example; children, pregnant women, and the elderly), extrapolation from animals to humans, and the completeness of available data. Thus, exposure doses at or below the established health guideline are not expected to result in adverse health effects because these values are much lower (and more human health protective) than doses, which do not cause adverse health effects in laboratory animal studies. For non-cancer health effects, the following health guidelines are described below in more detail. It is important to consider that the methodology used to develop these health guidelines does not provide any information on the presence, absence, or level of cancer risk. Therefore, a separate cancer evaluation is necessary for potentially cancer-causing chemicals detected in samples at this site. A more detailed discussion of the evaluation of cancer risks is presented in the following section.

Minimal Risk Levels (MRLs) – developed by ATSDR

ATSDR has developed MRLs for contaminants commonly found at hazardous waste sites. The MRL is an estimate of daily exposure to a contaminant below which non-cancer, adverse health effects are unlikely to occur. MRLs are developed for different routes of exposure, such as inhalation and ingestion, and for lengths of exposure, such as acute (less than 14 days), intermediate (15-364 days), and chronic (365 days or greater). At this time, ATSDR has not developed MRLs for dermal exposure. A complete list of the available MRLs can be found at http://www.atsdr.cdc.gov/mrls.html.

References Doses (RfDs) – developed by EPA

An estimate of the daily, lifetime exposure of human populations to a possible hazard that is not likely to cause non-cancerous health effects. RfDs consider exposures to sensitive sub-populations, such as the elderly, children, and the developing fetus. EPA RfDs have been developed using information from the available scientific literature and have been calculated for oral and inhalation exposures. A complete list of the available RfDs can be found at http://www.epa.gov/iris.

If the estimated exposure dose for a chemical is less than the health guideline value, the exposure is unlikely to result in non-cancer health effects. Non-cancer health effects from dermal exposure were evaluated slightly differently that ingestion and inhalation exposure. Since health guidelines are not available for dermal exposure, the calculated dermal dose was compared with the oral health guideline value (RfD or MRL).

If the calculated exposure dose is greater than the health guideline, the exposure dose is compared to known toxicological values for the particular chemical and is discussed in more detail in the text of the PHA. The known toxicological values are doses derived from human and animal studies that are presented in the ATSDR Toxicological Profiles and EPA's Integrated Information System (IRIS). A direct comparison of site-specific exposure doses to study-derived exposures and doses found to cause adverse health effects is the basis for deciding whether health effects are likely to occur. This in-depth evaluation is performed by comparing calculated exposure doses with known toxicological values, such as the no-observed adverse-effect-level (NOAEL) and the lowest-observed-adverse-effect-level (LOAEL) from studies used to derive the MRL or RfD for a chemical.

Cancer Risks

Exposure to a cancer-causing compound, even at low concentrations, is assumed to be associated with some increased risk for evaluation purposes. The estimated excess risk of developing cancer from exposure to contaminants associated with the site was calculated by multiplying the site-specific adult exposure doses, with a slight modification, by EPA's chemical-specific Cancer Slope Factors (CSFs or cancer potency estimates), which are available at http://www.epa.gov/iris. Calculated dermal doses were compared with the oral CSFs.

An increased excess lifetime cancer risk is not a specific estimate of expected cancers. Rather, it is an estimate of the increase in the probability that a person may develop cancer sometime during his or her lifetime following exposure to a particular contaminant. Therefore, the cancer risk calculation incorporates the equations and parameters (including the exposure duration and frequency) used to calculate the dose estimates, but the estimated value is divided by 25,550 days (or the averaging time), which is equal to a lifetime of exposure (70 years) for 365 days/year.

There are varying suggestions among the scientific community regarding an acceptable excess lifetime cancer risk, due to the uncertainties regarding the mechanism of cancer. The recommendations of many scientists and EPA have been in the risk range of 1 in 1 million to 1 in 10,000 (as referred to as 1×10^{-6} to 1×10^{-4}) excess cancer cases. An increased lifetime cancer risk of one in one million or less is generally considered an insignificant increase in cancer risk. Cancer risk less than 1 in 10,000 (or 1×10^{-5}) are not typically considered a health concern. An important consideration when determining cancer risk estimates is that the risk calculations incorporate several very conservative assumptions that are expected to overestimate actual exposure scenarios. For example, the method used to calculate EPA's CSFs assumes that high-dose animal data can be used to estimate the risk for low dose exposures in humans. As previously stated, the method also assumes that there is no safe level for exposure. Lastly, the method computes the 95% upper bound for the risk, rather than the average risk, suggesting that the cancer risk is actually lower, perhaps by several orders of magnitude.

Because of the uncertainties involved with estimating carcinogenic risk, ATSDR employs a weight-of-evidence approach in evaluating all relevant data. Therefore, the carcinogenic risk is also described in words (qualitatively) rather than giving a numerical risk estimate only. The numerical risk estimate must be considered in the context of the variables and assumptions involved in their derivation and in the broader context of biomedical opinion, host factors, and actual exposure conditions. The actual parameters of environmental exposures have been given careful and thorough consideration in evaluating the assumptions and variables relating to both toxicity and exposure. A complete review of the toxicological data regarding the doses associated with the production of cancer and the site-specific doses for the site is an important element in determining the likelihood of exposed individuals being at a greater risk for cancer.

Appendix D. ATSDR Glossary of Environmental Health Terms

The Agency for Toxic Substances and Disease Registry (ATSDR) is a federal public health agency with headquarters in Atlanta, Georgia, and 10 regional offices in the United States. ATSDR's mission is to serve the public by using the best science, taking responsive public health actions, and providing trusted health information to prevent harmful exposures and diseases related to toxic substances. ATSDR is not a regulatory agency, unlike the U.S. Environmental Protection Agency (EPA), which is the federal agency that develops and enforces environmental laws to protect the environment and human health.

This glossary defines words used by ATSDR in communications with the public. It is not a complete dictionary of environmental health terms. If you have questions or comments, call ATSDR's toll-free telephone number, 1-800-CDC-INFO (1-800-232-4636).

Absorption
The process of taking in. For a person or an animal, absorption is the process of a substance getting into the body through the eyes, skin, stomach, intestines, or lungs.

Acute
Occurring over a short time [compare with chronic].

Acute exposure
Contact with a substance that occurs once or for only a short time (up to 14 days) [compare with intermediate duration exposure and chronic exposure].

Additive effect
A biologic response to exposure to multiple substances that equals the sum of responses of all the individual substances added together [compare with antagonistic effect and synergistic effect].

Adverse health effect
A change in body function or cell structure that might lead to disease or health problems

Aerobic
Requiring oxygen [compare with anaerobic].

Ambient
Surrounding (for example, ambient air).

Anaerobic
Requiring the absence of oxygen [compare with aerobic].

Analyte
A substance measured in the laboratory. A chemical for which a sample (such as water, air, or blood) is tested in a laboratory. For example, if the analyte is mercury, the laboratory test will determine the amount of mercury in the sample.

Analytic epidemiologic study
A study that evaluates the association between exposure to hazardous substances and disease by testing scientific hypotheses.

Antagonistic effect
A biologic response to exposure to multiple substances that is less than would be expected if the known effects of the individual substances were added together [compare with additive effect and synergistic effect].

Background level
An average or expected amount of a substance or radioactive material in a specific environment, or typical amounts of substances that occur naturally in an environment.

Biodegradation
Decomposition or breakdown of a substance through the action of microorganisms (such as bacteria or fungi) or other natural physical processes (such as sunlight).

Biologic indicators of exposure study
A study that uses (a) biomedical testing or (b) the measurement of a substance [an analyte], its metabolite, or another marker of exposure in human body fluids or tissues to confirm human exposure to a hazardous substance [also see exposure investigation].

Biologic monitoring
Measuring hazardous substances in biologic materials (such as blood, hair, urine, or breath) to determine whether exposure has occurred. A blood test for lead is an example of biologic monitoring.

Biologic uptake
The transfer of substances from the environment to plants, animals, and humans.

Biomedical testing
Testing of persons to find out whether a change in a body function might have occurred because of exposure to a hazardous substance.

Biota
Plants and animals in an environment. Some of these plants and animals might be sources of food, clothing, or medicines for people.

Body burden
The total amount of a substance in the body. Some substances build up in the body because they are stored in fat or bone or because they leave the body very slowly.

CAP [see Community Assistance Panel.]

Cancer
Any one of a group of diseases that occur when cells in the body become abnormal and grow or multiply out of control.

Cancer risk
A theoretical risk for getting cancer if exposed to a substance every day for 70 years (a lifetime exposure). The true risk might be lower.

Carcinogen
A substance that causes cancer.

Case study
A medical or epidemiologic evaluation of one person or a small group of people to gather information about specific health conditions and past exposures.

Case-control study
A study that compares exposures of people who have a disease or condition (cases) with people who do not have the disease or condition (controls). Exposures that are more common among the cases may be considered as possible risk factors for the disease.

CAS registry number
A unique number assigned to a substance or mixture by the American Chemical Society Abstracts Service.

Central nervous system
The part of the nervous system that consists of the brain and the spinal cord.

CERCLA [see Comprehensive Environmental Response, Compensation, and Liability Act of 1980]

Chronic
Occurring over a long time [compare with acute].

Chronic exposure
Contact with a substance that occurs over a long time (more than 1 year) [compare with acute exposure and intermediate duration exposure]

Cluster investigation
A review of an unusual number, real or perceived, of health events (for example, reports of cancer) grouped together in time and location. Cluster investigations are designed to confirm case reports; determine whether they represent an unusual disease occurrence; and, if possible, explore possible causes and contributing environmental factors.

Community Assistance Panel (CAP)
A group of people from a community and from health and environmental agencies who work with ATSDR to resolve issues and problems related to hazardous substances in the community. CAP members work with ATSDR to gather and review community health concerns, provide information on how people might have been or might now be exposed to hazardous substances, and inform ATSDR on ways to involve the community in its activities.

Comparison value (CV)
Calculated concentration of a substance in air, water, food, or soil that is unlikely to cause

harmful (adverse) health effects in exposed people. The CV is used as a screening level during the public health assessment process. Substances found in amounts greater than their CVs might be selected for further evaluation in the public health assessment process.

Completed exposure pathway [see exposure pathway].

Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA)
CERCLA, also known as Superfund, is the federal law that concerns the removal or cleanup of hazardous substances in the environment and at hazardous waste sites. ATSDR, which was created by CERCLA, is responsible for assessing health issues and supporting public health activities related to hazardous waste sites or other environmental releases of hazardous substances. This law was later amended by the Superfund Amendments and Reauthorization Act (SARA).

Concentration
The amount of a substance present in a certain amount of soil, water, air, food, blood, hair, urine, breath, or any other media.

Contaminant
A substance that is either present in an environment where it does not belong or is present at levels that might cause harmful (adverse) health effects.

Delayed health effect
A disease or an injury that happens as a result of exposures that might have occurred in the past.

Dermal
Referring to the skin. For example, dermal absorption means passing through the skin.

Dermal contact
Contact with (touching) the skin [see route of exposure].

Descriptive epidemiology
The study of the amount and distribution of a disease in a specified population by person, place, and time.

Detection limit
The lowest concentration of a chemical that can reliably be distinguished from a zero concentration.

Disease prevention
Measures used to prevent a disease or reduce its severity.

Disease registry
A system of ongoing registration of all cases of a particular disease or health condition in a defined population.

DOD
United States Department of Defense.

DOE
United States Department of Energy.

Dose (for chemicals that are not radioactive)
The amount of a substance to which a person is exposed over some time period. Dose is a measurement of exposure. Dose is often expressed as milligram (amount) per kilogram (a measure of body weight) per day (a measure of time) when people eat or drink contaminated water, food, or soil. In general, the greater the dose, the greater the likelihood of an effect. An "exposure dose" is how much of a substance is encountered in the environment. An "absorbed dose" is the amount of a substance that actually got into the body through the eyes, skin, stomach, intestines, or lungs.

Dose (for radioactive chemicals)
The radiation dose is the amount of energy from radiation that is actually absorbed by the body. This is not the same as measurements of the amount of radiation in the environment.

Dose-response relationship
The relationship between the amount of exposure [dose] to a substance and the resulting changes in body function or health (response).

Environmental media
Soil, water, air, biota (plants and animals), or any other parts of the environment that can contain contaminants.

Environmental media and transport mechanism
Environmental media include water, air, soil, and biota (plants and animals). Transport mechanisms move contaminants from the source to points where human exposure can occur. The environmental media and transport mechanism is the second part of an exposure pathway.

EPA
United States Environmental Protection Agency.

Epidemiologic surveillance [see Public health surveillance].

Epidemiology
The study of the distribution and determinants of disease or health status in a population; the study of the occurrence and causes of health effects in humans.

Exposure
Contact with a substance by swallowing, breathing, or touching the skin or eyes. Exposure may be short-term [acute exposure], of intermediate duration, or long-term [chronic exposure].

Exposure assessment
The process of finding out how people come into contact with a hazardous substance, how often

and for how long they are in contact with the substance, and how much of the substance they are in contact with.

Exposure-dose reconstruction
A method of estimating the amount of people's past exposure to hazardous substances. Computer and approximation methods are used when past information is limited, not available, or missing.

Exposure investigation
The collection and analysis of site-specific information and biologic tests (when appropriate) to determine whether people have been exposed to hazardous substances.

Exposure pathway
The route a substance takes from its source (where it began) to its end point (where it ends), and how people can come into contact with (or get exposed to) it. An exposure pathway has five parts: a source of contamination (such as an abandoned business); an environmental media and transport mechanism (such as movement through groundwater); a point of exposure (such as a private well); a route of exposure (eating, drinking, breathing, or touching), and a receptor population (people potentially or actually exposed). When all five parts are present, the exposure pathway is termed a completed exposure pathway.

Exposure registry
A system of ongoing followup of people who have had documented environmental exposures.

Feasibility study
A study by EPA to determine the best way to clean up environmental contamination. A number of factors are considered, including health risk, costs, and what methods will work well.

Geographic information system (GIS)
A mapping system that uses computers to collect, store, manipulate, analyze, and display data. For example, GIS can show the concentration of a contaminant within a community in relation to points of reference such as streets and homes.

Grand rounds
Training sessions for physicians and other health care providers about health topics.

Groundwater
Water beneath the earth's surface in the spaces between soil particles and between rock surfaces [compare with surface water].

Half-life (t½)
The time it takes for half the original amount of a substance to disappear. In the environment, the half-life is the time it takes for half the original amount of a substance to disappear when it is changed to another chemical by bacteria, fungi, sunlight, or other chemical processes. In the human body, the half-life is the time it takes for half the original amount of the substance to disappear, either by being changed to another substance or by leaving the body. In the case of radioactive material, the half life is the amount of time necessary for one half the initial number of radioactive atoms to change or transform into another atom (that is normally not radioactive). After two half lives, 25% of the original number of radioactive atoms remain.

Hazard
A source of potential harm from past, current, or future exposures.

Hazardous Substance Release and Health Effects Database (HazDat)
The scientific and administrative database system developed by ATSDR to manage data collection, retrieval, and analysis of site-specific information on hazardous substances, community health concerns, and public health activities.

Hazardous waste
Potentially harmful substances that have been released or discarded into the environment.

Health consultation
A review of available information or collection of new data to respond to a specific health question or request for information about a potential environmental hazard. Health consultations are focused on a specific exposure issue. Health consultations are therefore more limited than a public health assessment, which reviews the exposure potential of each pathway and chemical [compare with public health assessment].

Health education
Programs designed with a community to help it know about health risks and how to reduce these risks.

Health investigation
The collection and evaluation of information about the health of community residents. This information is used to describe or count the occurrence of a disease, symptom, or clinical measure and to evaluate the possible association between the occurrence and exposure to hazardous substances.

Health promotion
The process of enabling people to increase control over, and to improve, their health.

Health statistics review
The analysis of existing health information (i.e., from death certificates, birth defects registries, and cancer registries) to determine if there is excess disease in a specific population, geographic area, and time period. A health statistics review is a descriptive epidemiologic study.

Indeterminate public health hazard
The category used in ATSDR’s public health assessment documents when a professional judgment about the level of health hazard cannot be made because information critical to such a decision is lacking.

Incidence
The number of new cases of disease in a defined population over a specific time period [contrast with prevalence].

Ingestion
The act of swallowing something through eating, drinking, or mouthing objects. A hazardous substance can enter the body this way [see route of exposure].

Inhalation
The act of breathing. A hazardous substance can enter the body this way [see route of exposure].

Intermediate duration exposure
Contact with a substance that occurs for more than 14 days and less than a year [compare with acute exposure and chronic exposure].

In vitro
In an artificial environment outside a living organism or body. For example, some toxicity testing is done on cell cultures or slices of tissue grown in the laboratory, rather than on a living animal [compare with in vivo].

In vivo
Within a living organism or body. For example, some toxicity testing is done on whole animals, such as rats or mice [compare with in vitro].

Lowest-observed-adverse-effect level (LOAEL)
The lowest tested dose of a substance that has been reported to cause harmful (adverse) health effects in people or animals.

Medical monitoring
A set of medical tests and physical exams specifically designed to evaluate whether an individual’s exposure could negatively affect that person’s health.

Metabolism
The conversion or breakdown of a substance from one form to another by a living organism.

Metabolite
Any product of metabolism.

mg/kg
Milligram per kilogram.

mg/cm^2
Milligram per square centimeter (of a surface).

mg/m^3
Milligram per cubic meter; a measure of the concentration of a chemical in a known volume (a cubic meter) of air, soil, or water.

Migration
Moving from one location to another.

Minimal risk level (MRL)
An ATSDR estimate of daily human exposure to a hazardous substance at or below which that substance is unlikely to pose a measurable risk of harmful (adverse), noncancerous effects. MRLs are calculated for a route of exposure (inhalation or oral) over a specified time period

(acute, intermediate, or chronic). MRLs should not be used as predictors of harmful (adverse) health effects [see reference dose].

Morbidity
State of being ill or diseased. Morbidity is the occurrence of a disease or condition that alters health and quality of life.

Mortality
Death. Usually the cause (a specific disease, a condition, or an injury) is stated.

Mutagen
A substance that causes mutations (genetic damage).

Mutation
A change (damage) to the DNA, genes, or chromosomes of living organisms.

National Priorities List for Uncontrolled Hazardous Waste Sites (National Priorities List or NPL)
EPA's list of the most serious uncontrolled or abandoned hazardous waste sites in the United States. The NPL is updated on a regular basis.

National Toxicology Program (NTP)
Part of the Department of Health and Human Services. NTP develops and carries out tests to predict whether a chemical will cause harm to humans.

No apparent public health hazard
A category used in ATSDR's public health assessments for sites where human exposure to contaminated media might be occurring, might have occurred in the past, or might occur in the future, but where the exposure is not expected to cause any harmful health effects.

No-observed-adverse-effect level (NOAEL)
The highest tested dose of a substance that has been reported to have no harmful (adverse) health effects on people or animals.

No public health hazard
A category used in ATSDR's public health assessment documents for sites where people have never and will never come into contact with harmful amounts of site-related substances.

NPL [see National Priorities List for Uncontrolled Hazardous Waste Sites]

Physiologically based pharmacokinetic model (PBPK model)
A computer model that describes what happens to a chemical in the body. This model describes how the chemical gets into the body, where it goes in the body, how it is changed by the body, and how it leaves the body.

Pica
A craving to eat nonfood items, such as dirt, paint chips, and clay. Some children exhibit pica-related behavior.

Plume
A volume of a substance that moves from its source to places farther away from the source. Plumes can be described by the volume of air or water they occupy and the direction they move. For example, a plume can be a column of smoke from a chimney or a substance moving with groundwater.

Point of exposure
The place where someone can come into contact with a substance present in the environment [see exposure pathway].

Population
A group or number of people living within a specified area or sharing similar characteristics (such as occupation or age).

Potentially responsible party (PRP)
A company, government, or person legally responsible for cleaning up the pollution at a hazardous waste site under Superfund. There may be more than one PRP for a particular site.

ppb
Parts per billion.

ppm
Parts per million.

Prevalence
The number of existing disease cases in a defined population during a specific time period [contrast with incidence].

Prevalence survey
The measure of the current level of disease(s) or symptoms and exposures through a questionnaire that collects self-reported information from a defined population.

Prevention
Actions that reduce exposure or other risks, keep people from getting sick, or keep disease from getting worse.

Public availability session
An informal, drop-by meeting at which community members can meet one-on-one with ATSDR staff members to discuss health and site-related concerns.

Public comment period
An opportunity for the public to comment on agency findings or proposed activities contained in draft reports or documents. The public comment period is a limited time period during which comments will be accepted.

Public health action
A list of steps to protect public health.

Public health advisory
A statement made by ATSDR to EPA or a state regulatory agency that a release of hazardous substances poses an immediate threat to human health. The advisory includes recommended measures to reduce exposure and reduce the threat to human health.

Public health assessment (PHA)
An ATSDR document that examines hazardous substances, health outcomes, and community concerns at a hazardous waste site to determine whether people could be harmed from coming into contact with those substances. The PHA also lists actions that need to be taken to protect public health [compare with health consultation].

Public health hazard
A category used in ATSDR's public health assessments for sites that pose a public health hazard because of long-term exposures (greater than 1 year) to sufficiently high levels of hazardous substances or radionuclides that could result in harmful health effects.

Public health hazard categories
Public health hazard categories are statements about whether people could be harmed by conditions present at the site in the past, present, or future. One or more hazard categories might be appropriate for each site. The five public health hazard categories are no public health hazard, no apparent public health hazard, indeterminate public health hazard, public health hazard, and urgent public health hazard.

Public health statement
The first chapter of an ATSDR toxicological profile. The public health statement is a summary written in words that are easy to understand. The public health statement explains how people might be exposed to a specific substance and describes the known health effects of that substance.

Public health surveillance
The ongoing, systematic collection, analysis, and interpretation of health data. This activity also involves timely dissemination of the data and use for public health programs.

Public meeting
A public forum with community members for communication about a site.

Radioisotope
An unstable or radioactive isotope (form) of an element that can change into another element by giving off radiation.

Radionuclide
Any radioactive isotope (form) of any element.

RCRA [see Resource Conservation and Recovery Act (1976, 1984)]

Receptor population
People who could come into contact with hazardous substances [see exposure pathway].

Reference dose (RfD)
An EPA estimate, with uncertainty or safety factors built in, of the daily lifetime dose of a substance that is unlikely to cause harm in humans.

Registry
A systematic collection of information on persons exposed to a specific substance or having specific diseases [see exposure registry and disease registry].

Remedial investigation
The CERCLA process of determining the type and extent of hazardous material contamination at a site.

Resource Conservation and Recovery Act (1976, 1984) (RCRA)
This Act regulates management and disposal of hazardous wastes currently generated, treated, stored, disposed of, or distributed.

RFA
RCRA Facility Assessment. An assessment required by RCRA to identify potential and actual releases of hazardous chemicals.

RfD [see reference dose]

Risk
The probability that something will cause injury or harm.

Risk reduction
Actions that can decrease the likelihood that individuals, groups, or communities will experience disease or other health conditions.

Risk communication
The exchange of information to increase understanding of health risks.

Route of exposure
The way people come into contact with a hazardous substance. Three routes of exposure are breathing [inhalation], eating or drinking [ingestion], or contact with the skin [dermal contact].

Safety factor [see uncertainty factor]

SARA [see Superfund Amendments and Reauthorization Act]

Sample
A portion or piece of a whole. A selected subset of a population or subset of whatever is being studied. For example, in a study of people the sample is a number of people chosen from a larger population [see population]. An environmental sample (for example, a small amount of soil or water) might be collected to measure contamination in the environment at a specific location.

Sample size
The number of units chosen from a population or an environment.

Solvent
A liquid capable of dissolving or dispersing another substance (for example, acetone or mineral spirits).

Source of contamination
The place where a hazardous substance comes from, such as a landfill, waste pond, incinerator, storage tank, or drum. A source of contamination is the first part of an exposure pathway.

Special populations
People who might be more sensitive or susceptible to exposure to hazardous substances because of factors such as age, occupation, sex, or behaviors (for example, cigarette smoking). Children, pregnant women, and older people are often considered special populations.

Stakeholder
A person, group, or community who has an interest in activities at a hazardous waste site.

Statistics
A branch of mathematics that deals with collecting, reviewing, summarizing, and interpreting data or information. Statistics are used to determine whether differences between study groups are meaningful.

Substance
A chemical.

Substance-specific applied research
A program of research designed to fill important data needs for specific hazardous substances identified in ATSDR’s toxicological profiles. Filling these data needs would allow more accurate assessment of human risks from specific substances contaminating the environment. This research might include human studies or laboratory experiments to determine health effects resulting from exposure to a given hazardous substance.

Superfund [see Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and Superfund Amendments and Reauthorization Act (SARA)]

Superfund Amendments and Reauthorization Act (SARA)
In 1986, SARA amended the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and expanded the health-related responsibilities of ATSDR. CERCLA and SARA direct ATSDR to look into the health effects from substance exposures at hazardous waste sites and to perform activities including health education, health studies, surveillance, health consultations, and toxicological profiles.

Surface water
Water on the surface of the earth, such as in lakes, rivers, streams, ponds, and springs [compare with groundwater].

Surveillance [see public health surveillance]

Survey
A systematic collection of information or data. A survey can be conducted to collect information from a group of people or from the environment. Surveys of a group of people can be conducted by telephone, by mail, or in person. Some surveys are done by interviewing a group of people [see prevalence survey].

Synergistic effect
A biologic response to multiple substances where one substance worsens the effect of another substance. The combined effect of the substances acting together is greater than the sum of the effects of the substances acting by themselves [see additive effect and antagonistic effect].

Teratogen
A substance that causes defects in development between conception and birth. A teratogen is a substance that causes a structural or functional birth defect.

Toxic agent
Chemical or physical (for example, radiation, heat, cold, microwaves) agents that, under certain circumstances of exposure, can cause harmful effects to living organisms.

Toxicological profile
An ATSDR document that examines, summarizes, and interprets information about a hazardous substance to determine harmful levels of exposure and associated health effects. A toxicological profile also identifies significant gaps in knowledge on the substance and describes areas where further research is needed.

Toxicology
The study of the harmful effects of substances on humans or animals.

Tumor
An abnormal mass of tissue that results from excessive cell division that is uncontrolled and progressive. Tumors perform no useful body function. Tumors can be either benign (not cancer) or malignant (cancer).

Uncertainty factor
Mathematical adjustments for reasons of safety when knowledge is incomplete. For example, factors used in the calculation of doses that are not harmful (adverse) to people. These factors are applied to the lowest-observed-adverse-effect-level (LOAEL) or the no-observed-adverse-effect-level (NOAEL) to derive a minimal risk level (MRL). Uncertainty factors are used to account for variations in people’s sensitivity, for differences between animals and humans, and for differences between a LOAEL and a NOAEL. Scientists use uncertainty factors when they have some, but not all, the information from animal or human studies to decide whether an exposure will cause harm to people [also sometimes called a safety factor].

Urgent public health hazard
A category used in ATSDR’s public health assessments for sites where short-term exposures (less than 1 year) to hazardous substances or conditions could result in harmful health effects that require rapid intervention.

Volatile organic compounds (VOCs)
Organic compounds that evaporate readily into the air. VOCs include substances such as benzene, toluene, methylene chloride, and methyl chloroform.

Other glossaries and dictionaries:
Environmental Protection Agency (http://www.epa.gov/OCEPAterms/)
National Library of Medicine (NIH)
(http://www.nlm.nih.gov/medlineplus/mplusdictionary.html)

Appendix 35

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1980 - 2010
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YEARS OF
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EPA Review of Standards for Uranium and Thorium Milling Facilities @ 40 CFR Parts 61 and 192.

Comments by Steven H Brown, CHP
Revised November 7, 2010

I am Steven Brown from Centennial Colorado. I appreciate the opportunity to provide these comments for EPA's consideration regards to review of EPA standards for Uranium and Thorium Milling Facilities @ 40 CFR Parts 61 and 192.

I have been a practicing health physicist for over 40 years. I am certified by the American Board of Health Physics and a Diplomat of the American Academy of Health Physics. I am a past president of Central Rocky Mountain Chapter of the Health Physics Society.

The Health Physics Society, formed in 1956, is a scientific organization of professionals who specialize in radiation safety. Its mission is to support its members in the practice of their profession and to promote excellence in the science and practice of radiation safety. Today its nearly 6,000 members represent all scientific and technical areas related to radiation safety including academia, government, medicine, research and development, analytical services, consulting, and industry in all 50 states and the District of Columbia.

I would like to provide EPA with some broad scientific perspectives related to the adequacy of existing public exposure standards for uranium mills and in situ recovery facilities that are promulgated in 40 CFR Parts 61, 190 and 192. Specifically, these are the 20 picocuries per meter squared per second (pCi / m2-sec) radon flux criteria for uranium mill tailings impoundments specified in Part 61 Subpart W and Part 192, Subpart D as well as the 25 mrem /year public exposure standard in Part 190 as referenced in Part 192.

My remarks will address the following seven questions:

1. Are the existing radiation dose limits in the regulations (Federal and Agreement States) for uranium milling facilities (including in situ recovery plants) adequate to protect the public from additional radiation exposure above our natural background exposure?
2. Is the existing 20 picocuries per meter squared per second (pCi/meter^2 – sec) radon flux (emission) standard in 40 CFR Parts 61, Subpart W and 192, Subpart D adequate to protect the public from additional radiation exposure above our natural background exposure?
3. What do we know about radon releases from water impoundments?
4. What do we know about radon emissions from ISRs?
5. What are current practices and results in estimating doses to the public from uranium recovery facilities?
6. What is known about the potential health effects to populations living in the vicinity of uranium mines and mills?
7. What is known about the health impacts (e.g., lung cancer) to many uranium miners who worked underground in the 1950s and 1960s?

1. Are the existing regulations (Federal or USNRC Agreement States) for uranium milling facilities (including in situ recovery plants) adequate to protect the public from additional radiation exposure above our natural background exposure?

Our lifestyles, where we choose to live, what we eat and drink, has a much larger impact on our radiation exposure than exposure at current regulatory limits. The basic regulatory limits that operating uranium mills and ISRs must comply with are 100 millirem* per year from all sources including radon and 25 millirem / year excluding radon** (US Nuclear Regulatory Commission: 10 CFR 20 and 10 CFR 40 Appendix A; US Environmental Protection Agency: 40 CFR 190; Texas Department of State Health Services, Title 30 of the Texas Administrative Code, Chapter 336; Colorado Department Health of Public and Environment, 6 CCR 1007 - 1, Part 4)

*NOTE: a millirem is a unit of effective radiation dose. It is related to the amount of energy absorbed by human tissue and other factors. 1,000 millirem = one rem.

** Radon is a naturally occurring radioactive gas, which is released into the atmosphere at the Earth's surface from the decay of radium. Both radium and radon are daughter products of uranium.

Now lets compare these numbers to the annual radiation doses we receive as citizens of planet Earth. Figure 1 below depicts the typical components of human exposure in the US to ionizing radiation.

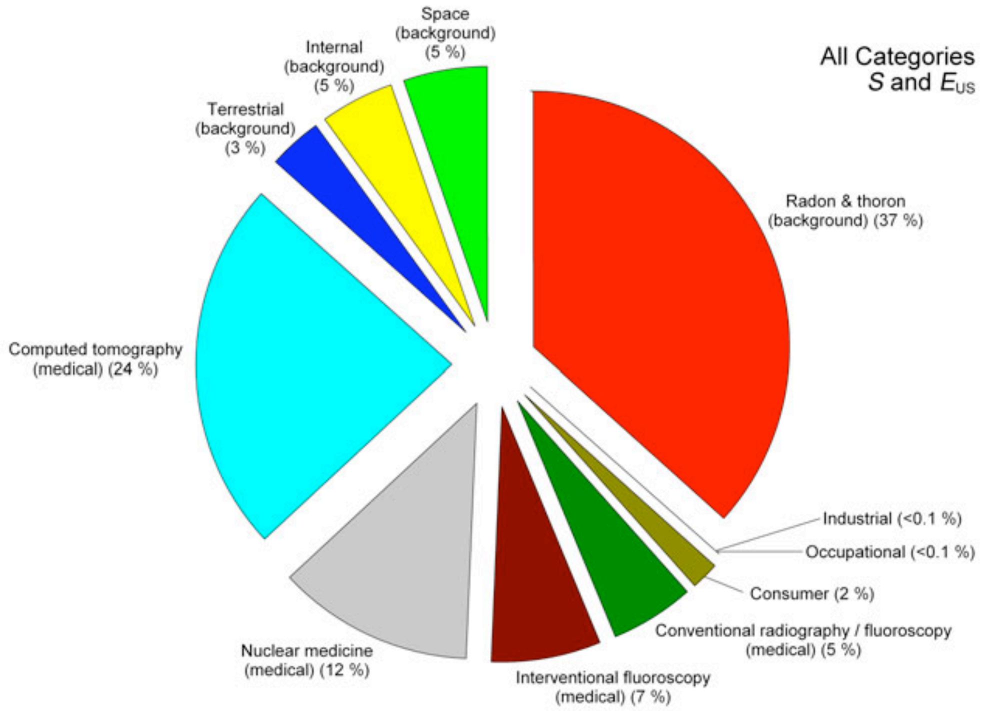


Figure 1: Percent contribution of various sources of exposure to the total radiation dose of a typical resident in the US. Reproduced from National Council on Radiation Protection and Measurements. Report No. 160*, Ionizing Radiation Exposure of the Population in the United States.* 2009.

As can be seen from figure 1, background radiation exposure is about 50% of the total exposure; the other 50% is primarily from medical exposures. Consumer products we use everyday that contain radioactive materials (e.g., smoke detectors, luminous watches, etc) contribute about 2 % of our dose. Other man made sources of radiation, including the nuclear industry, contribute < 0.1% of our annual dose.

Natural background can vary considerable from place to place across the United States or over relatively small areas within a region. This is due to effects of elevation (higher cosmic radiation exposure at higher elevations), greater levels of naturally occurring radioactive elements in soil and water in mineralized areas (e.g., igneous formations in Rocky Mountains) and other factors like local geology and chemistry. This is depicted in Table 1, which compares average annual background radiation exposure for the US, all of Colorado and Leadville, CO. (high elevation and in mineralized area) as contrasted to coastal areas like Virginia and Oregon. This table shows the major components of natural background radiation including terrestrial radiation (uranium, radium, thorium and a naturally radioactive form of potassium in soil, rocks and water), cosmic radiation (high energy particles and rays from space) and internal radiation (from food, water and radon gas from natural uranium decaying in the ground).

The data in Table 1 demonstrates that the differences in annual background exposure based on where one chooses to live, what one chooses to eat and drink have a much greater impact on public exposure than the regulatory dose limits we discussed above.

Source	US Avg.[1]	Colorado [2]	Leadville, CO. [2]	Virginia [3]	Oregon [3]
Cosmic Radiation	31	50	85	28	28
Terrestrial Radiation	19	49	97	20	27
Radon and Other Internal	260	301	344	182	102
Totals	310	400	526	230	157

TABLE 1: Comparison of average radiation backgrounds in US (units of millirem / yr)

[1] National Council on Radiation Protection and Measurements. Report No. 160*, Ionizing Radiation Exposure of the Population in the United States.* 2009.
[2] Moeller D, Sun LSC*. Comparison of Natural Background Dose Rates for Residents of the Amargosa Valley, NV, to those in Leadville, CO, and the States of Colorado and Nevada.* Health Physics 91:338-353; 2006
[3] USEPA. Assessment of Variations in Radiation Exposure in the United States. Contract Number EP-D-05-002 (Revision 1). Washington, DC. 2006

Because background radiation varies significantly across the U.S., it follows that population exposure varies accordingly. As indicated in Table 1, if for example, one chooses to live in Colorado vs. Oregon, the difference in his or her annual radiation dose is more than 240 mrem /yr which is more than twice the Federal public exposure limit for uranium mills of 100 mrem /yr. In other words, if you are a resident of Colorado and leave to visit your sister for a month in Oregon, you could “save” 20 – 30 mrem of exposure, which is about equal to the EPA 40 CFR 190 limit of 25 mrem /year excluding radon.

2. Is the existing 20 picocurie/meter^2 – second (pCi/m2-sec) radon flux /emission standard in 40 CFR Parts 61, Subpart W and 192, Subpart D adequate to protect the public from additional radiation exposure above our natural background exposure ?

Specifically regarding natural background exposure to radon, note that Figure 1 and Table 1 demonstrate that radon can contribute much more than 50 % of our total background exposure and almost 300 mrem / yr in the Rocky Mountain States (due to higher levels of natural uranium and radium in the soil and rocks than, e.g., the coastal plains of the US).

It is recognized that EPA’s public exposure criteria for radon in 40 CFR 61, Subpart W and Part 192, Subpart D is expressed as a “flux” (emission rate from a surface) of 20 pCi/m2-

sec. This limit however includes natural background, which is typically 1-2 pCi/m^2-sec almost anywhere on the earth's surface and can be several times higher than this in mineralized areas. So in some places, the EPA radon flux limit could be just a few times the existing background rate.

It is also recognized that 40 CFR Subpart W also imposes work practice requirements @ 61.252(b)(1) limiting the operator to two tailings impoundments of no more than 40 acres each. Accordingly, if it is assumed that the entire 80- acres are emitting radon at the limit of 20pCi/m2 -sec, the annual "source term" can be directly calculated to be about 200 Curies. This is approximately equal to the "source term" from 2-3 square miles of the earth, almost anywhere, at a typical planet wide background flux of 1 - 2 pCi/m2- sec.

However, the quantity or emission rate of a radionuclide from a source within the restricted area of a licensed facility is not the primary criteria for public radiation protection. This is routinely achieved by demonstrating compliance with the fundamental public dose limit of 100 mrem /year including radon (e.g., @ 10 CFR 20.1301 and commensurate sections of Agreement State regulations) and in demonstrating compliance to concentrations of radionuclides permitted to be released to unrestricted areas (e.g., at the site boundary) specified in 10 CFR 20, Appendix B, Table 2 (for radon = 1 X 10^{-8} uCi/ml w/o progeny; 1 X 10^{-10} with progeny).

It is at the site boundary and/or locations where people actually live, not at a somewhat arbitrary* location within the restricted area inaccessible to the public, that public radiation protection criteria should be applied. Although the historical need is understood for establishment of the radon flux criteria to limit radiological impact to a future public who may have access to formerly decommissioned uranium tailings sites, for licensed operating facilities, other mature regulatory controls as referenced here provide much greater assurances that exposure of the public is maintained ALARA in support of optimizing the risk vs. benefit relationship.

* "Arbitrary" relative to the most likely pathways of exposure to a member of the pubic including considerations of local meteorology and demography

3. What Do We Know About Radon Releases from Water Impoundments?

In response to concerns regards to radon releases from the decay of its radium parent contained in water impoundments (e.g., evaporation ponds) associated with uranium recovery facilities, two recent reports provide some valuable insight:

(1) SENES Consultants Ltd, *Evaporation Pond Radon Flux Analysis, Piñon Ridge Mill Project, Montrose County, Colorado*. August 2010 for Energy Fuels Resources Corporation; included as Appendix D of Energy Fuels' *Application for Approval for Construction, Pinon Ridge Mill, Montrose County,* Colorado as *s*ubmitted to US EPA Region VIII, Denver, Colorado August 31 2010. This report is posted along with the complete application on the EPA Subpart W web

site under “Applications”, *Pinon Ridge Mill: Application for Approval of Construction of Tailings Facility.*

This study provided estimates of radon flux from and concentrations above proposed water impoundments (evaporation ponds containing raffinate solution) with a specified radium concentration and compared results to other existing models. Conservative estimates of radon flux indicates that the emissions are low and less than or similar to the pre-operational average background radon flux of 1.7 pCi m^{-2} s^{-1} observed at various locations within the proposed tailings areas on the site. The estimated radon flux levels from the evaporation ponds is also a small fraction (less than 10%) of the 20 pCi m^{-2} s^{-1} limit for pre-1989 uranium tailings that has been assumed here for context. This conservative estimate was based on the Nielson and Rogers model *.

* Nielson, K.K. and V.C. Rogers 1986. *Surface Water Hydrology Considerations in Predicting Radon Releases from Water-Covered Areas of Uranium Tailings Ponds.* Proc. Eighth Annual Symposium on Geotechnical & Hydrological Aspects of Waste Management, Geotechnical Engineering Program, Colorado State University & A.A. Balkema, Fort Collins, CO, USA, February 507, PP:215-222.

The model assumes that the emission rates are enhanced by the turbulence at the top layer of the water column where all the radon in the top one-meter of water is assumed to be released to air instantaneously. For comparison purposes, the same parameters were used to estimate the radon emissions using an on-line program that is available on the World Information Services on Energy (WISE) website. The on-line model, which is attributed to the Rogers and Nielson model, produced identical results.

The results of this assessment also indicated that the radon emissions associated with the evaporation of the raffinate solution and the emissions due to the operation of sprinkler systems are extremely low and insignificant compared to the radon flux from the ponds due to diffusional and turbulence processes.

Finally, the calculations indicated that the incremental air concentration due to the emission of radon from the evaporation ponds is very small (on the order of 3%) relative to the assumed background radon concentration.

(2) K.R. Baker and A.D. Cox 2010. *Radon Flux from Evaporation Ponds*. Presented at National Mining Association (NMA) / Nuclear Regulatory Commission (NRC) Uranium Recovery Workshop 2010, Denver, CO, May 26-27.

A presentation by Baker and Cox at the most recent NMA/NRC workshop in Denver (May 2010) and subsequently at the National Health Physics Society Annual Meeting in Salt Lake City (June 2010) considers the situation where appreciable concentrations of radon are present in the ponded water, as may arise for example from elevated levels of Ra-226 dissolved in the pond water. Baker and Cox, reporting on a stagnant film model and some measurement data*, suggest a radon flux of the order of 1 pCi m^{-2} s^{-1} per 100 pCi/L of dissolved radon in the ponded water.

* A modified version of EPA Method 115 was used to measure radon flux from the pond surface

4. What do we know About Radon Emissions from ISRs?

Regarding radon evolution from in situ uranium recovery facilities, the majority of radon, which is released at the surface is not (as at a conventional mill) a result of on-surface decay of radium over time in tailings impoundments since ISRs do not generated conventional tailings as a radon source. At ISRs, the radon is brought to the surface dynamically, dissolved in the lixiviant returning from underground. Just as dynamically, that portion of the total dissolved radon that is above the solution's saturation value is released when encountering atmospheric pressures and temperatures.

Modern ISR uranium recovery processes are operated under “closed loop’ conditions. The circulating lixiviant goes directly from well field header houses thru the ion exchange process and is then reconstituted and returned directly to the well field as an essentially closed system. Atmospheric conditions are initially encountered during resin transfer at the shaker screens. Accordingly, the vast majority of the “radon source term” for these facilities is associated with small releases from the well heads and header houses in the well fields and from the IX - resin – elution system interface where the process is first opened to atmospheric pressure. For facilities that have water retention ponds at the back end of the process (barren lixiviant bleeds, restoration wastes, etc), only a small percentage of the radon originally dissolved in the pregnant lixiviant initially returning from the well fields would be expected to remain. ISRs in Texas are currently operating without these “surge ponds” and send liquid wastes directly to a permitted deep disposal well.*

* For general discussions of the radiological characteristics of ISRs, including mechanisms of radon evolution, see: National Mining Association. *Generic Environmental Report in Support of the Nuclear Regulatory Commission’s Generic Environmental Impact Statement for In Situ Uranium Recovery Facilities,* K Sweeney, NMA to L Camper, USNRC November 30, 2007; Brown, S. *The New Generation of Uranium In Situ Recovery Facilities: Design Improvements Should Reduce Radiological Impacts Relative to First Generation Uranium Solution Mining Plants*. Proceedings of the 2008 Waste Management Symposium, Phoenix. ASME Press, New York, NY, ISBN # 978160560422. 2008.

For more on mechanisms of ISR radon source terms see: Brown**,** S. and Smith, R., 1982. *A Model for Determining the Radon Loss (Source) Term for a Commercial In Situ Leach Uranium Facility.* In: M. Gomez (Editor), Radiation Hazards in Mining-Control, Measurement, and Medical Aspects. Soc. Min. Eng., pp. 794—800; Marple, M.L and Dziuk, T, Texas Department of Health, Bureau of Radiation Control. *Radon Source Terms at In Situ Uranium Extraction Facilities in Texas.* Proceedings of the Sixth Annual Uranium Seminar, South Texas Minerals Section of AIME. Corpus Christi. September 11-14, 1982

5. What are Current Practices and Results in Estimating Doses to the Public from Uranium Recovery Facilities?

Calculations performed in accordance with existing NRC guidance are used to estimate source terms and calculate off-site dose to the public. For example, USNRC Regulatory Guide 3.59, Section 2.6 provides methods acceptable to NRC for estimating the radon source term during ISR operations. Additionally, USNRC NUREG 1569, Appendix D, provides the MILDOS – AREA computer code methodology acceptable to the NRC, which includes expressions for calculating the annual Rn-222 source terms from various aspects of ISR operations which is then used by MILDOS to calculate off-site public dose and demonstrate compliance with dose limits of 10 CFR 20.1301.

See e.g.: U.S. Nuclear Regulatory Commission, NUREG-1569, *Standard Review Plan for In Situ Leach Uranium Extraction License Applications*, June 2003. Yuan, Y.C., J.H.C. Wang and A. Zielen. 1989. *MILDOS-AREA: An Enhanced Version of MILDOS for Large-area Sources.* Argonne National Laboratory (ANL) report ANL/ES-161. June 1989; U.S. Nuclear Regulatory Commission (NRC), 1987*. Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations*. Regulatory Guide 3.59.

Regards to historical estimates of offsite radon concentrations and public dose from ISRs as reported by its licensees, the U.S. Nuclear Regulatory Commission, in NUREG-1910, *Generic Environmental Impact Statement for In-Situ Leach Uranium Milling Facilities (*2009), Chapter 4.2 indicates:

- Quarterly and biannual measurements of downwind concentrations of radon at an operational ISR facility boundary from 1991 to early 2007 were below 74 Bq/m3 [2.0 pCi/liter] with a majority of measurements below 37 Bq/m3 [1 pCi/liter]. For comparison, these measured values are well below the NRC effluent limit for radon at 10 CFR Part 20, Appendix B of 370 Bq/m3 [10 pCi/liter] and in fact, are probably just background values.

- Argonne National Laboratory's MILDOS-AREA computer code (Argonne National Laboratory, 1989 – see above) is typically used to calculate radiation doses to individuals and populations from releases occurring at operating uranium recovery facilities. The code is capable of modeling airborne radiological effluent releases applicable to both conventional mills and ISR facilities (including radon gas from well fields and processing facilities and yellowcake particulates from thermal drying operations)

- All reported doses have been well within the 10 CFR Part 20 annual radiation dose limit for the public of 1 mSv [100 mrem/yr] including dose from radon and its progeny and within the EPA fuel cycle annual limit (40 CFR 190) of 0.25 mSv [25 mrem], which does not include dose due to radon and its progeny.

6. What is known about the potential health effects to populations living in the vicinity of uranium mines and mills?

Uranium is a heavy metal and acts similarly to other heavy metals in the body (like molybdenum, lead, mercury). Accordingly, for natural uranium, national and international human exposure standards are based on the possible *chemical toxicity* of uranium (e.g., effect on kidney—nephrotoxicity), not on radiation and possible "cancer effects" (radiotoxicity). However, there has never been a death or permanent injury to a human from uranium poisoning*.

* See e.g.: (1) U.S. Nuclear Regulatory Commission. *Standards for Protection Against Radiation*; 10 CFR 20, Appendix B., Table 1. 1992. (2) International Commission on Radiological Protection. *Limits for Intakes of Radionuclides by Workers*. ICRP Publication 30, 1979. (3) US Dept. of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry. *Toxicological Profile for Uranium.* 1999. *(4) Acute Chemical Toxicity of Uranium.* Kathryn, RL and Burkin, RK. Health Physics, 94(2), pp 170-179, February 2008)

Regarding ionizing radiation in general, the health effects are well understood. No health effects have been observed in human populations at the exposure levels within the range and variability of natural background exposures in the US. An official position of the National Health Physics Society is that below 5,000 – 10,000 millirem (which includes the range of both occupational and environmental exposures), risks of health effects are either to small to be observed or non- existent (see *Radiation Risks in Perspective* @hps.org/hpspublications/positionstatements). International and national authorities that establish exposure standards for workers and the public rely on the work of scientific committees of the highest professional standing for their evaluations of the scientific information on the health effects of ionizing radiation. These scientific committees include the United Nations Scientific Committee on the Effects of Ionizing Radiation (UNSCEAR); the International Commission on Radiological Protection (ICRP); the National Academy of Science's Biological Effects of Ionizing Radiation (BEIR) Committee, the National Council on Radiation Protection and Measurements (NCRP) and others.

But what about the specific concerns regarding health effects to populations living close to uranium recovery facilities? Despite much confusion and misunderstanding, possible health effects in populations living near uranium mines and mills have been well studied. No additional effects have been observed when compared to the health status of other similar populations not living nearby. A few sources providing the scientific evidence that supports this conclusion include:

- US Department of Health and Human Services, Public Health Services, Agency for Toxic Substance and Disease Registry, *Toxicological Profile for Uranium*, 1999. Chapter 1: Public Health Statement for Uranium, Section 1.5: How Can Uranium Effect My Health? – " No human cancer of any type has ever been seen as a result of exposure to natural or depleted uranium" (Available at:

http://www.atsdr.cdc.gov/toxprofiles/tp150.html)

- *Cancer and Noncancer Mortality in Populations Living Near Uranium and Vanadium Mining and Milling Operations in Montrose County, Colorado, 1950 -2000*. Boice, JD, Mumma, MT et al. International Epidemiology Institute, Rockville, MD and Vanderbilt University, Vanderbilt-Ingram Cancer Center, Nashville, TN. Journal of Radiation Research, 167:711-726; 2007: " The absence of elevated mortality rates of cancer in Montrose County over a period of 51 years suggests that the historical milling and mining operations did not adversely affect the health of Montrose County residents"

- *Cancer Mortality in a Texas County with Prior Uranium Mining and Milling Activities, 1950 – 2001.* Boice, JD, Mumma, M et al. International Epidemiology Institute, Rockville, MD and Vanderbilt University, Vanderbilt-Ingram Cancer Center, Nashville, TN Journal of Radiological Protection, 23:247 – 262; 2003 – "No unusual patterns of cancer mortality could be seen in Karnes County over a period of 50 years suggesting that the uranium mining and milling operations had not increased cancer rates among residents".

- *Cancer Incidence and Mortality in Populations Living Near Uranium Milling and Mining Operations in Grants, New Mexico, 1950–2004.* Boice, JD, Mumma, M et al. International Epidemiology Institute, Rockville, MD and Vanderbilt University, Vanderbilt-Ingram Cancer Center, Nashville, TN. Journal of Radiation Research, 174, 624–636. 2010 – "With the exception of male lung cancer (*in former underground miners*), this study provides no clear or consistent evidence that the operation of uranium mills and mines adversely affected cancer incidence or mortality of county residents".

7. But what about the known health impacts (e.g., lung cancer) to many uranium miners who worked underground in the 1950s and 1960s?

These miners worked in conditions that by today's standards we would consider unacceptable. They were exposed to very high levels of radon progeny (which are decay products of uranium) in poorly ventilated underground mines. Many of these miners also had severe smoking habits, which enhanced the ability of the radon daughters to deliver radiation dose to the lung. Follow up of 68,000 former miners over many years indicated the occurrence of about 2700 lung cancers in this population; much higher than the expected incidence. This is an incidence rate of about 4%. As a point of comparison, the baseline incident rate of lung cancer in non-smoker, Caucasian males today is about 0.4 % (Dr. John Boice, International Epidemiology Institute, Vanderbilt University – personal communication)

These conditions existed before we had Federal Agencies (Occupational Safety and Health

Administration - OSHA, Mine Safety and Health Administration - MSHA, US Nuclear Regulatory Commission - NRC) and laws to better protect workers throughout American industry (construction, manufacturing, farming, mining, etc). Based on the best scientific information available, we consider as safe the occupational exposure standards we have today as enforced by these agencies. The level of exposure of some of these early uranium miners was 100 – 1000 times higher than our current Federal standards.

As just one of many possible historical comparisons regards to working conditions in American industry decades ago, it is of note that almost 100 men died from construction and related accidents in the building of the Hoover Dam in the 1920s, long before Federal regulations were in place to protect workers. These circumstances would of course also be unacceptable today

Conclusions:

(1) The existing public radiation exposure criteria for uranium mills and in situ recovery facilities in 40 CFR Parts 61, 190 and 192 are adequately protective since they represent small fractions of the natural radiation background variation across the US. Our lifestyles, where we choose to live, what we eat and drink, has a much larger impact on our radiation exposure than exposure at these very low regulatory limits.

(2) Regarding ionizing radiation in general, the health effects are well understood. No health effects have been observed in human populations at the exposure levels within the range and variability of natural background exposures in the US.

(3) Radon emission rates (flux) from water impoundments (evaporation ponds) at licensed conventional mills and ISRs are not expected to be significantly different than that from typical background radon emission associated with land surfaces almost anywhere due to the very poor diffusion of radon through water.

(4) Historical environmental measurements made in the vicinity of uranium recovery facilities and public dose assessment performed and reported to the USNRC indicate radon concentrations at site boundary locations and doses to the public are consistently well below Federal limits.

(5) The possibility of health effects in populations living near uranium mines and mills over 50 years have been well studied by national scientific bodies of the highest professional standing. No additional effects have been observed when compared to the health status of other similar populations not living nearby.

(6) However, given that 40 CFR 192 was released in 1983, changes and updates have been made in the basic dosimetry models and science we use today to estimate radiological doses and risks. Accordingly, EPA should consider reassessing exposure terminology and criteria (e.g., as used in 40 CFR 190) to be consistent with current national and international methods and models, e.g., (1) International Commission on Radiological

Protection, 2008. “Publication 103 Recommendations of the ICRP, Annals of the ICRP.” 2008 and (2) National Research Council, 2006. “Health Risks for Exposure to Low Levels of Ionizing Radiation; BEIR VII, Phase II.”

Appendix 36

Radon Emissions from Tailings and Evaporation Ponds

Presented To:

NRCs Uranium Recovery Licensing Workshop

Denver, January 11-12, 2011

Presented By:

Steve Brown and Doug Chambers

SENES Consultants Limited

Regulatory Context

- ❑ **40 CFR 61, Subpart W NESHAP limits radon emissions from operating mill tailings (EPA 1989)**
- ❑ **Defines the Regulatory limit in Subpart W for tailings impoundments in existence as of December 15, 1989**
  - ➢ Flux of 20 pCi m^{-2} s^{-1}
- ❑ **After that date, two work practice requirements:**
  - ➢ Total area in operation* at any time 2 X 40 acres
  - ➢ Limited to 10 acres uncovered at any time

* Operated per § 192.32(a) as determined by NRC

Why Regulatory History is of Current Importance

- ☐ **Per Settlement Agreement with Plaintiffs of November 2009, EPA agreed to review and potentially revise 40 CFR 61**
- ☐ **Subsequently, EPA has conducted series of public meetings and solicited public input**
- ☐ **EPA has indicated they are considering applying work practice requirements of Sub W to water ponds (e.g., conventional U mill and ISR evaporation ponds)**

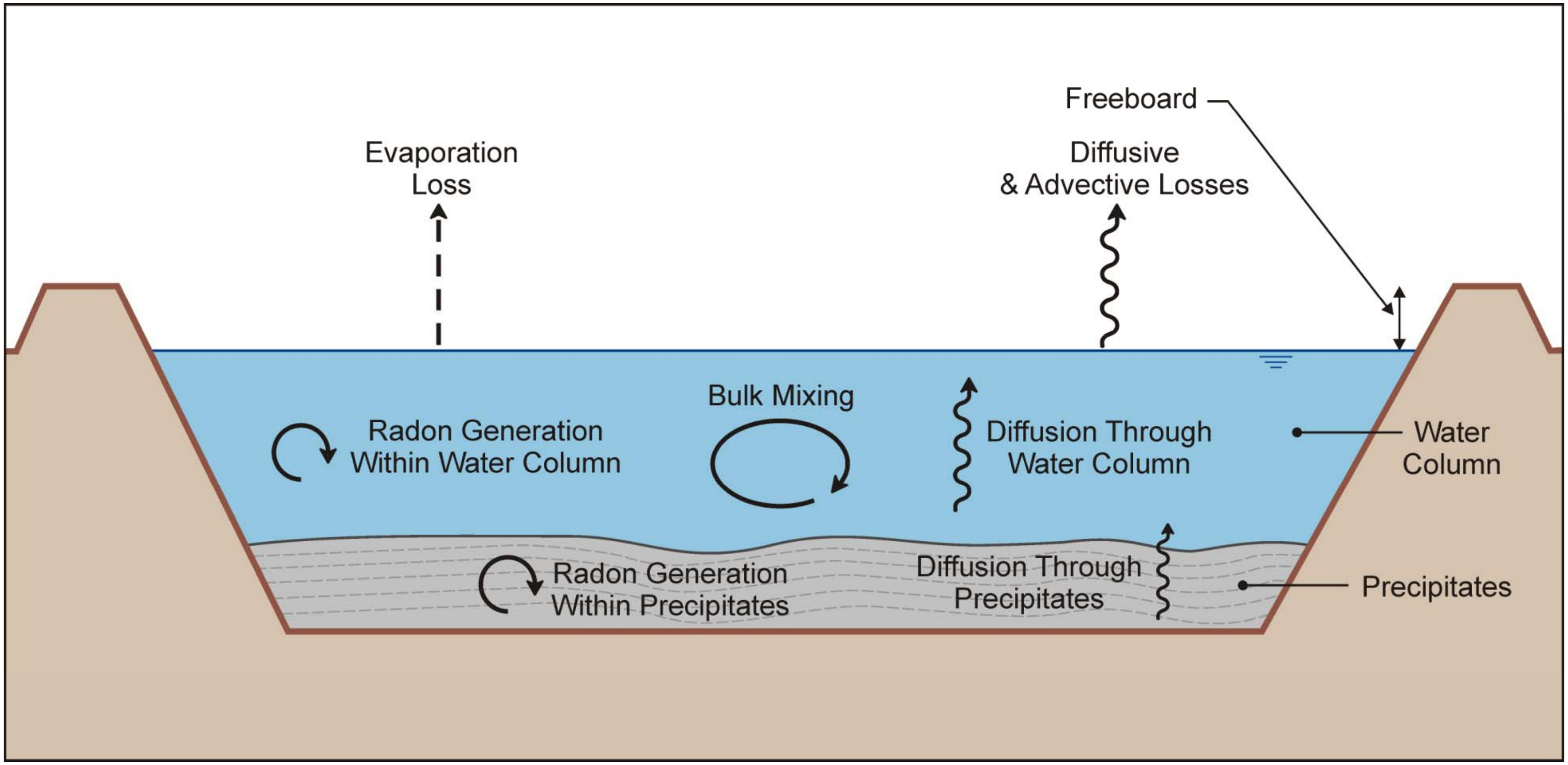
Issues and Concerns

- ☐ **Direct measurement of radon flux over water surfaces via accepted methods (e.g., EPA # 115) is problematic**
- ☐ **Application of Work practice acreage limitations to include water ponds at new uranium recovery facilities could severely limit production and could make operation in some cases “impossible”**
- ☐ **The basic physics, historical and recent studies of radon emission from water surfaces suggests it is “trivial” and is the subject of this presentation**

Sources of Radon

- ☐ **Tailings Impoundment**
  - ➢ Radon as the decay product of Ra-226 dissolved in solution
  - ➢ Radon from Ra-226 in tailings solids
- ☐ **Evaporation Ponds**
  - ➢ Radon as the decay product of the Ra-226 dissolved in solution
  - ➢ Radon from Ra-226 in the precipitates
- ☐ **ISRs**
  - ➢ Dissolved Radon from formation

Radon Release Mechanisms



Diffusion Length

$$L = \sqrt{\frac{D}{\lambda P}}$$

Where:

L = diffusion length

= distance to which concentration decreases by factor of *e* (= 2.718)

D = bulk diffusion coefficient (cm^2/s)

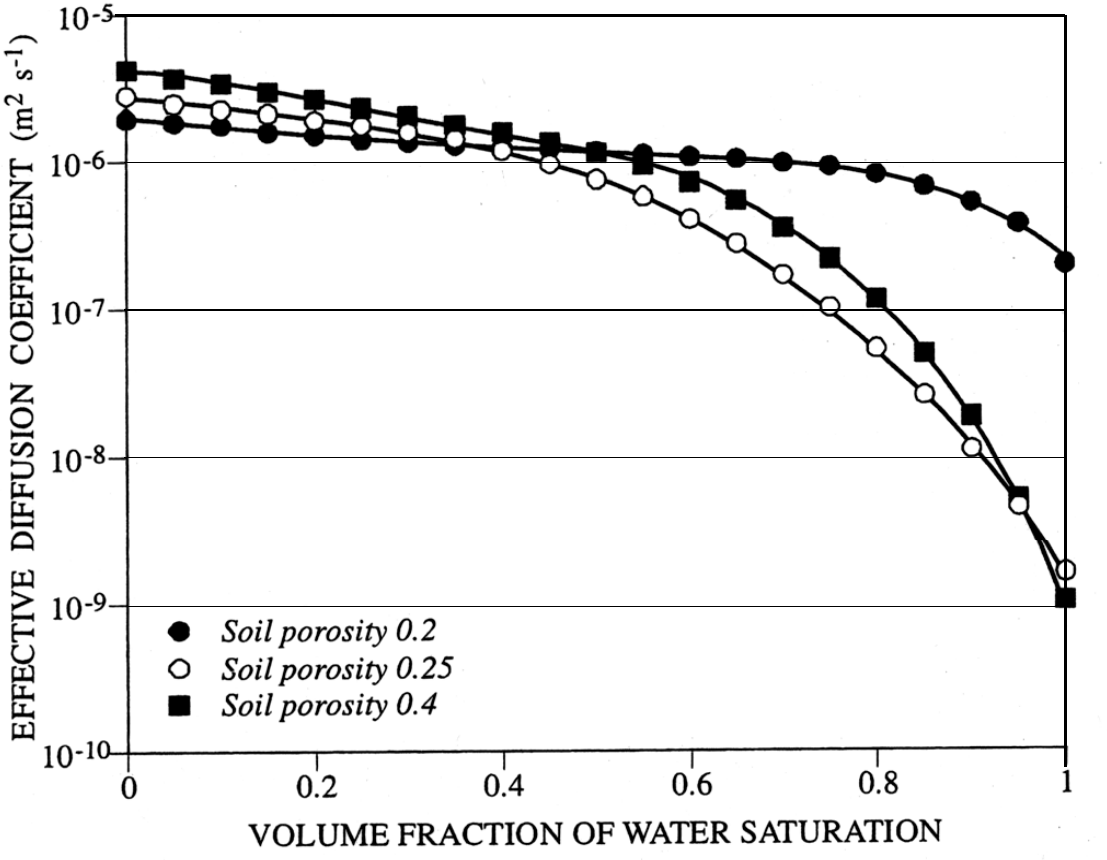
λ = radon decay constant

= 2.1×10^{-6}/s

P = porosity (void volume/total volume)

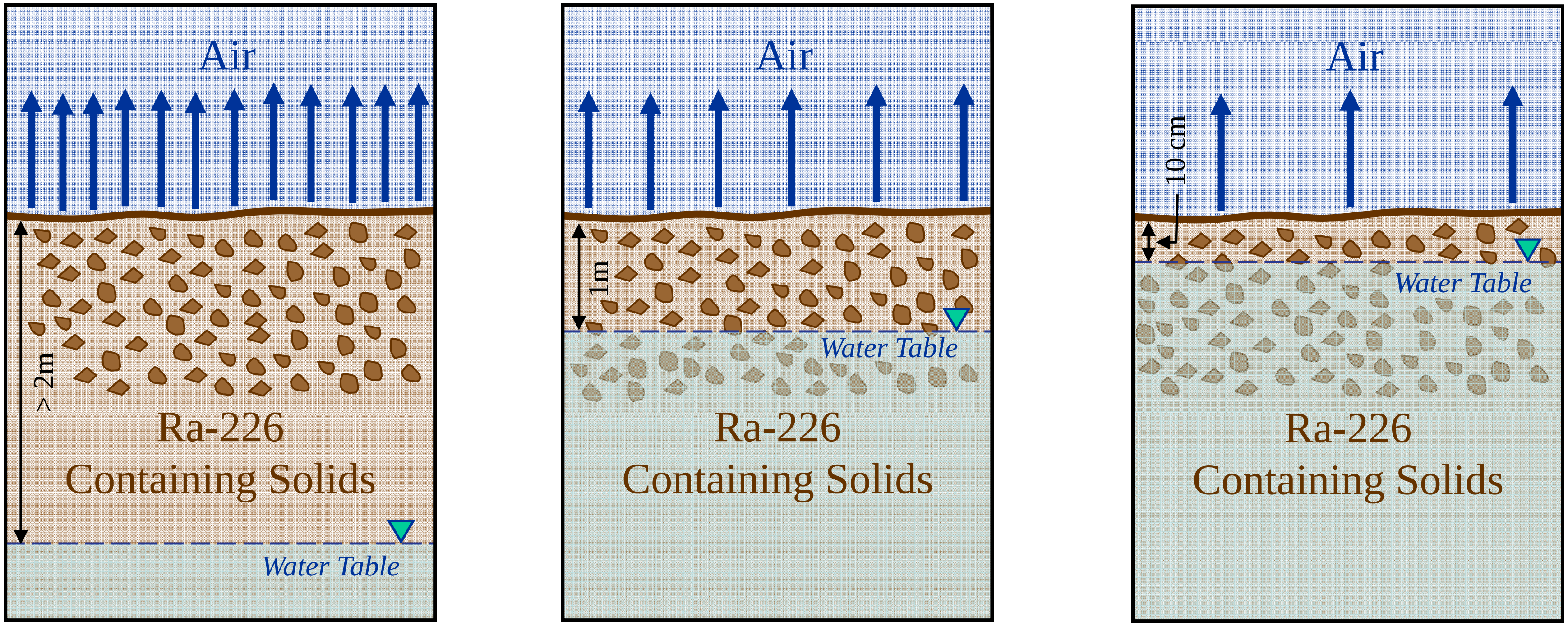
Experimental Diffusion Coefficients

[UNSCEAR 2000]



SOURCE: After UNSCEAR 2000

Effects of Water Saturation



Radon from Water Covered Tailings Solids and Precipitates

- ☐ **Diffusion coefficient of radon through solids decreases with increasing water content**
- ☐ **Tailings solids and precipitates under water will be saturated**
- ☐ **For practical purposes, “zero” radon flux as radon produced within tailings solids/precipitates decays before migrating to water/solids interface**

Radon Release Mechanisms

- ☐ **Diffusion**
- ☐ **Diffusion enhanced by mechanisms such as natural convection in the water column and wind action**
- ☐ **Evaporation**

Release via Diffusion

- **Radon in still water diffuses toward the air-water interface where it is released to the ambient air**
- **The diffusion of radon is described by Fick's Law: the flux density of the diffusing radon is linearly proportional to:**
  - its concentration gradient
  - its diffusion coefficient in water

Release via Diffusion

- **Diffusion Coefficient of Radon in Water and Air at 20°C** [Drago, 1998]

Medium	Value	Unit
water	1.2×10^{-5}	cm^2/s
air	1.4×10^{-1}	cm^2/s

- **The diffusion coefficient of radon in air is approximately 10,000 times larger than its diffusion coefficient in water**

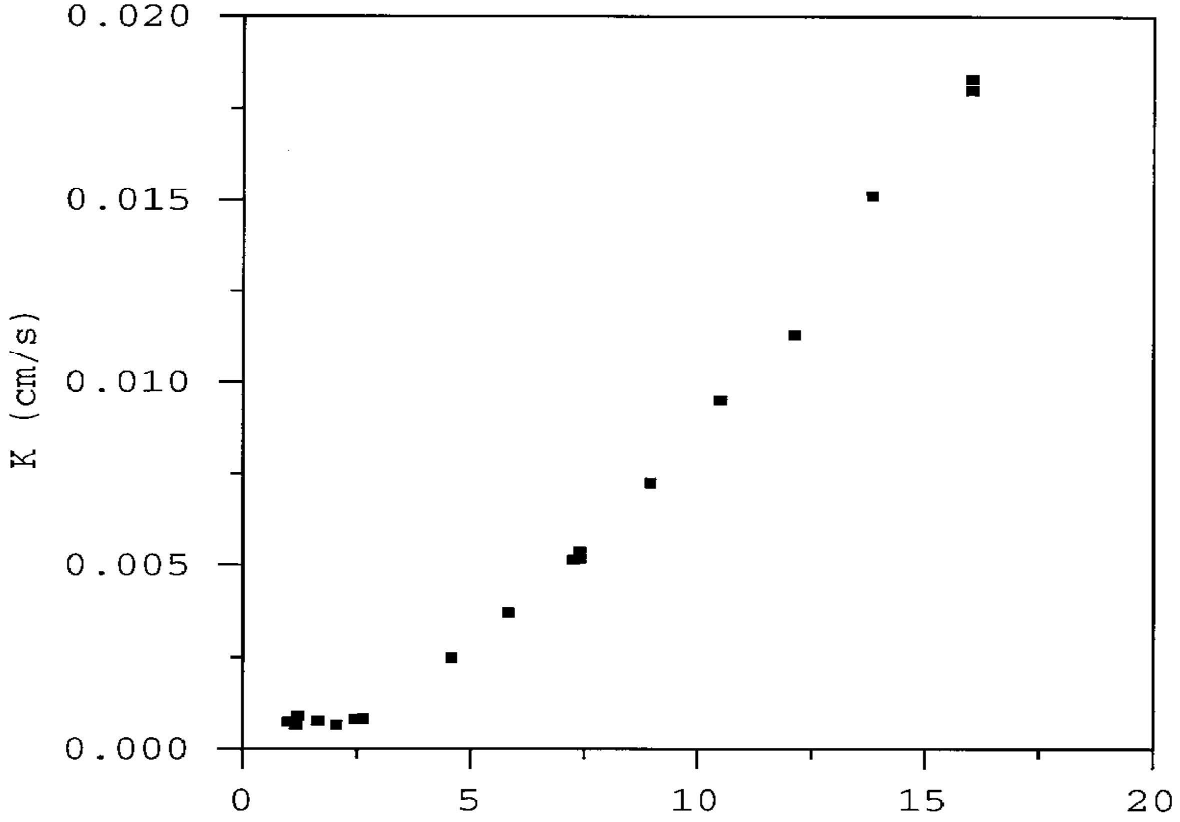
General Release Mechanism - 1

- In reality, gaseous diffusion is enhanced by various mechanisms such as natural convection in the water column and wind action
- Hence, Fick’s Law is expressed as an effective diffusion coefficient
- In addition, the radon flux across the air/water interface is expressed as overall mass transfer coefficient – a compound factor of diffusion in water, air and the effect of convections in both water column (wave action) and air (wind action)

General Release Mechanism - 2

Typical Plot of Mass Transfer Coefficient K versus Wind Speed (m/s)

[Source: Saylor and Handler,1997]



General Release Mechanism - 3

- ☐ **At wind speed of 8 miles/hour (3 m/s) or less, no significant wave action expected. At these wind speeds, release rates are typically independent of wind speed (diffusion controlled)**
- ☐ **The wave dimensions versus wind speed depend on the geometry and size of ponds**
- ☐ **For typical tailings impoundments (40acres) and evaporation ponds, the maximum wave depth would be less than 1 ft for the wind speed of 23.4 miles/hour (8.1 m/s)**

Radon From Wave Action

- **Rn-222 is produced at the rate of 2.1 x 10^{-6}/s from Ra-226**
- **Wave action induced turbulence assumed to release radon at air/water interface as it is produced from Ra-226 within “turbulent” layer**

Solution Ra-226 (pCi/L)	Depth of Turbulent Mixing (cm)	Rn-222 (pCi/m^2 • s)
10	**10**	**0.002**
	50	**0.01**
100	**10**	**0.02**
	50	**0.1**
1000	**10**	**0.2**
	50	**1**

NRC Models

- ☐ **NRC uses the Rogers et. al. models (based on the Fick's Law of diffusion) in NRC 1984 handbook for uranium tailings cover design**
- ☐ **Nielson and Rogers work is also basis for NRC's Regulatory Guide 3.64 on radon attenuation by earthen tailings covers (NRC 1989)**
- ☐ **The "NRC" model considered that mixing leading to non-diffusive radon emissions could take place in the top 1 m of water cover within tailings impoundments**
- ☐ **Over evaporation ponds, the magnitude of the wave dimensions may not be large enough to induce complete mixing in the top 1 m of the water column**

Evaporative Emission

- **A 2010 analysis by SENES (conventional mill currently under licensing review) showed that evaporative loss of ponds is extremely insignificant compared to diffusional release of radon**
  - Continuous evaporation from thin film at interface based on Henry's Law constant for radon and concentration of radon in ambient air
  - Assumes 75% radon removal efficiency [Rost, 1981] for radon produced from radium in solution and used for spray evaporation
- **The SENES calculations indicated that the total radon emission from evaporation is insignificant vs. estimated value based on Neilson and Rogers model (diffusion and wave action from the evaporation ponds).**

Radon and ISRs

- **Two mechanisms of release:**
  - Dynamic release of Rn dissolved in lixiviant when initially exposed to atmospheric pressure (small leaks in well fields, IX - elution interface, surge ponds, restoration)
  - From decay of Ra 226 dissolved in water
- **Since sources are many and diffuse, cannot measure directly**
- **Accordingly, historical approach for demonstrating compliance to, e.g. 10 CFR 40.65 semi annual effluent reporting and public dose limits is via calculations and environmental monitoring**

Estimating Radon Releases – 10 CFR 40.65 Reporting Requirements for ISRs

- ☐ **NRC regulatory Guide 3.59* used to estimate Radon source terms and/or**
- ☐ **Results of environmental monitoring (Rn passive detectors, air particulate sampling) compared to 10 CFR 20, Appendix B, Table 2 unrestricted area concentration limits**
- ☐ **Offsite doses estimated via ratios of environmental monitoring results to 10 CFR 20, App. B limits X 100 mrem / yr or via RG 3.59 + MILDOS – AREA computer code (Argonne National Lab, 1997 – See Appendix D, NUREG 1569)**

* RG 3.59, 1987 - *Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations,* Section 2.6: Radon Release During In Situ Operations

Rn from ISRs – Example Results

- ☐ **Estimates of Rn source terms via RG 3.59 and/or MILDOS – AREA (NUREG 1569) in recent applications and in 40.65 reports = several hundred to several thousand Ci/yr. ***
- ☐ **Rn concentrations in unrestricted areas via environmental monitoring by licensees consistently << 10 CFR 20, App. B, Table 2 limits and offsite doses consistently < 10 CFR 20.1301 public dose limits**
- ☐ **From NRC NUREG 1910 (ISR GEIS), Table 4.2-2: "Calculated doses are solely for radon releases**.. these sites have no yellowcake emissions since they use vacuum dryer technology.. All doses reported are well within the 10 CFR Part 20 annual radiation dose limit for the public of 1 mSv [100 mrem/yr)"**

* As a frame of reference, at a typical almost anywhere, natural background radon flux of 1 - 2 pCi/m^2-sec, a square mile of earth has a " Rn source term" of 50 – 100 Ci/yr.

** Dose (TEDE) as calculated by MILDOS is actually from the radon progeny since radon, as an inert gas, is dosimetrically insignificant

Radon , ISRs and 40 CFR 61 Subpart W

- ☐ Accordingly, application of Sub W Rn emission limit and/or work practices should not be necessary for ISRs since:
  - Adequate public protection and standards of care are provided under the AEA (e.g., 10 CFR 20; 10 CFR 40 App A)
  - Operating experience consistently demonstrates unrestricted area concentrations and public dose limits are achieved

QUESTIONS ?

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Appendix 37

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370101-4

30 August 2010

Energy Fuels Resources Corporation
44 Union Boulevard, Suite 600
Lakewood, CO 80128

Attention: **Frank Filas, P.E., Environmental Manager**

Re: **Evaporation Pond Radon Flux Analysis, Piñon Ridge Mill Project, Montrose County, Colorado**

Dear Frank,

This letter is to address Task 1 of our proposal of 16 June 2010 relative to radon flux from evaporation ponds, namely:

- Task 1: Estimate the radon flux from the proposed Piñon Ridge Mill evaporation ponds for both an initial 40 acres of ponds and a potential increase to 80 acres. In addition, the effect of spraying to enhance evaporation has been considered.

Task 1 is directed towards providing information to the U.S. Environmental Protection Agency (EPA) relative to their current Subpart W NESHAP rulemaking. We understand that this information will be provided as a courtesy to the EPA since Energy Fuels does not believe that the ponds are within EPA's regulatory mandate.

As shown below, using a model from Nielson and Rogers for water-covered uranium tailings, [whose work has been the primary basis for NRC and EPA radon emission models from uranium tailings impoundments], it can be shown that the radon flux from the evaporation ponds at the Piñon Ridge Mill site is expected to be well within the range of pre-operational background radon flux rates measured at the proposed tailings locations. The basis for this conclusion is presented in subsequent sections of this letter.

We would be pleased to answer any questions you may have concerning our evaluation. In my absence, please communicate with my colleague Dr. Douglas Chambers.

Yours very truly,

For SENES Consultants Limited

Steven H. Brown, CHP

cc: Dr. Douglas Chambers, dchambers@senes.ca

ATTACHMENT

1.0 INTRODUCTION

1.1 Background

Energy Fuels Resources Corporation (EFRC) is in the process of completing designs for a uranium mill, termed the Piñon Ridge Project, located in Montrose County, Colorado. The mill is designed for start-up operations at 500 tons per day (tpd) (Phase I), with a potential to expand to 1,000 tpd (Phase II). The design raffinate flows from the process circuit are in excess of that needed for re-circulation to the mill; therefore, the design of the mill requires construction of 10 evaporation ponds (Phase I) and another 10 evaporation ponds (Phase II) for the disposal of the excess raffinate solution from the milling operation. The evaporation ponds are expected to be very small sources of radon emissions to the ambient air. To confirm this assumption, and in the interest of demonstrating that radon emissions to unrestricted areas from operation of the Piñon Ridge Mill will be maintained ALARA, these potential radon emissions are the subject of this assessment.

The emission of radon from uranium tailings has been studied and modeled for many years. For example, the U.S. Nuclear Regulatory Commission (NRC) makes use of their 1984 handbook for uranium tailings cover design (Rogers et al. 1984).

Because of the very low diffusion of radon through water (as compared to partially air-filled unsaturated tailings pores), the diffusion of radon through water-covered tailings has been argued to be effectively zero (e.g. Chambers 2009). The EPA has previously assumed zero radon emissions from ponded areas of uranium tailings impoundments (e.g. EPA 1986). This is based on the assumption of no or low measurable radium concentrations in water covering the tailings; that is, the source of radon-222 (radon) is primarily the radon from the radium-226 (Ra-226) in the tailings. However, during a recent presentation at the annual National Mining Association /Nuclear Regulatory Commission (NMA/NRC) Uranium Workshop in Denver, Colorado, representatives of the United States Environmental Protection Agency (EPA) stated that the work practice standards in its 40 CFR Part 61, Subpart W *National Emissions Standards for Radon Emissions from Operating Mill Tailings* apply to evaporation ponds at conventional and in situ uranium recovery (ISR) sites licensed by NRC or its Agreement States.

A presentation by Baker and Cox (2010) at the most recent NMA/NRC workshop in Denver considers the situation where appreciable concentrations of radon are present in the ponded water, as may arise for example from elevated levels of Ra-226 dissolved in the pond water. Baker and Cox, reporting on a stagnant film model and some measurement data, suggest a radon flux of the order of 1 pCi m^{-2} s^{-1} per 100 pCi/L of dissolved radon in the ponded water.

1.2 Published Models and Regulatory Context

As previously noted, much of the work on radon emission models undertaken by Rogers and Associates has been adopted by the U.S. NRC and is widely used by the NRC and others in assessing radon releases from uranium tailings. Besides the NRC use of the Rogers et al models in the NRC 1984 handbook for uranium tailings cover design (Rogers et al 1984), their work is also the basis for NRC's Regulatory Guide 3.64 on radon attenuation by earthen tailings covers (NRC 1989).

In some earlier work, Nielson and Rogers (1986) examined the issue of surface water considerations in predicting radon emissions from water-covered uranium tailings impoundments. They suggest that radon emissions from water-covered tailings can be non-zero. These authors attribute this to advective mixing, as opposed to straight radon diffusion mechanisms. Although there are various papers on the diffusion and transport of radon available from published literature, the 1986 work of Rogers and Nielson is of direct relevance to the present study of radon emissions from evaporation ponds, and was adopted for application here.

The Nielson and Rogers model (1986) makes use of equations based on the well-known first Fick's Law of gaseous diffusion (non-reactive) through media in order to estimate surface radon flux rates. They considered that mixing leading to non-diffusive radon emissions could take place in the top 1 m of water cover within tailings impoundments. In their analysis, they divided radon releases into three components:

- radon originating from tailings covered with < 1 m of water;
- radon originating from tailings covered with > 1 m of water; and
- radon originating from dissolved radium in the pond water.

In this approach used by Nielson and Rogers, the emission of radon from shallow waters is controlled by the emanation of radon and diffusion through the pore water. However, the radon emission from tailings covered with deep water (>1 m) is controlled by the diffusion of radon through the water column. As noted further below, the assumption of complete release in the top 1 m is conservative in that the mixing advective layer would likely be less than 1 m deep.

Regulatory Context

It is beyond the scope of this analysis to comment on the applicability of the Subpart W NESHAP limits on radon emissions from operating mill tailings (EPA 1989), other than to note that the applicability of the rule to evaporation ponds has been questioned. For present purposes, to provide a context for the estimates of radon flux described below, a reference value of 20 pCi m^{-2} s^{-1} has been assumed for uranium tailings impoundments. This flux rate, which represents the regulatory limit in Subpart W for tailings impoundments constructed prior to December 1989, was typical of tailings impoundments operating in the 1980s.

The baseline radon flux for the site represents a second point of reference. The Piñon Ridge site has been used historically for grazing cattle and has not been impacted by uranium mining or milling activities. Radon emission rates were measured at nine locations within the proposed tailings areas on three separate occasions (fall, spring, and summer). The radon-measuring canisters were analyzed using EPA Test Method 115, Monitoring for Radon-222 Emissions. The background radon flux rates ranged from 0.41 to 3.78 pCi m^{-2} s^{-1} and averaged 1.7 pCi m^{-2} s^{-1} (ERG 2009).

1.3 Approach to the Present Problem

In this study, we examined the effect of various wind speeds on the radon emission rates from the evaporation ponds based on the Nielson and Rogers model. In order to improve performance of the evaporation pond system (i.e., enhance the evaporative capabilities), the design of the ponds includes implementation of a sprinkler system. The sprinklers will be placed and sized to maximize evaporation and minimize the potential for wind drift beyond the extent of the lined evaporation pond area. In this assessment, the emission of radon from sprinkler systems was also estimated.

While the Nielson and Rogers model can theoretically be used for estimation of radon emissions from the evaporation ponds, the following potential limitations should be noted. The tailings are relatively thick and a significant radon concentration gradient may be developed across the thickness of the tailings due to diffusional movement of radon towards the solid-liquid interface. In the evaporation ponds, however, the precipitate layer may be much thinner and the concentration of radon in the pore water can be assumed to be uniform across the thickness of the precipitate layer.

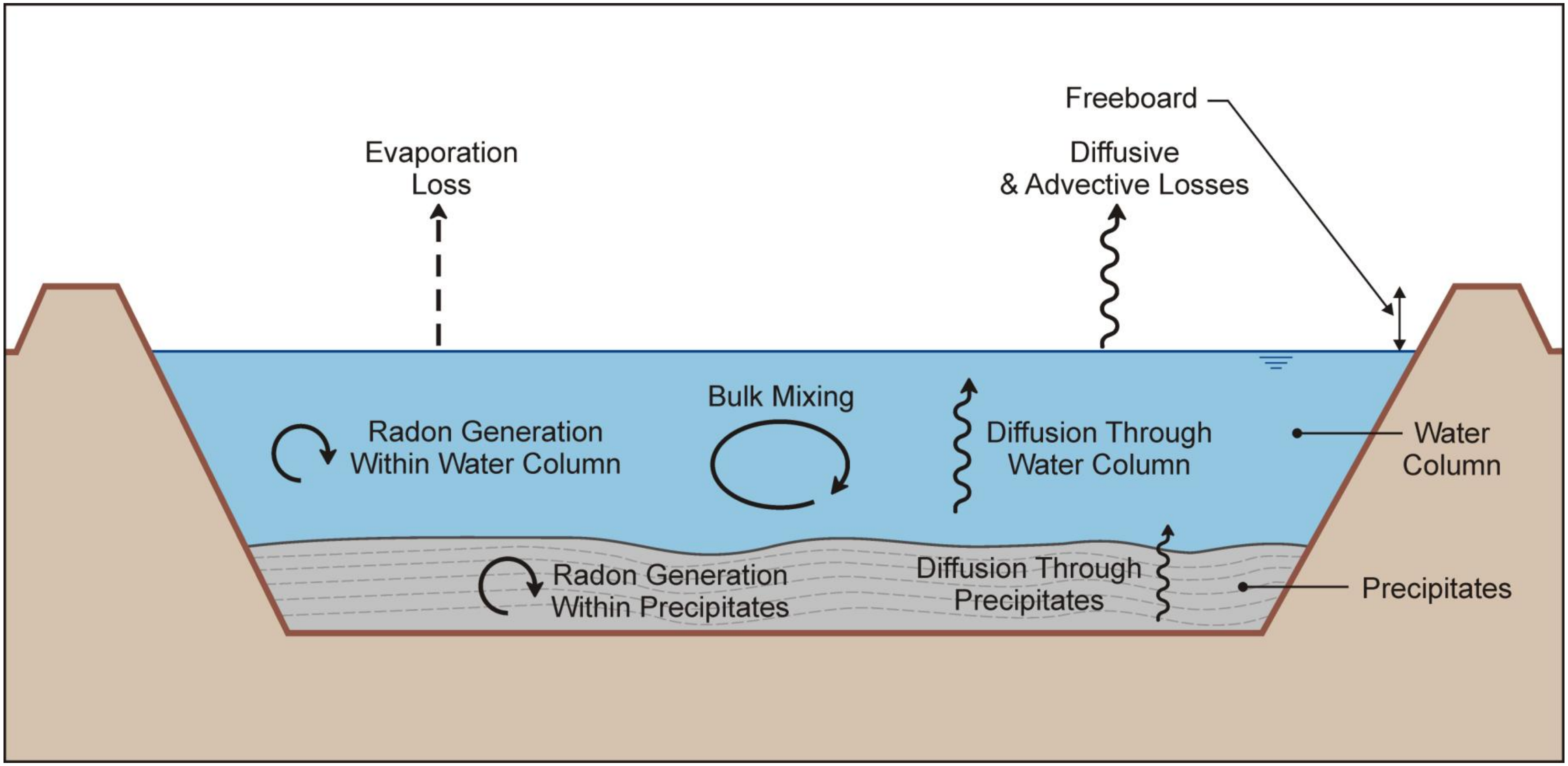
The Nielson and Rogers model provides a conservative estimate of radon emissions based on the assumption of complete mixing in the top 1 m layer of the water covering the tailings. Nielson and Rogers based their model on observed wave action at the air-water interface. On a smaller scale, such as over evaporation ponds, the magnitude of the wave dimensions may not be large enough to induce complete mixing in the top 1 m of the water column.

2.0 RADON EMISSION MECHANISMS

2.1 Overview of Radon Emanation Mechanisms

Radon occurs in raffinate and precipitates in the evaporation ponds naturally as the decay product of the dissolved radium in pond water and radium in the precipitates. Figure 1 shows various mechanisms involved in the release of radon from the evaporation ponds.

Figure 1: Mechanisms Involved in the Release of Radon from the Evaporation Ponds



Radon produced in water diffuses toward the direction of its decreasing concentration in water (in most cases toward the air-water interface where it is released to the ambient air). In stagnant water columns, the diffusion of radon can be described by Fick's Law, which states that the flux density of the diffusing radon is linearly proportional to its concentration gradient and its diffusion coefficient in water. In water columns, the diffusion of radon is enhanced by various mechanisms such as natural convection in the water column and wind action. As a result, the Fick's Law is expressed in term of effective diffusion coefficient. Typically, the gas transport across the air-water interface is expressed using the overall mass transfer coefficient. This coefficient is very sensitive to the thickness of the boundary layers in both sides of the interface and the wind speed over the water surface.

In addition to the above transfer mechanisms, the transport of radon produced inside the solid particles is also influenced by the diffusion of radon within the solid particle. After being generated, the radon atoms tend to move away from their original location toward the pore spaces in the medium. Consequently, depending on their original location within the solid phase, the pore distribution, and the moisture content of the solid particles, the newly created radon atoms may end up within the same solid particle in which they were created, or within the pore of the medium. Table 1 shows nominal diffusion coefficients for radon in water and in air as reported by Drago (1998).

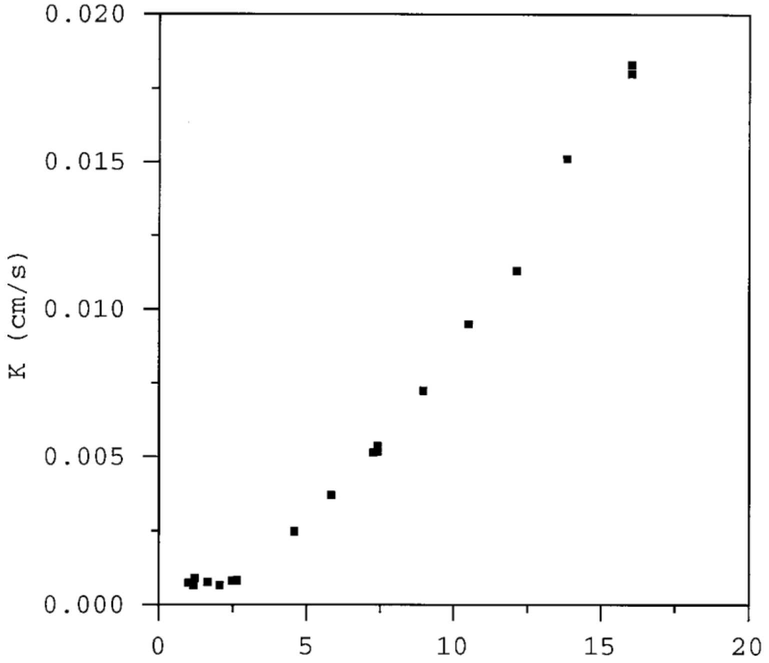
Table 1: Diffusion Coefficient of Radon in Water and Air at 20°C
Source: Drago (1998)

Medium	Value	Unit
water	1.2×10^{-5}	cm^2/s
air	0.12	cm^2/s

Since the diffusion coefficient of radon in air is approximately 10,000 times larger than its diffusion coefficient in water, the migration of radon in saturated solids is much different than its migration in unsaturated solids. The fraction of the total amount of radon produced by radium decay that escapes from the solids particles and gets into the pores of the medium is referred to as the radon emanation coefficient or emanation fraction (often written as E). The radon emanation coefficient is strongly influenced by the moisture content of the medium, particularly within the range of low water saturation.

A clear change in trend of the data, separating these two regimes, occurs at u=3 m/s as shown in Figure 2. Ocampo-Torres et al (1994) note that this critical wind speed corresponds to the lowest value of u at which waves are observed. In another study, Kanwisher (1963) observed a sudden increase in the rate of CO_2 outgassing in a wind/wave tunnel, at a wind velocity of about 3 m/s where the waves begin to emerge. It is suggested that the random surface drift velocities observed at the surface of water may act to generate some degree of bulk mixing.

Figure 2: Typical Plot of Mass Transfer Coefficient K versus Wind Speed in a Wind/Wave Tunnel. Source: Saylor and Handler (1997)



The wave dimensions versus wind speed depend on the geometry and size of the ponds and could not be easily established for this study. However based on the information available from the pond design documents regarding the depth of the freeboard (1 ft), it is expected that the maximum wave depth would be less than 1 ft for the maximum wind speed (18.1 miles/hour or 8.1 m/s) for the site[1]. The average wind speed for the site is considerably less at 6.2 miles/hour or 2.8 m/s. According to the above observations, no significant wave action is expected to occur at the surface of the ponds at the average wind speed.

3.0 PHYSICAL PARAMETERS

3.1 Description of Evaporation Ponds

The design flow rates of raffinate associated with the start-up (500 ton per day) and ultimate production rates (1,000 ton per day) are 63 and 126 gallons per minute (gpm), respectively. The average volumetric flow rate to the evaporation ponds for the 1,000 tpd scenario is somewhat less at 117 gpm (7.4 L/s) (Golder 2008). The evaporation pond system is designed for construction in two phases. Phase I includes 10 ponds (or cells), each with a surface dimension of 300 feet by 600 feet (i.e., 91 m by 182 m), designed to evaporate the inflows associated with the 500 tpd production schedule. Similarly, Phase II includes an additional 10 ponds with the

---

[1] Maximum average daily wind speed recorded over 730-day period. From Pinon Ridge Meteorological Data Base maintained by Energy Fuels Resources Corporation (2010).

same dimensions designed to evaporate the flows associated with the 1,000 tpd production schedule Golder 2008).

Both phases of construction are designed with an additional one foot of freeboard (above the required design capacities). The water depth in each pond will be similar, maximizing the evaporative surface area. In order to improve performance of the evaporation pond system (i.e., enhance the evaporative capabilities), the design includes implementation of a sprinkler system. The sprinklers will be placed and sized to maximize evaporation and minimize the potential for wind-drift beyond the extents of the lined evaporation pond area.

3.2 Parameters Used for the Modeling

Table 2 shows the physical parameters used for the current evaluation. These parameters were compiled from data provided by Energy Fuels based on their current designs for the evaporation ponds (Golder 2008). In addition, Energy Fuels contracted with J.E. Litz and Associates to undertake bench-scale studies to characterize the raffinate (Energy Fuels 2010). Measurement data on radium concentrations in precipitate and pond water were available from the studies. Relative to the pond water, the measured radium concentrations ranged from 59 to 600 pCi/L, with an average of 241 pCi/L. For this analysis, the maximum value of 600 pCi/L was conservatively assumed.

Table 2: Physical Parameters Used for the Current Evaluation

Parameter	Value	Unit	Reference
Concentration of radium in precipitates	7.9	pCi/g	Energy Fuels (2010)
Concentration of radium in pond water	600	pCi/L	Energy Fuels (2010)
Ambient air radon concentration	270	pCi/m^3	Estimate*
Bulk density of precipitates	2	g/cm^3	Estimate
Radon emanation coefficient	0.35	-	Nielson and Rogers 1986
Radon decay constant	2.1×10^{-6}	1/s	Nielson and Rogers 1986
Radon diffusion coefficient in water	1.2×10^{-5}	cm^2/s	Drago 1998
Radon diffusion coefficient in air	0.12	cm^2/s	Drago 1998
Effective diffusion coefficient of radon in deep water**	0.003	cm^2/s	Nielson and Rogers 1986
Radon Henry's Constant	4.08	dimensionless	Drago 1998
Pond width	91	m	Golder 2008
Pond length	182	m	Golder 2008
Number of ponds	10 (P I) and 20 (PII)	-	Golder 2008
Total evaporation rate	117	GPM	Raffinate flow rate, Golder 2008
Average evaporation rate	4.4×10^{-5}	L m^{-2} s^{-1}	Estimated based on data in Golder 2008

* Based on a generic value in the order of 10 Bq/m^3 for background radon (UNSCEAR 2009, NCRP 2009).

** Effective diffusion coefficient incorporates the effect of natural convection and other mixing in water column on the diffusional transport of radon in water column toward the surface.

4.0 ESTIMATION OF THE RADON FLUX

4.1 Diffusive and Advective Radon Emission

Estimates based on Nielson and Rogers

The information in previous sections was used in the Nielson and Rogers (1986) model as implemented by SENES to estimate the radon emissions from the ponds at high surface turbulence conditions. This model considers both diffusion and turbulence at the air-surface interface by assuming that the radon in the top 1-m layer of water is released to air instantly. Table 3 shows the results of the emission estimation for two depth scenarios. The input and output values, as well as the equations used for calculations, are provided in Appendix A.

Table 3 summarizes the results (Appendix A) of the emission estimates for two water cover depth scenarios. For comparison purposes, the same parameters shown in Table 2 were used to estimate the radon emissions using the on-line program that is available from the World Information Services on Energy (WISE) website, also attributed to the Nielson and Rogers (1986) model. It is not known if or to what degree the on-line program has been independently verified; however, the program produced the same results as generated by the model and scenarios used in this assessment (see http://www.wise-uranium.org/ctb.html). [Appendix B provides details on the parameter values used in the calculations with the on-line model.] It should be noted that unlike the edges of tailings impoundments, the precipitates in the evaporation ponds would be covered by water (i.e., submerged) at all times.

Table 3: The Results of the Emission Estimation for Two Depth Scenarios

Depth Scenario	Radon Flux (pCi m^{-2} s^{-1})	Total Radon Emission (Phase I) (pCi/s)	Total Radon Emission (Phase II) (pCi/s)
Water cover less than 1 m deep	0.91	1.52×10^5	3.04×10^5
Water cover 3 m deep	1.27	2.12×10^5	4.24×10^5

The results of calculations indicate that, for the current situation, as the depth of water increases, the radon emissions increase. According to the Neilson and Rogers model (1986), this is because the radium concentration in the water column becomes a major contributor of the total radon flux from the ponds.

As mentioned before, the results shown in Table 3 (based on the Neilson and Rogers model) represent highly turbulent surface conditions on the ponds. This will provide a conservative estimate of the emissions as in the majority of time, the surface of the ponds will be relatively calm and free of significant waves.

Effect of Wind speed

As shown on Figure 2 in Section 2.2, the mass transfer coefficient, K, is small and only weakly dependent on wind speed, u, when u is below 3 m/s. K is much larger and more sensitive to u at higher wind speeds.

Considering that the transfer rate at the air-water interface has a linear relationship with the mass transfer coefficient, the emission rate is expected to be much less at average wind speeds (6.2 miles/hour or 2.8 m/s) compared with the emission rates at the maximum average wind speed (18.1 miles/hour or 8.1 m/s) where waves of less than 1 ft (0.3 m) are expected to form at the surface of the ponds. Table 4 shows the effect of various wind speeds on radon emissions from the ponds. [The mass transfer coefficients (K) in Table 4 were estimated from Figure 2.] Appendix A provides additional details of the radon flux calculations.

Table 4: The Effect of Wind Speed on the Radon Flux*

Wind Speed, m/s	**Mass Transfer Coefficient (K) (cm/s)**	**Radon Flux (pCi m^{-2} s^{-1})**	
		Water Depth: 3 m	**Water Depth: 1 m**
8.1	0.0055	1.27	0.91
6.0	0.003	0.69	0.50
4.0	0.002	0.46	0.33
2.8	0.0014	0.32	0.23
2.4	0.001	0.23	0.17

*Sample calculation (3 m depth):

Maximum flux at maximum wind speed (8.1 m/s) = 1.27 pCi m^{-2} s^{-1} (at 3 m depth from Table 3)
Mass transfer coefficient at maximum wind speed = 0.0055 cm/s (Figure 2)
Mass transfer coefficient at 2.8 m/s wind speed = 0.0014 cm/s (estimated from Figure 2)
Radon flux at 2.8 m/s wind speed = 1.27 pCi m^{-2} s^{-1} * 0.0014 / 0.0055 = 0.32 pCi m^{-2} s^{-1} (assuming linearity)

4.2 Evaporative Radon Emission

Radon produced in the water column could be released to ambient air via evaporation. It is expected that the entire radon content dissolved in the portion of the water evaporated is released. As a thin film at the interface is being evaporated all the time, the concentration of radon in the water right at the interface can be estimated. This was done using the Henry's Law constant for radon and the concentration of radon in ambient air provided in Table 2. The concentration of radon at the interface was estimated at 1.1 pCi/L as shown below:

Ambient air radon concentration = 270 pCi/m^3 (Table 2)
Henry's constant for radon = 4.08 (Table 2)
Water activity concentration = Henry's constant * Air activity concentration =
4.08 * 270 pCi/m^3 = 1102 pCi/m^3 = 1.1 pCi/L

The evaporation rate of water was estimated using the average flow of raffinate to the ponds (117 gpm or 7.4 L/s) over the total surface area of the ponds ($1.67x10^5$ m^2) which is $4.4x10^{-5}$ L m^{-2} s^{-1}:

Evaporation rate = 7.4 L/s / ($1.67x10^5$ m^2) = $4.4x10^{-5}$ L m^{-2} s^{-1}.

The radon release was estimated as follows:

Radon release = Interface water concentration * Evaporation rate

= 1.1 pCi/L * $4.4x10^{-5}$ L/m^2/s = $4.9x10^{-5}$ pCi m^{-2} s^{-1}

This value is extremely insignificant compared to the diffusional release of radon.

4.3 Radon Emission from the sprinklers.

Rost (1981) demonstrated the ability of spray aeration to remove radon from well water at private homes in Maine. One-stage aeration system achieved 75.7% radon removal efficiency. It was assumed that the rate of removal of radon from sprinkler systems is similar to the removal rate of radon from spray aeration system used by Rost (1981).

The radium concentration in raffinate, the raffinate average flow rate, and the removal efficiency of sprinkler were used to estimate the radon release from the sprinkler systems. It was assumed that the sprayed water is in contact with air for 10 seconds and sprinklers are one-stage systems with the removal efficiency of 75%.

Evaporation rate = 117 gpm = 7.4 L/s
Radium concentration in water = 600 pCi/L (Table 2)
Total radium loading in 10 seconds = 7.4 L/s * 10 s * 600 pCi/L = 44,400 pCi
Radon production = Total radium * Radon decay constant =
44,400 pCi * $2.1x10^{-6}$ s^{-1} = 0.0.093 pCi/s
Radon release (75% efficiency) = 0.093 pCi/s * 0.75 = 0.07 pCi/s

The calculations indicate that the total radon emission is approximately 0.07 pCi/s for the sprinkler system. This value is extremely insignificant compared to the estimated value based on the Neilson and Rogers model (diffusion and wave action from the evaporation ponds).

5.0 ESTIMATION OF THE AIR CONCENTRATION

The method used to calculate the concentration of radon in the atmosphere over the evaporation ponds was based on the box model developed by Schiager (1974) to calculate the atmospheric radon concentrations near the uranium mill tailings piles. Assuming that 5 ponds were placed end to end, the following equation was used for calculations (Schiager 1974):

$C_{Rn} = \Phi X/u\sigma_z$

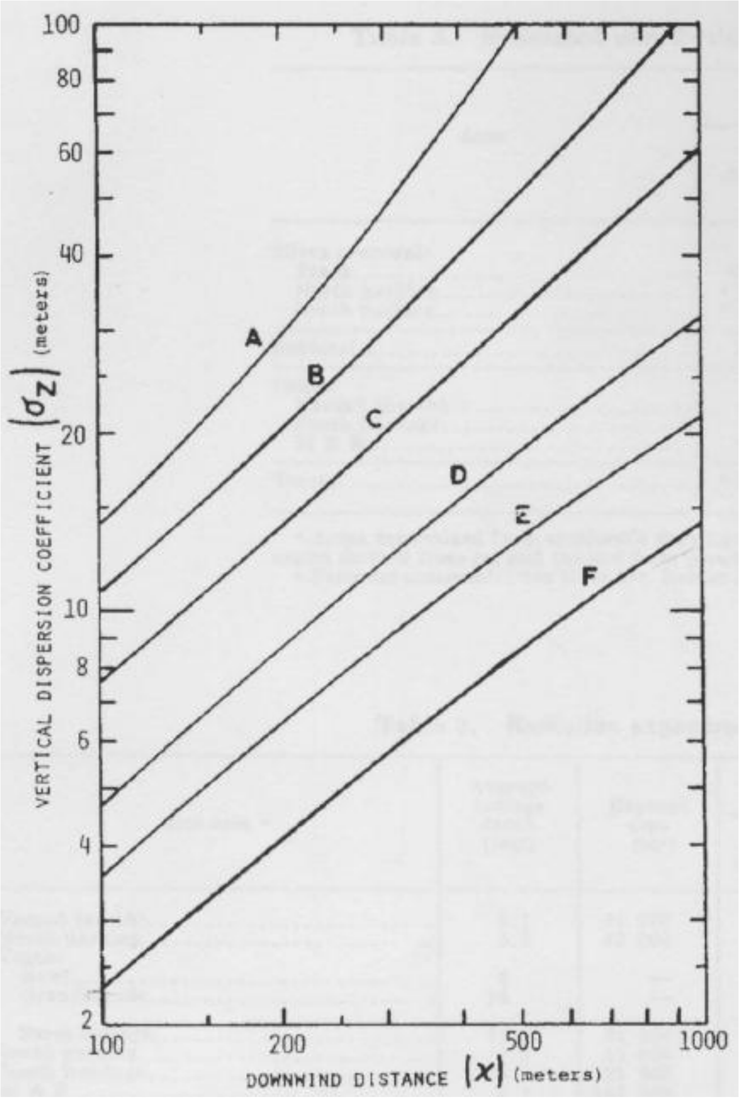
where:

C_{Rn} = radon concentration in atmosphere (pCi/m^3)
Φ = radon emission flux (0.32 pCi m^{-2} s^{-1} for the average wind speed of 2.8 m/s)
X = maximum length of the evaporation ponds in the direction of the wind (5 ponds * 182 = 910 m)
u = average wind speed (2.8 m/s)
σ_z = vertical dispersion coefficient (14 m from Figure 3 based on a conservative assumption of F stability class, i.e. the least atmospheric dispersion)

The resulting radon concentration is:

$$C_{Rn} = 0.32 \text{ pCi m}^{-2} \text{ s}^{-1} * 910 \text{ m} / (2.8 \text{ m/s} * 14 \text{ m}) = 7.4 \text{ pCi/m}^3$$

Figure 3: Vertical Dispersion Coefficient by Atmospheric Stability Class (Schiager 1974)



The above estimate of 7.4 pCi/m^3 is the incremental (above background) air concentration due to the emission of radon from the evaporation ponds. This value is very small (3%) compared to the assumed background atmospheric radon concentration of 270 pCi/m^3 (Table 2).

6.0 DISCUSSION AND CONCLUSION

Conservative estimates of radon flux indicates that the emissions are low and less than or similar to the pre-operational average background radon flux of 1.7 pCi m^{-2} s^{-1} observed at various locations within the proposed tailings areas on the site. The estimated radon flux levels from the evaporation ponds is also a small fraction (less than 10%) of the 20 pCi m^{-2} s^{-1} limit for pre-1989 uranium tailings that has been assumed here for context. This conservative estimate was based on the Nielson and Rogers model. The model assumes that the emission rates are enhanced by the turbulence at the top layer of the water column where all the radon in the top one-meter of water is assumed to be released to air instantaneously. For comparison purposes, the same parameters were used to estimate the radon emissions using an on-line program that is available on the World Information Services on Energy (WISE) website. The on-line model, which is attributed to the Rogers and Nielson model, produced identical results.

The results of this assessment also indicated that the radon emissions associated with the evaporation of the raffinate solution and the emissions due to the operation of sprinkler system are extremely low and insignificant compared to the radon flux from the ponds due to diffusional and turbulence processes.

Finally, the calculations indicated that the incremental air concentration due to the emission of radon from the evaporation ponds is very small (on the order of 3%) relative to the assumed background radon concentration.

7.0 REFERENCES

Baker, K.R. and A.D. Cox 2010. *Radon Flux from Evaporation Ponds*. Presented at National Mining Association (NMA) / Nuclear Regulatory Commission (NRC) Uranium Recovery Workshop 2010, Denver, CO, May 26-27.

Chambers, D.B. 2009. *Radon Emissions from Tailings Ponds.* Presented at National Mining Association (NMA) / Nuclear Regulatory Commission (NRC) Uranium Recovery Workshop 2009, Denver, CO, July 2.

Drago, J. A. 1998. *Critical Assessment of Radon Removal Systems for Drinking Water Supplied, Chapter 3, Table 3.2.* American Water Work Association.

Energy Fuels Resources Corporation (2010). *Raffinate Characterization, Piñon Ridge Mill, Montrose County, Colorado*. Prepared for U.S. Environmental Protection Agency, Region 8, August.

Environmental Protection Agency (EPA) 1989. *Subpart W – National Emission Standards for Radon Emissions from Operating Mill Tailings.* 40 CFR Part 61, Federal Register, 15 December.

Environmental Protection Agency (EPA) 1986. *Final Rule for Radon-222 Emissions from Licensed Uranium Mill Tailings – Background Information Document.* EPA 520/1-86-009, August.

Environmental Restoration Group, Inc (ERG) 2009. *Baseline Investigation Radiological Report*. Rev. 1. Submitted to Radiation Management Unit, Colorado Department of Public Health and Environment, 5 October.

Golder Associates Inc. 2008. *Evaporation Pond Design Report Piñon Ridge Project Montrose County, Colorado.* Report prepared for Energy Fuels Resources Corporation, Lakewood Colorado.

Kanwisher, J. 1963. *On the Exchange of Gases between the Atmosphere and the Sea*. Deep-Sea Res. 10, 195, 1963.

National Council on Radiation Protection and Measurements (NCRP) 2009. *Ionizing Radiation Exposure of the Population of the United States*. NCRP Report No. 160.

Nielson, K.K. and V.C. Rogers 1986. *Surface Water Hydrology Considerations in Predicting Radon Releases from Water-Covered Areas of Uranium Tailings Ponds.* Proc. Eighth Annual Symposium on Geotechnical & Hydrological Aspects of Waste Management, Geotechnical Engineering Program, Colorado State University & A.A. Balkema, Fort Collins, CO, USA, February 507, PP:215-222.

Nuclear Regulatory Commission (NRC) 1989. *Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers.* Regulatory Guide 3.64, June.

Ocampo-Torres, F. J., and M. A. Donelan, N. Merzi, and F. Jia 1994. *Laboratory Measurements of Mass Transfer of Carbon Dioxide and Water Vapour for Smooth and Rough Flow Conditions.* Tellus 46B, A Journal Published by the International Meteorological Institute in Stockholm.

Rogers, V.C., K.K. Nielson and D.R. Kalkwarf 1984. *Radon Attenuation Handbook for Uranium Mill Tailings Cover Design.* Prepared for the U.S. Nuclear Regulatory Commission, NUREG/CR-3533. April.

Saylora, J. R., and R. A. Handler 1997. *Gas Transport Across an Air/Water Interface Populated with Capillary Waves*. Phys. Fluids 9 (9).

Schiager, K. J., 1974. *Analysis of Radiation Exposures on or near Uranium Mill Tailings Piles*. Radiation Data and Reports 15(7): 411-425. Publisher: U. S. Environmental Protection Agency, Office of Radiation Programs, Washington D.C.

Shwarzenbach, R.P., P.M. Gshwend and D.M. Imboden 2002. Environmental Organic Chemistry, Second edition, Wiley-Interscience. Published by John Wiley & Sons, Inc., Hoboken, NJ.

United Nations Scientific Committee on the Effects of Atomic Radiation 2009. *Effects of Ionizing Radiation.* UNSCEAR 2006 Report to the General Assembly with Scientific Annexes. Volume II, Annexes C, D and E. Annex E: Sources-to-Effects Assessment for Radon in Homes and Workplaces.

APPENDIX A: INPUT PARAMETERS FOR NIELSON AND ROGERS MODEL

The input parameters for Nielson and Rogers (1986) model for a 3 m deep water column:

Ra	tailings Ra content	7.9	pCi/g
Raw	Raffinate Ra content	0.6	pCi/cm3
dens	bulk density of tailings	2	g/cm3
E	Rn emanation coeff	0.35	-
lambda	Rn decay constant	2.1E-06	1/s
D	diff. coeff. in tailings	1.2E-05	cm2/s
Fs	fraction of pond with < 1 m depth	0	-
Dtr	eff. stagnant water transport coeff	0.003	cm2/s
Xp	avg. pond depth for areas > 1 m depth	250	cm

The output from Nielson and Rogers (1986) model for 3 m deep water column:

At	attenuation factor for deep water	1.89E-02	
J	Radon flux	1.27E+00	pCi m^{-2} s^{-1}

The input parameters for Nielson and Rogers (1986) model for a 1 m deep water column:

Ra	tailings Ra content	7.9	pCi/g
Raw	Raffinate Ra content	0.6	pCi/cm3
dens	bulk density of tailings	2	g/cm3
E	Rn emanation coeff	0.35	-
lambda	Rn decay constant	2.1E-06	1/s
D	diff. coeff. in tailings	1.2E-05	cm2/s
Fs	fraction of pond with < 1 m depth	1	-
Dtr	eff. stagnant water transport coeff	0.003	cm2/s
Xp	avg. pond depth for areas > 1 m depth	Not Applicable	cm

The output from the Nielson and Rogers (1986) model for a 1 m deep water column:

At	attenuation factor for deep water	1.89E-02	
J	Radon flux	9.08E-01	pCi m^{-2} s^{-1}

The following equation was used to calculate the attenuation factor (A_t):

A_t = exp [-sqrt (λ/D_{tr}) * (X_p -100)]   (Nielson and Rogers 1986)

where:

λ = radon decay constant ($2.1\text{x}10^{-6}$ s^{-1})
D_{tr} = effective diffusion coefficient in water column (cm^2/s)
X_p = average pond depth for areas greater than 1 meter deep (cm)

The following equation was used to calculate the radon flux (J) from the evaporation ponds:

$J = 10^4\ R\rho E * \text{sqrt}(\lambda D)[f_S + (1-f_S)*A_t] + 10^6\ R_w\lambda S_d(1-0.5f_S)$ (Nielson and Rogers 1986)

where:

J = radon flux from the exposed pond surface (pCi m^{-2} s^{-1})
R = solids radium content (pCi/g)
R_w = water radium content (pCi/cm^3)
ρ = bulk solid density (g/cm^3)
E = radon emanation coefficient for solids (dimensionless)
D = radon diffusion coefficient in pore water (cm^2/s)
f_S = fraction of pond area with less than 1 m deep
S_d = depth of surface layer from which all radon is assumed to be released = 1 m

The 10^4 factor converts the flux units from pCi cm^{-2} s^{-1} to pCi m^{-2} s^{-1}. The 10^6 factor converts the water radium content (R_w) from units of pCi/cm^3 to pCi/m^3. For consistency of units, the S_d parameter, not explicitly shown in Nielson and Rogers (1986), was included here.

APPENDIX B: PARAMETER VALUES USED IN ON-LINE MODEL

Input Parameters: 3 m deep water column

Parameter	Parameter Values Used in On-Line Model	Units
Ra-226 Activity Concentration in tailings	7.9	pCi/g
Ra-226 Activity Ratio in slimes vs. sand	4 (default value)	-
Rn-222 Emanation Fraction in slimes	0.35	-
Rn-222 Emanation Fraction in sand	0.15 (default value)	
Fraction Passing #200 Mesh (75 µm)	0.4 (default value)	-
Fraction of pond area with less than 1 m depth	0	
Average pond depth for areas greater than 1 m deep:	2.5	m
Ra-226 Activity Concentration in ponding water	600	pCi/L
Ratio of radium in solution to radium in tailings solids	-	g/cm^3
Effective stagnant water transport coefficient	3E-7	m^2/s

Tailings Zone	Submerged	Saturated	Unsaturated
Surface Area $[m^2]$	1.0E5	-	-
Bulk Density $[g/cm^3]$	2.0	-	-
Porosity	0.41(default value)	-	-
Moisture Contents [dry wt %]	(Saturation)	-	-
Fraction Passing #200 Mesh (75 µm)	0.5 (default value)	-	-
Rn-222 Eff. Diffusion Coefficient $[m^2/s]$	1.2E-9	-	-

Output: Radon flux = 1.27 pCi $m^{-2}s^{-1}$

Input parameters: 1m deep water column

Parameter	Parameter Values Used in On-Line Model	Units
Ra-226 Activity Concentration in tailings	7.9	pCi/g
Ra-226 Activity Ratio in slimes vs. sand	4 (default value)	-
Rn-222 Emanation Fraction in slimes	0.35	-
Rn-222 Emanation Fraction in sand	0.15 (default value)	
Fraction Passing #200 Mesh (75 µm)	0.4 (default value)	-
Fraction of pond area with less than 1 m depth	1	
Average pond depth for areas greater than 1 m deep:	Not applicable	m
Ra-226 Activity Concentration in ponding water	600	pCi/L
Ratio of radium in solution to radium in tailings solids	-	g/cm^3
Effective stagnant water transport coefficient	3E-7	m^2/s

Tailings Zone	Submerged	Saturated	Unsaturated
Surface Area [m^2]	1.0E5	-	-
Bulk Density [g/cm^3]	2.0	-	-
Porosity	0.41(default value)	-	-
Moisture Contents [dry wt %]	(Saturation)	-	-
Fraction Passing #200 Mesh (75 µm)	0.5 (default value)	-	-
Rn-222 Eff. Diffusion Coefficient [m^2/s]	1.2E-9	-	-

Output: Radon flux = 0.91 pCi m^{-2} s^{-1}

REPORT

URANIUM MILL TAILINGS RADON FLUX CALCULATIONS

PIÑON RIDGE PROJECT
MONTROSE COUNTY, COLORADO

Submitted To: Energy Fuels Resources Corporation
44 Union Boulevard, Suite 600
Lakewood, Colorado 80228

Submitted By: Golder Associates Inc.
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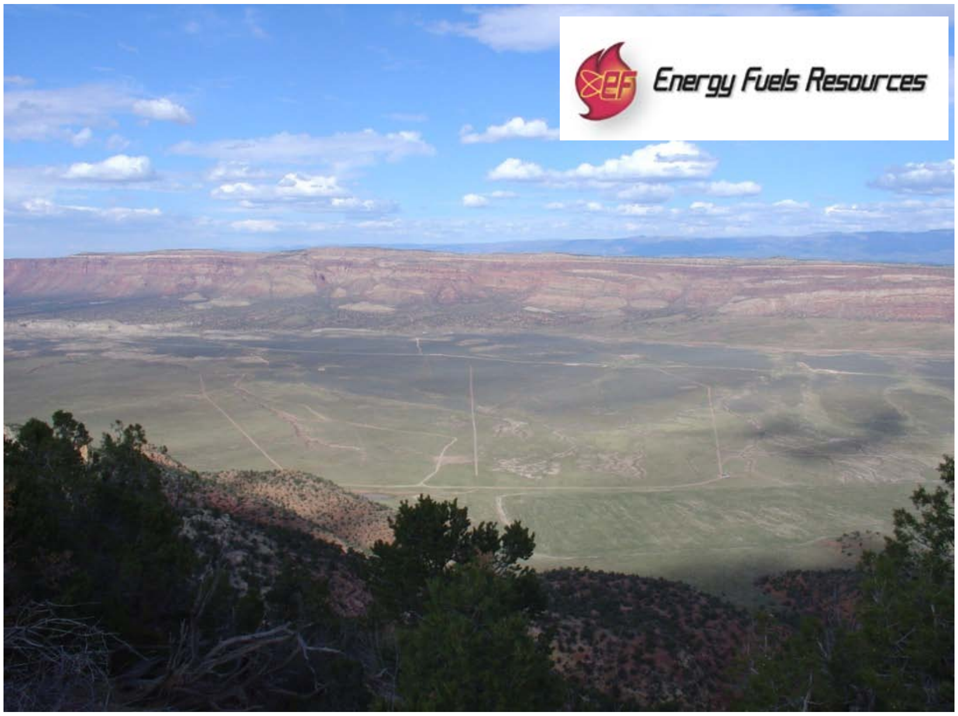
Lakewood, Colorado 80228



August 2010 **Project No. 073-81694.23**

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EXECUTIVE SUMMARY

Energy Fuels Resources Corporation (EFRC) proposes to license, construct, and operate a conventional acid leach uranium and vanadium mill at the Piñon Ridge Property in western Montrose County, Colorado. The Piñon Ridge Mill includes an administration building, a 17-acre mill, a 30.5-acre tailings cell with phased expansion capacity to 91.5 acres, a 40-acre evaporation pond area with an expansion capacity to 80 acres, an approximately 6-acre ore storage pad, and access roads. The mill is designed to process ore containing uranium and vanadium produced from mines located within a reasonable haul distance on the Colorado Plateau.

Golder Associates Inc. (Golder) was commissioned by EFRC to evaluate the operations of the uranium mill tailings storage facility at the Piñon Ridge Mill in terms of the 20 pCi/m^2s radon (Rn-222) flux standard that applies to uranium tailings facilities constructed prior to 1989. Although this flux standard does not apply to new facilities such as the Piñon Ridge Mill, it did play an inherent role in establishing the tailings disposal practices and maximum areas specified for new facilities under the U.S. Environmental Protection Agency (EPA) regulations found in 40 CFR 61 Subpart W, "National Emission Standards for Radon Emissions from Operating Mill Tailings" (EPA, 1998). EFRC had expressed a desire to maintain radon flux levels from the tailings to "As Low As Reasonably Achievable" (ALARA) levels, as required by State of Colorado and U.S. Nuclear Regulatory Commission (NRC) regulations. To achieve this goal, EFRC requested that Golder evaluate radon flux levels under a range of potential operating conditions.

The radon flux calculations presented in this report were conducted using the WISE Uranium Mill Tailings Radon Flux Calculator, as updated on November 23, 2009 (WISE, 2009). The results of these calculations show that the radon flux levels of the proposed uranium mill tailings facility at the Piñon Ridge Mill site will be less than 20 pCi/m^2s under normal operating procedures whereby the tailings are maintained in a saturated state. Golder also assessed various unsaturated scenarios that could occur in the event of temporary equipment failure or during pre-closure operations when the water cover will be eliminated, and found that the radon flux remained less than 20 pCi/m^2s under drying conditions with up to 20 percent of the tailings surface being unsaturated.

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1.0 INTRODUCTION

This report was prepared by Golder Associates Inc. (Golder) to assist Energy Fuels Resources Corporation (EFRC) in developing its operating plan for the Piñon Ridge tailings cells and evaporation ponds (EFRC, 2010). The average radon (Rn-222) flux levels for its proposed tailings cells were evaluated under normal operating conditions and under drying conditions where a portion of the tailings may lose saturation. The resulting flux levels were compared to the 20 pCi/m²s flux limit adopted for the much larger pre-1989 tailings facilities in 40 CFR 61 Subpart W, "National Emission Standards for Radon Emissions from Operating Mill Tailings" (EPA, 1998). This standard does not apply to the Piñon Ridge Mill per se, as the mill tailings facility meets the standard found in 40 CFR Subpart W 61.252 (b) (1) for facilities constructed after December 15, 1989 for phased disposal. This standard limits phased disposal to no more than two tailings impoundments in operation at any one time and limits the maximum size of the impoundments to 40 acres. However, EFRC plans to reduce radon flux levels to "As Low As Reasonably Achievable" (ALARA) levels, as defined in the Colorado Department of Public Health and Environment (CDPHE) and U.S. Nuclear Regulatory Commission (NRC) regulations by implementing tailings operating practices designed to limit radon flux. The 20 pCi/m²s flux level represents a convenient yardstick for evaluating tailings operating practices, as this flux rate was used by the U.S. Environmental Protection Agency (EPA) in its previous Subpart W rulemaking in assessing the associated health risks of both pre- and post-1989 tailings facilities.

The radon flux calculations in this report were conducted using the WISE Uranium Mill Tailings Radon Flux Calculator, as updated on November 23, 2009 (WISE, 2009). The results of these calculations show that the proposed uranium mill tailings facilities at the Piñon Ridge Mill site will produce substantially less than 20 pCi/m²s radon flux under normal operating conditions and procedures whereby the tailings are maintained in a saturated state. This report also assessed various unsaturated scenarios that could occur in the event of temporary equipment failure or during standby or pre-closure periods when water cover would be reduced and found that the 20 pCi/m²s flux level was not exceeded under drying conditions with up to 20 percent of the tailings surface being unsaturated.

2.0 SITE DESCRIPTION

EFRC proposes to license, construct, and operate a conventional acid leach uranium and vanadium mill at the Piñon Ridge Property in western Montrose County, Colorado. The property covers approximately 880 acres in the southeastern portion of Paradox Valley. The proposed Piñon Ridge Mill is located at 16910 Highway 90, approximately 7 miles east of Bedrock, Colorado, and 12 miles west of Naturita, Colorado. Figure 1 shows the location of the proposed project site.

The Piñon Ridge Mill is designed to process ore containing uranium and vanadium produced from mines located within a reasonable haul distance on the Colorado Plateau. The facility includes an administration building, a 17-acre mill, a 30.5-acre tailings cell with phased expansion capacity to 91.5 acres, a 40-acre evaporation pond area with an expansion capacity to 80 acres, an approximately 6-acre ore storage pad, and access roads. The phased expansion plan is designed to meet the standard found in 40 CFR Subpart W 61.252 (b) (1), as only two 30.5-acre tailings cells would be in operation at any one time. This would only occur for a relatively short transition period when the first cell is reaching its full capacity and a second cell is being put into service. The proposed uranium mill and tailings facilities at full build-out are shown in Figure 2.

The mill will initially process 500 tons of ore per day (tpd), but is designed to accommodate future expansion of production capacity to 1,000 tpd. The projected operating life of the facility is 40 years, operating 24 hours per day, 350 days per year at 500 tpd.

The ore to be processed at the mill contains elevated concentrations of natural uranium and its decay products. The average uranium content in the blended ore is 0.23 percent U_3O_8.

3.0 MILL TAILINGS RADON FLUX EVALUATION

3.1 Description of the Uranium Mill Tailings Radon Flux Calculator

The Uranium Mill Tailings Radon Flux Calculator evaluates the radon flux from a bare and/or water-covered uranium mill tailings storage area. The calculator is based on the modeling work of Nielson (Nielson and Rogers, 1986).

The model performs one-dimensional, steady-state radon diffusion calculations for various areas of the tailings deposit. For the submerged area, the model calculates the radon transport from the tailings through the impounded water to the top of the surface, and radon released from radium dissolved in the impounded water that covers the submerged tailings. It assumes that all radon reaching the top 1-meter (3.28 foot) layer of the water is released into the air, as well as all radon produced from dissolved radium in this top layer. The following areas are calculated in the model:

- Submerged Tailings Under Impounded Water. This area is primarily comprised of the smaller particle size material in the tailings ("slimes") which are preferentially accumulated in the center of the tailings storage facility as tailings are deposited. The submerged tailings consider two separate areas in the calculation:
    - Submerged area at a depth of 1 meter or less; and
    - Submerged area at greater than 1 meter.
- Saturated Beach. This area is located on the perimeter of the tailings storage facility and represents a mixture of particle size material ("slimes and sands") which deposits on the perimeter beaches. This area, while not covered with tailings water, will be wetted with recycled raffinate solution or tailings water to keep the tailings fully saturated. Keeping the tailings saturated in this manner minimizes the radon flux from the beach areas of the tailings cell.
- Unsaturated Zone. While it is the intent of EFRC to keep all beaches fully saturated, there may be some interim period where small areas of the tailings surface may become temporarily unsaturated due to mechanical failure of the water recycle system, or due to reduction in water cover during standby or pre-closure periods. Hence, calculations were performed to evaluate the maximum percentage of unsaturated tailings exposure that would still result in a radon flux level below 20 pCi/m²s.

The various areas used for the radon flux calculations are shown in Figure 3.

3.2 Input Data

The physical and radiological properties of the uranium mill tailings that were input into the model are defined below. While the model allows for default parameters to be used, the most meaningful results for actual site conditions are obtained if site-specific data is used. Since the tailings facility has not been built and no actual tailings have been processed, data from other representative uranium mill sites has been used wherever possible together with sampling data for typical Salt Wash ores that will comprise the proposed feed to the Piñon Mill. The effective radon diffusion coefficients were obtained using methods developed by Nielson and Rogers (1986) and Rogers and Nielson (1991).

3.2.1 General Tailings Properties

This section provides discussion of the general tailings properties used in the radon flux modeling and the specific values used for the Piñon Ridge project.

3.2.1.1 Ra-226 Activity Concentration in the Uranium Tailings [pCi/g]

This input parameter is the overall activity concentration of radium-226 in the bulk tailings material. The value for the equilibrium concentration of radium-226 was calculated based on the average grade of the ore that will be processed. The average uranium content in the blended ore is expected to be 0.23 percent U_3O_8.

The activity of U-238 in the Piñon Ridge uranium tailings was evaluated as follows:

EQUATION 1

$$Activity = \left[\frac{0.0023(g_{U_3O_8})}{(g_{ore})}\right] \cdot \left[\frac{0.85(g_{U-238})}{(g_{U_3O_8})}\right] \cdot \left[\frac{330{,}000(pCi_{U-238})}{(g_{U-238})}\right] = 647\frac{(pCi_{U-238})}{(g_{ore})}$$

Assuming secular equilibrium in the ore between uranium-238 and radium-226, and that all radium goes into the tailings, the activity of radium-226 will be 647pCi/g.

3.2.1.2 Ra-226 Activity Ratio in Slimes vs. Sand

This input parameter estimates the ratio of radium-226 activity concentrations in the slimes fraction vs. the sand fraction of the tailings material. The radium-226 activity concentrations typically increase with decreasing particle size and the slimes will contain a higher concentration of radium-226. A ratio of 4 has been used in the calculations, which corresponds to the value used by Nielson and Rogers (1986) in the development of the model.

3.2.1.3 Rn-222 Emanation Fraction in Slimes

This input parameter is the fraction of the total amount of radon-222 produced by radium decay that escapes from the solid fraction of the slimes tailings particles and gets into the pores of the material. The value depends on the tailings material and the moisture content. It varies over a range of 0.1 to 0.4 with typical values in the range of 0.2 to 0.3. Nielson and Rogers (1986) uses a value of 0.22 for the tailings slimes, and this value was used in the calculation for the Piñon Ridge project.

3.2.1.4 Rn-222 Emanation Fraction in Sand

This input parameter is the fraction of the total amount of radon-222 produced by radium decay that escapes from the solid fraction of the sand tailings particles and gets into the pores of the material. The value depends on the tailings material and the moisture content. This parameter typically varies over a range of 0.1 to 0.4. Nielson and Rogers (1986) uses a value of 0.15 for the tailings sands, and this value was used in the calculation for the Piñon Ridge project.

3.2.1.5 Fraction Passing #200 Mesh (75 µm)

This input parameter is the fraction by weight of the overall bulk tailings material passing a No. 200 mesh, corresponding to a particle diameter of 75 µm or less. Since a 75-µm particle diameter typically marks the sand/silt dividing line, this figure denominates the fraction that is not sand, or the fraction of combined silt and clay contents ("slimes").

The value used for this parameter is taken from data as reported in Golder (2008a). The fraction for the bulk tailings material passing the #200 mesh is 0.379 (i.e., 37.9 percent). This gradation is based on data obtained from processing of Salt Wash ores at the White Mesa Mill in Blanding, Utah.

3.2.1.6 Fraction of Pond Area with less than 1 m depth

This input parameter is the fraction of the pond area that has less than 1 meter of water cover. This fraction was determined graphically for various percentages of total water cover based on the projected slope of the underlying coarse and fine tailings. The tailings with less than 1 meter of water cover contribute to the radon flux of the facility.

3.2.1.7 Average Pond Depth for Areas greater than 1 m deep

This input parameter is the depth of the pond area that has greater than 1 meter of water cover. This depth was determined graphically for various percentages of total water cover based on the projected slope of the underlying coarse and fine tailings. The tailings with greater than 1 meter of water cover do not contribute to the radon flux of the facility.

3.2.1.8 Ra-226 Activity Concentration in Impounded Water [pCi/L]

This input parameter is the activity concentration of dissolved radium-226 in the impounded water covering the deposited tailings material. As previously discussed, the uranium content of the projected ore to be processed at the Piñon Ridge Mill has been determined to be 0.23 percent U_3O_8 , which leads to a radium activity of 647 pCi/g (refer to Section 3.2.1.1). The specific Ra-226 content of the impounded water in equilibrium with the tailings material was estimated using the values previously established for a model mill in the U.S. Nuclear Regulatory Commission (NRC) NUREG-0706 “Final Generic EIS on Uranium Milling” (NRC, 1980; Table 5.3). This document lists an activity level of 250 pCi/L Ra-226 for tailings solution at the model mill based on an activity level of 280 pCi/g Ra-226 in the ore. Scaling up to the expected higher uranium and radium activity levels in the Piñon Ridge ore of 647 pCi/g, the calculated radium activity level of the tailings solution in equilibrium with the tailings is 581 pCi/L.

3.2.1.9 Effective Stagnant Water Transport Coefficient [m^2/s]

This parameter describes radon transport in water. The established value for this parameter is $3x10^{-7}$ m^2/s, as determined by Nielson and Rogers (1986).

3.2.2 Zone-Specific Tailings Properties

The following parameters describe the specific properties of each tailings area: (i) the area submerged under impounded water; (ii) the saturated beach area; and (iii) the unsaturated area.

3.2.2.1 Surface Area [m²]

This parameter is the surface area for a given type of tailings. A calculation was made for each of the three areas in the tailings cell: the submerged area, the saturated area, and the unsaturated area. If no tailings exist in any particular area, then a value of zero (0) is entered and the area is discarded. The calculations were based on a tailings cell area of approximately 30.5 acres (120,365 m²).

3.2.2.2 Bulk Density [g/cm³]

Each area of the tailing cell will have specific bulk density properties due to the nature of the deposition of tailings in the tailings cell. As reported in the tailings settlement report (Golder, 2010), the average dry density of tailings after initial settlement with release of water to the tailings pool is expected to be 79.2 pounds per cubic foot (pcf), or 1.27 grams per cubic centimeters (g/cm^3). The submerged, saturated, and unsaturated areas in the tailings cell will each have different dry densities depending on the amount of slimes and sands in these areas.

For the submerged area, which is mostly comprised of finer particle material (“slimes”), a bulk density value of 70 pcf was used. This corresponds to the expected average density for the material that will collect in the central part of the tailings cell, which will be submerged for most of the time while the tailings cell is being filled. This corresponds to a dry bulk density of 1.12 g/cm^3. For the saturated transition area, which is comprised mostly of sandy material with some amount of slimes, an average bulk density value of 80 pcf was used. This corresponded to a dry bulk density of 1.28 g/cm^3. For the sandy beach material, a bulk density of 90 pcf was used, which corresponds to a dry bulk density of 1.44 g/cm^3.

These dry density determinations were made after reviewing the available physical parameter information for the Atlas Moab tailings area (Golder, 2005), which indicated that the tailings density ranged from 50.2 pcf to 88.6 pcf for the slimes to a range of 81 to 106 pcf for the sand materials. The Piñon Ridge Mill tailings facility is expected to achieve higher densities because dewatering will be facilitated by the barge-mounted pump-back system and the tailings cell underdrain system. It is important to note that the dry density of 70 to 90 pcf for the Piñon Ridge tailings applies only to the near-surface tailings that are contributing to the radon flux. Tailings at depth will have substantially higher densities due to consolidation. The tailings density will also increase further after placement of the soil cover during cell closure.

3.2.2.3 Porosity

The porosity (n) of the tailings material is the ratio of the pore volume (air- and water-filled) to the total volume of the tailings. This value was calculated using the following relationship:

EQUATION 2

$$n = \frac{e}{1+e}$$

where e is the void ratio. Limited data on void ratio is available for existing tailings facilities. The data from the Moab tailings area showed that the void ratio for the finer particle material (“slimes”) was 1.35 using the same criteria for densification modifications that were used for the determination of the dry bulk densities. This corresponds to a porosity of 0.57 for the slimes. This value, which was input into the model, is higher than the default value used in the model and is considerably more conservative (i.e., a higher porosity results in a higher radon flux).

For the average tailings material in the saturated area and unsaturated area of the tailings cell, a void ratio of 0.65 was used based on data from the Moab tailings area, which resulted in a porosity of 0.39. The model uses a default value of porosity of 0.4 for all areas of the tailings cell.

3.2.2.4 Moisture Content [dry wt %]

During the majority of operations, the tailings will either be submerged or fully saturated. The only area where percent moisture needs to be specified in the model is the unsaturated area. The moisture content of unsaturated tailings was assumed to be 15 percent, which is a relatively conservative estimate. By comparison, the moisture content in the unsaturated Atlas tailings ranged from approximately 21 percent to 28 percent when measured in the early 1980s (Golder, 2005).

3.2.2.5 Fraction Passing No. 200 Mesh (75 μm)

The fraction of material passing the No. 200 mesh provides an indication of the particle size of the material. Since 75 μm (the opening size of the No. 200 mesh) typically marks the dividing line between silts/clays (“slimes”) and sands, each of the zones in the tailings cell will have different characteristics for this parameter. The average amount of fines passing a No. 200 mesh in the tailings discharge has been estimated to be 0.379 (Golder, 2008a). An estimate of the distribution of these fines through the various areas of the tailings cell was made based on a material balance calculation. Assuming that the tailings cell consists of 33.3% submerged fines, 33.3% transitional sands/fines and 33.3% sandy material, the fraction passing through the No. 200 mesh would be 0.72, 0.36 and 0.05 respectively. These proportions are roughly based on the percentages of fines observed in the Atlas Tailings Impoundment of 0.95, 0.45, and 0.21 for slimes, sand/slimes, and sands, respectively (Golder, 2005). However, the Atlas Mill processed ores from several different formations (using both acid and alkaline leach processes) and the resultant tailings contained more fines than the proposed Salt Wash ores.

The model uses a default distribution for minus No. 200 mesh tailings of 0.5, 0.3 and 0.0 for the three areas. Because the model has a higher default value for fines passing a No. 200 mesh in all of the tailings (i.e., 0.40) than the Salt Wash ores (0.379), it is apparent that the model assumes a proportionately larger area of slimes. This large slime area was common at historic tailings impoundments, which were typically 100 acres or more in size and the tailings were discharged from only a few points. This resulted in greater segregation between finer and coarser particles and a larger slime area. The smaller Piñon Ridge tailings cells will have multiple discharge points around the perimeter of each cell that is expected to result in the concentration of finer tailings within the center of each cell and in the development of a larger and more uniform transitional area between the slimes and sands.

3.2.2.6 Rn-222 Effective Diffusion Coefficient [m²/s]

The effective diffusion coefficient (De) for radon-222 is defined from Fick's equation as the ratio of the diffusive flux density of radon activity across the pore area to the gradient of the radon activity concentration in the pore or interstitial space. The diffusion coefficient in porous media is a property of the diffusing species, the pore structure, the type of fluids present in the pores, the adsorption properties of the solid matrix, the fluid saturations, and temperature. The Radon Flux Calculator Model calculates this value from the correlations from Nielson and Rogers (1986) using porosity and moisture content. The model also allows the input of experimental radon diffusion coefficients or coefficients obtained from more reliable sources.

The effective radon diffusivity values in porous media can vary over a wide range of values depending on the porosity of the material and particularly on its degree of water saturation. In a fully saturated soil material, the radon diffusion coefficient may be as low as 10^{-10} m²/s and, at the upper limit, the diffusion coefficient for air of $1.1\text{x}10^{-5}$ m²/s. Typically, the effective diffusion coefficient of radon in unconsolidated soil material with varying moisture content ranges from 10^{-6} m²/s to 10^{-10} m²/s. While the radon flux model uses an existing correlation to determine the effective radon diffusion coefficient, the user is encouraged to input experimentally determined effective diffusion coefficients or other more reliable diffusion coefficient information to increase the accuracy of the calculation.

Subsequent to the correlations that were used in developing the radon flux model, Rogers and Nielson (1991) have conducted additional correlations and proposed an updated correlation for the effective diffusion coefficient, D_e, as follows:

EQUATION 3

$$D_e = D_o p_t \exp(-6 p_t R_s - 6 R_s^{14 p_t})$$

where D_o (equal to 1.1×10^{-5} m²/s) is the radon diffusivity in open air, p_t is the total soil porosity, and R_s is the water saturation in the soil (or the fraction of the pore space filled with water, also called the saturation ratio).

This correlation has also been used in the latest User's Manual for RESRAD modeling (Yu et al., 2001) and in the support documentation for the modeling impacts on radioactive soils (Yu et al., 2003).

Calculations to determine the effective radon diffusion coefficients were made using this updated correlation. For example, the calculation of D_e for the case of saturated tailings (i.e., $R_s = 1$) having a total porosity (p_t) of 0.39 is as follows:

EQUATION 4

$$D_e = (1.1x10^{-5}\ m^2/s)\exp((-6)\cdot(0.39)\cdot(1)-(6)\cdot(1)^{(14\cdot 0.39)}) = 1.03x10^{-9}\ m^2/s$$

4.0 RADON FLUX MODELING RESULTS

4.1 Mill Tailings Operational Scenarios

Details of the design and operation of the proposed 30.5-acre tailings facility are given in Golder (2008b). The evaluation of radon flux from various operational scenarios from initial filling of the tailings cell to full capacity has been calculated for the following cases:

- Case 1: Initial Fill - 100% water cover;
- Case 2: Partial Fill - 80% water cover;
- Case 3: Partial Fill - 50% water cover;
- Case 4: Partial Fill - 20% water cover; and
- Case 5: Final Fill - 0% water cover.

Typically, the tailings cell will operate with 20 to 80 percent water cover with the smaller water cover occurring during the summer evaporation season and the larger water cover occurring in the winter. One hundred percent water cover would normally occur only during the initial filling of the cell when the area of tailings deposition is much smaller, or after a very large precipitation event. Zero percent water cover would normally occur only during the pre-closure period when the tailings solution is removed to achieve final deposition grades and allow for the start of closure activities (EFRC, 2010).

For each of the scenarios, it is assumed that the tailings will be deposited uniformly on the tailings beaches around the tailings cell perimeter, and that all of the surface area of the tailings cell will contain tailings. This represents a point in the operation of the tailings facility when the cell is nearing full capacity.

The proposed operating procedures for the filling and maintenance of the tailings facility dictates that the tailings will be kept saturated by applying tailings or raffinate solutions on the deposited tailings material. The raffinate is the barren process solution that is pumped to the evaporation ponds for disposal. Since water saturation will aid in the retardation of radon release, the normal mode of operation will be to keep the tailings wet at all times. The tailings facility will be considered to be in an operational mode from initial filling through the pre-closure steps described in the “Operating Plan, Tailings Cells and Evaporation Ponds” (EFRC, 2010). Once full, the tailings cell will be considered in closure mode and a radon and evapotranspiration cover will be placed over the tailings to permanently suppress radon flux in accordance with plans approved by the Radiation Control Program of the Colorado Department of Public Health and Environment (CDPHE).

Although EFRC plans to continuously keep the beach areas on the perimeter saturated during operations, there may be some interim period where a limited amount of the tailings surface may temporarily become unsaturated due to mechanical failure of the water recycle system, other unforeseen circumstances, or during the transition from operational to closure mode. While it is not the intent of EFRC to allow areas of unsaturated tailings to be exposed for any significant length of time, a series of model runs were performed which evaluated how much unsaturated tailings material could be allowed on an interim basis while still staying below 20 pCi/m²s of radon flux.

4.2 Radon Flux Model Calculation Results

The radon model was run for the various water cover scenarios outlined in Section 4.1. The results of these calculations are presented in Table 1 and Figure 4. The results indicate that the radon flux will be below 20 pCi/m²s for all scenarios. The radon flux generated for the case with 100 percent water cover is primarily attributable to the area with less than 1 meter of water cover. The model input parameters and data output are provided in Appendix A.

TABLE 1

RESULTS OF RADON FLUX MODEL

Case	Water Cover (%)	Radon Flux (pCi/m²s)
1	100	2.62
2	80	3.27
3	50	5.05
4	20	6.79
5	0	7.44

Modeling of unsaturated tailings was also performed to determine how much unsaturated material could be exposed during operations should the solution application system be temporarily shut down for repairs or other reasons. These results are shown in Table 2 for the worst case of zero percent water cover. Other percentages of water cover of course would show allowable unsaturated tailings areas in excess of the values in Table 2. The percentages calculated were of the saturated material rather than the whole of the tailings area. As can be seen from this table, the radon flux for all cases shows that some degree of unsaturated tailings can be allowed while still remaining below 20 pCi/m²s of radon flux.

TABLE 2

RADON FLUX WITH UNSATURATED TAILINGS EXPOSURE

Case	Water Cover (%)	Unsaturated Tailings (%)	Radon Flux (pCi/m²s)
1	0	5	10.57
2	0	10	13.70
3	0	20	19.95

The details of these calculations are provided in Appendix B.

4.3 Atmospheric Radon Concentrations

The results of radon flux values for the tailings facility cannot readily be converted to airborne radon concentrations due to the need for meteorological modeling and determination of where the airborne concentrations would be measured. EPA has estimated the maximum radon air concentration at the edge of a uranium tailings cell (WISE, 2009; EPA, 1983). Based on these estimates, and assuming a maximum radon flux at the surface of the tailings cell of 20 pCi/m^{2}sec, the maximum radon in the air would be approximately 0.28 pCi/l. Since the tailings cells will typically have a radon flux well below 20 pCi/m^{2}sec, the air concentration of radon near the Piñon Ridge tailings cells is expected to be proportionately lower.

The report “Estimates of Radiation Doses to Members of the Public from the Piñon Ridge Mill” (Two Lines, 2009) also provides insight on the potential radon doses resulting from the ore stockpile, tailings cells, and mill emissions. This report is included in EFRC’s Radioactive Materials License Application to the Radiation Control Program of CDPHE. This study was conducted using the MILDOS Area model, which includes material properties, emission rates, and site-specific meteorological data as model inputs. The study projected that radon doses at the property’s fence line from all sources would range from 1.2 to 9.0 millirems per year (mrem/yr), and the nearest residents to the mill would receive a dose of less than 1 mrem/year. The study conservatively assumed that one tailings cell had reached capacity and a second tailings cell was in the initial stages of operation.

5.0 CONCLUSIONS

Golder was commissioned by EFRC to evaluate the operations of the uranium mill tailings storage facility at the Piñon Ridge Mill in terms of radon flux. The evaluation focused on identifying the flux levels produced during normal operations whereby tailings would be maintained in a saturated state with varying levels of water cover depending on the season and stage of operations. Operating flux levels were compared to the 20 pCi/m²s flux limit established by the U.S. Environmental Protection Agency (EPA) in 40 CFR 61 Subpart W, “National Emission Standards for Radon Emissions from Operating Mill Tailings” (EPA, 1998) for pre-1989 tailings impoundments. The evaluation also looked at the flux levels that would occur as tailings lose some level of saturation due to drying conditions.

The radon flux calculations presented in this report were conducted using the WISE Uranium Mill Tailings Radon Flux Calculator, as updated on November 23, 2009 (WISE, 2009). The results of the radon flux modeling calculations demonstrate that the proposed normal mode of operation will maintain radon flux levels well below 20 pCi/m²s. The modeling has also shown that some fraction of the tailings deposition can be unsaturated while still maintaining flux levels below 20 pCi/m²s. This situation could occur as a result of equipment breakdown or during the transition from operational to closure mode.

6.0 USE OF THIS REPORT

This report has been prepared exclusively for the use of Energy Fuels Resources Corporation (EFRC) for specific application to the Piñon Ridge Project. The analyses reported herein were performed in accordance with accepted practices. No third-party engineer or consultant shall be entitled to rely on any of the information, conclusions, or opinions contained in this report without the written approval of Golder and EFRC.

Golder sincerely appreciates the opportunity to support EFRC on the Piñon Ridge Project. Please contact the undersigned with any questions or comments on the information contained in this report.

Respectfully submitted,

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Associate - Senior Project Manager

Erich W. Tiepel
Erich Tiepel, PhD., P.E.
Principal

7.0 REFERENCES

Energy Fuels Resources Corporation (EFRC). 2010. “Operating Plan, Tailings Cells and Evaporation Ponds.”

Golder Associates Inc. (Golder). 2005. “Materials Handling Evaluation Study for the Moab Tailings Impoundment, Moab, Utah.” Submitted to S.M. Stoller. Reference No. 053-2269. 21 September 2005.

Golder Associates Inc. (Golder). 2008a. “Project Design Criteria, Piñon Ridge Geotechnical Services.” Revision C. 5 May 2008.

Golder Associates Inc. (Golder). 2008b. “Tailings Cell Design Report, Piñon Ridge Project, Montrose County, Colorado.” Prepared for Energy Fuels Resources Corporation. Reference No. 073-81694. October.

Golder Associates Inc. (Golder). 2010. “Tailings Cell Foundation and Closure Cover System Settlement Analyses Addendum, Piñon Ridge Project, Montrose County, Colorado,” Letter report to Mr. Frank Filas, Energy Fuels Resources Corporation, April.

Nielson, K.K., and V.C. Rogers. 1986. “Surface Water Hydrology Considerations in Predicting Radon Releases from Water-Covered Areas of Uranium Tailings Ponds,” Geotechnical & Geohydrological Aspects of Waste Management, Fort Collins, Colorado, pp. 215-222.

Rogers, V.C., and K.K. Nielson. 1991. "Multiphase Radon Generation and Transport in Porous Materials," Health Physics, No. 60, pp. 807-815.

U.S. Environmental Protection Agency (EPA). 1983. “Final Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (40 CFR 1092),” Vol. 1, Report No. EPA/520/1-83-008-1, September.

U.S. Environmental Protection Agency (EPA). 1998. Regulations as found in 40 CFR 61 Subpart W, National Emission Standards for Radon Emissions from Operating Mill Tailings, April.

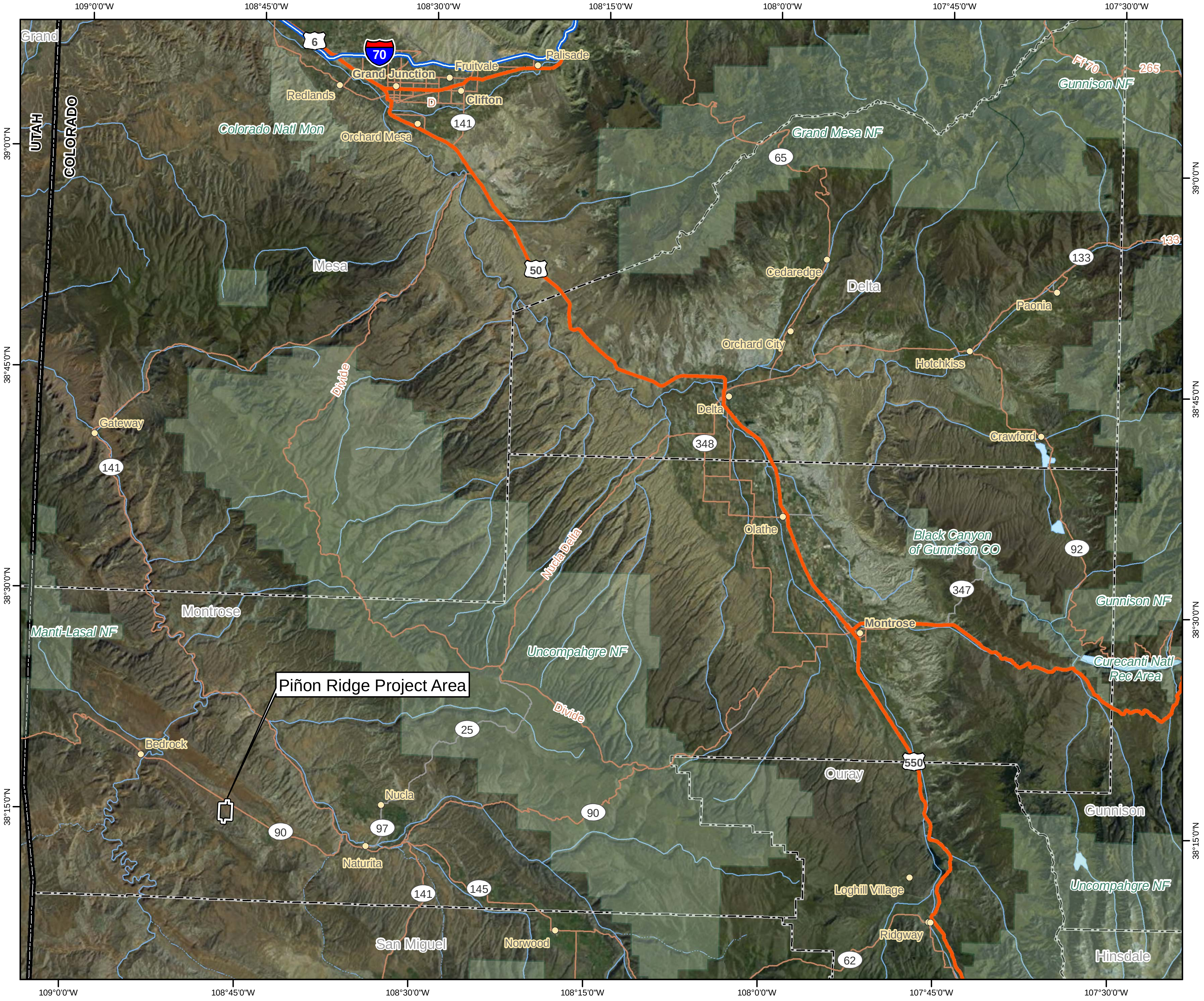
U.S. Nuclear Regulatory Commission (NRC). 1980. NUREG-0706, “Final Generic EIS on Uranium Milling.” Office of Nuclear Material, Safety and Safeguards, Washington, D.C., September. 850 pp.

WISE Uranium Project (WISE). 2009. Uranium Mill Tailings Radon Flux Calculator, November. http://www.wise-uranium.org/ctb.html?unit=c

Yu, C., C. Loureiro, J.J. Cheng, L.G. Jones, Y.Y. Wang, Y.P. Chia, and E. Faillace. 1993. Data Collection Handbook to Support Modeling Impacts of Radioactive Material in Soil. Environmental Assessment and Information Sciences Division, Argonne National Laboratory, Argonne, Illinois, April.

Yu, C., A.J. Zielen, J.J. Cheng, D.J. LePoire, E. Gnanapragasam, S. Kamboj, J. Arnish, A. Wallo III, W.A. Williams, and H. Peterson. 2001. Users’ Manual for RESRAD Version 6, Environmental Assessment Division, ANL/EAD-4, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois. EPA regulations as found in 40 CFR 61 Subpart W, National Emission Standards for Radon Emissions from Operating Mill Tailings, April 1998.

FIGURES



LEGEND

═	Property Boundary
●	Town
═	Interstate
━	Highway
—	Major Road
—	Local Road
▭	National Park or Forest
━	State
⬚	County
—	Stream
┄	Intermittent Stream
—	Dam
▭	Reservoir

REFERENCES

Base Data: ESRI, 2009.
Imagery: ESRI API, Assorted Dates.
Projection: StatePlane, Colorado South, NAD83, Feet.

10 5 0 10 MILES

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SCALE 1:500,000
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PROJECT

ENERGY FUELS RESOURCES CORPORATION
PIÑON RIDGE PROJECT
MONTROSE COUNTY, COLORADO

TITLE

SITE LOCATION MAP

Golder Associates
Denver, Colorado

PROJECT No.		073-81694	FILE No.	11x17_SiteLoc.mxd	
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GIS	AJR	08/04/2010	FIGURE 1		
CHECK	SS	08/04/2010			
REVIEW	KFM	08/04/2010			

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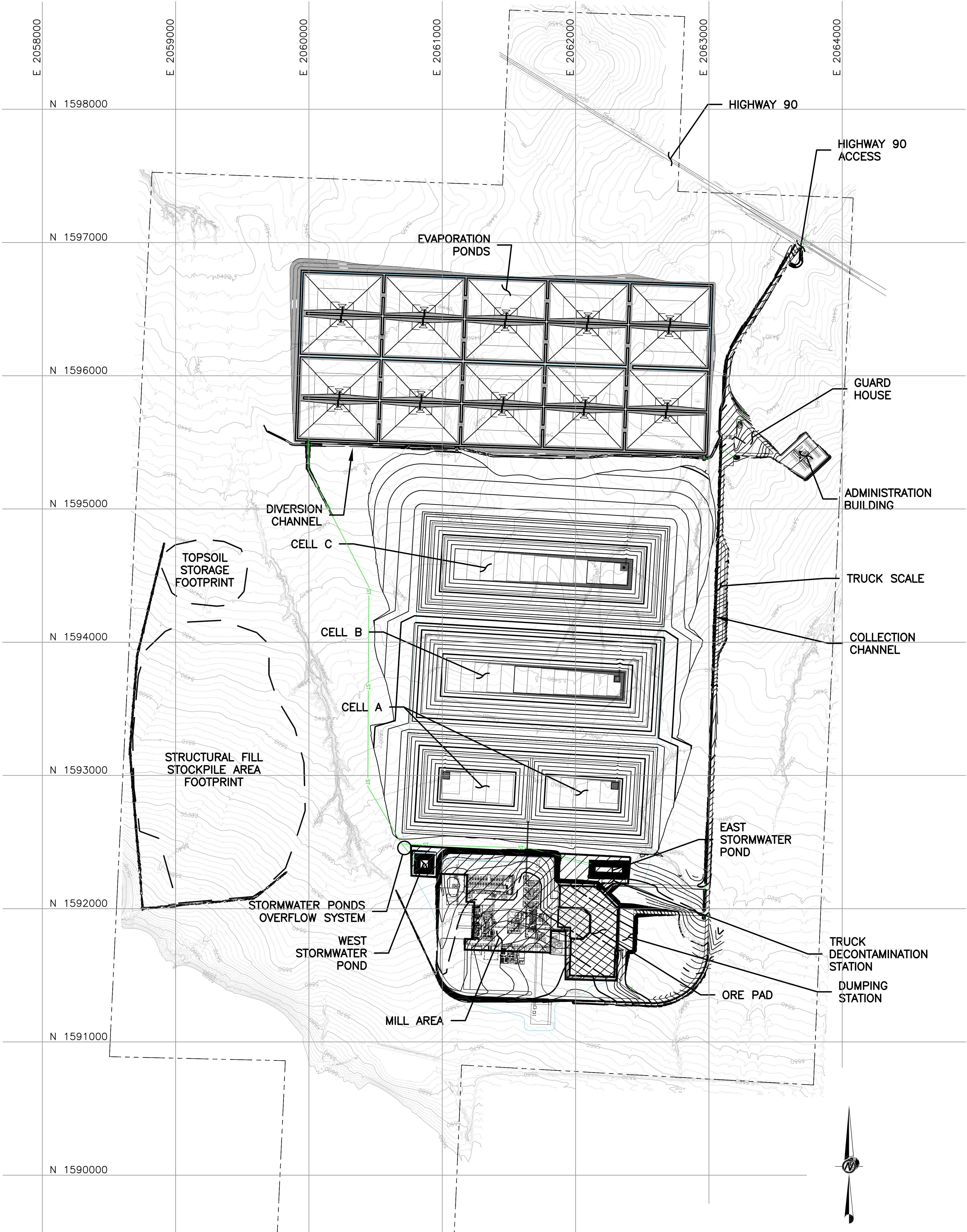
Last Plot: Aug 04, 2010 13:12 By: dsaunders



LEGEND

▨	EXISTING GROUND TOPOGRAPHY
▨	PROPOSED GRADES
— · — · —	PROJECT BOUNDARY
—ST—	STORMWATER PONDS OVERFLOW SYSTEM
— — —	STOCKPILE AREA FOOTPRINTS

PRO.

ENERGY FUELS RESOURCES CORPORATION
PIÑON RIDGE PROJECT
MONTROSE COUNTY, COLORADO

TITLE

SITE FACILITIES MAP
FULL BUILD-OUT

Golder Associates
DENVER, COLORADO

PROJECT No.		073-81694	FILE No.	07381694E001
DESIGN	SPS	08/02/10	SCALE AS SHOWN	REV. A
CADD	NKR	08/02/10	**FIGURE 2**	
CHECK	SPS	08/02/10		
REVIEW	KFM	08/02/10		

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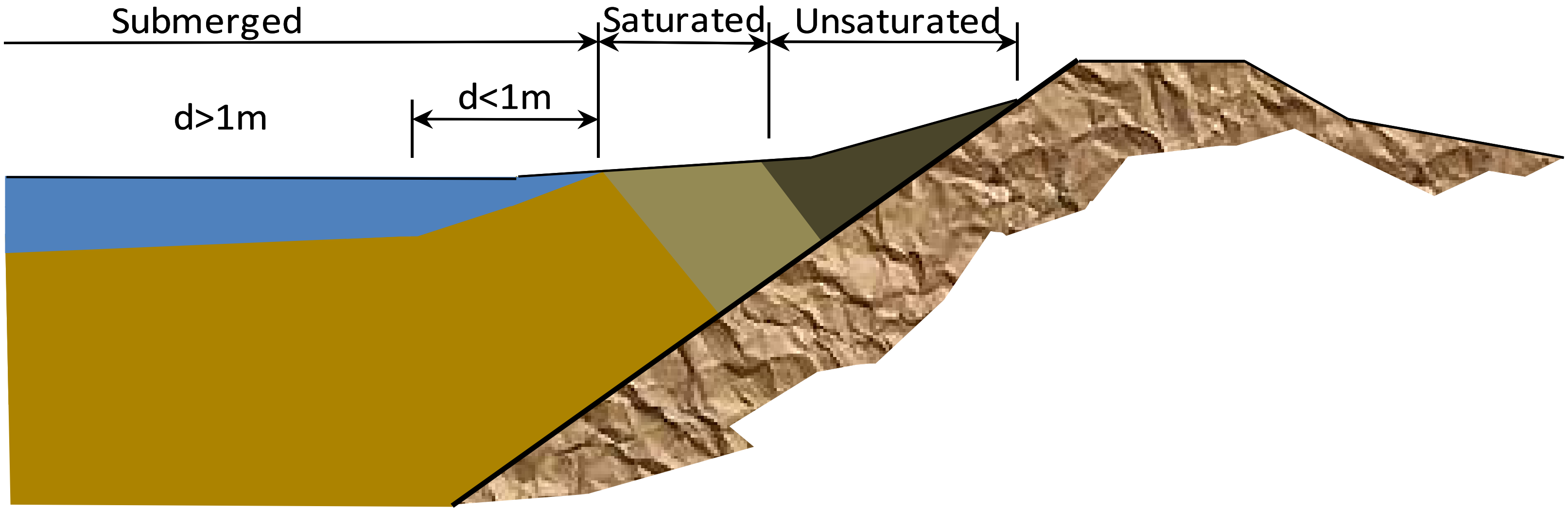
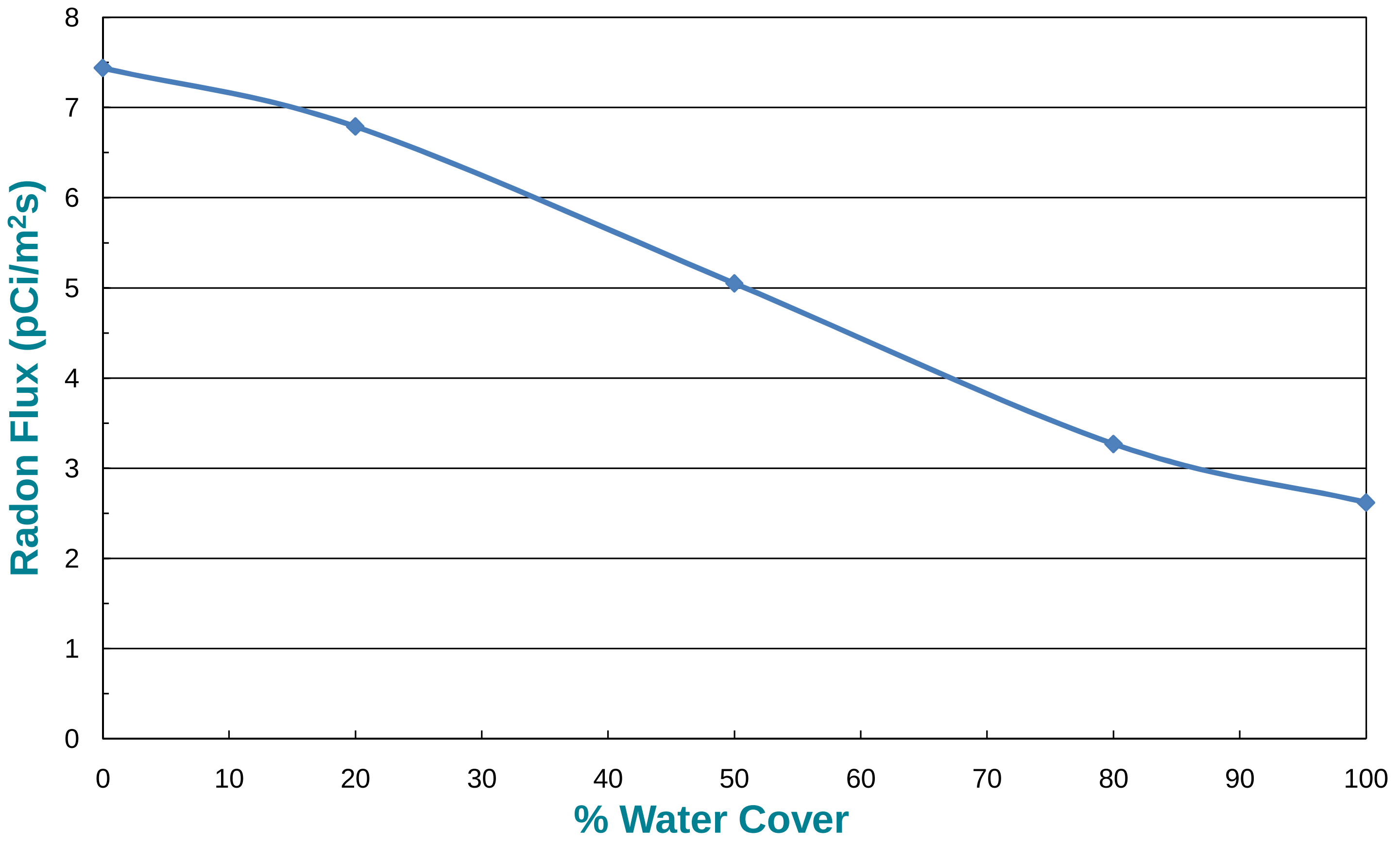


Golder Associates	Denver, Colorado	TITLE	**Tailings Zonation Model Assumptions**		
CLIENT/PROJECT **ENERGY FUELS RESOURCES CORP.** **PIÑON RIDGE PROJECT**		DRAWN **KFM**	DATE **Jul-10**	JOB NO. **073-81694.0002**	
		CHECKED **ET**	SCALE **NTS**	DWG. NO. **N/A**	
		REVIEWED **ET**	FILE NO **TailingsZonationFigure.xls**	FIGURE NO. **3**	



Golder Associates

Denver, Colorado

TITLE

Radon Flux vs. Percent Water Cover

CLIENT/PROJECT

ENERGY FUELS RESOURCES CORP.
PIÑON RIDGE PROJECT

DRAWN	**ET**	DATE	**Aug-10**	JOB NO.	**073-81694.0023**
CHECKED	**KFM**	SCALE	**NTS**	DWG. NO.	**N/A**
REVIEWED	**ET**	FILE NO.	07381694 RadonFluxCalc Fig4.xls	FIGURE NO.	**4**

APPENDIX A

DETAILS OF RADON FLUX CALCULATIONS FOR SATURATED AND SUBMERGED TAILINGS

Uranium Mill Tailings Radon Flux Calculations

Input Data / 0% Water Cover / 0% Unsaturated

Tailings Data

Ra - 226 Activity Concentrations in Tailings (pCi/g)	Ra - 226 Activity Ratio in slimes vs. sand	Ra - 222 Emanation Fraction in slimes	Ra - 222 Emanation Fraction in sand	Fraction Passing #200 Mesh (75 µm)	Fraction of Pond Area with less than 1 m deep	Average Pond Depth for Areas Greater than 1 m deep	Ra - 226 Activity Concentration in Ponding Water (pCi/l)	Effective Stagnant Water Transport coefficient (m^2/s)
647	4	0.22	0.15	0.379	1	0	578	3.00E-07

Zone - Specific Tailings Properties

Tailings Zone	Surface Area (m^2)	Bulk Density (g/cm^3)	Porosity	Moisture Contents (dry wt_%)	Fraction Passing #200 Mesh (75 µm)	Rn - 222 Effective Diffusion Coefficient (m^2/s)
Submerged	0	1.12	0.57	Saturated	0.72	5.08E-10
Saturated	120365	1.28	0.39	Saturated	0.36	1.03E-09
Unsaturated	0	1.44	0.39	15	0.05	3.53E-05

Radon Flux Results pCi/m^2s
7.44

Uranium Mill Tailings Radon Flux Calculations

Input Data / 20% Water Cover / 0% Unsaturated

Tailings Data

Ra - 226 Activity Concentrations in Tailings (pCi/g)	Ra - 226 Activity Ratio in slimes vs. sand	Ra - 222 Emanation Fraction in slimes	Ra - 222 Emanation Fraction in sand	Fraction Passing #200 Mesh (75 µm)	Fraction of Pond Area with less than 1 m deep	Average Pond Depth for Areas Greater than 1 m deep	Ra - 226 Activity Concentration in Ponding Water (pCi/l)	Effective Stagnant Water Transport coefficient (m^2/s)
647	4	0.22	0.15	0.379	0.358	1.83	578	3.00E-07

Zone - Specific Tailings Properties

Tailings Zone	Surface Area (m^2)	Bulk Density (g/cm^3)	Porosity	Moisture Contents (dry wt_%)	Fraction Passing #200 Mesh (75 µm)	Rn - 222 Effective Diffusion Coefficient (m^2/s)
Submerged	24073	1.12	0.57	Saturated	0.72	5.08E-10
Saturated	96292	1.28	0.39	Saturated	0.36	1.03E-09
Unsaturated	0	1.44	0.39	15	0.05	3.53E-05

Radon Flux Results pCi/m^2s
6.79

Uranium Mill Tailings Radon Flux Calculations

Input Data / 50% Water Cover / 0% Unsaturated

Tailings Data

Ra - 226 Activity Concentrations in Tailings (pCi/g)	Ra - 226 Activity Ratio in slimes vs. sand	Ra - 222 Emanation Fraction in slimes	Ra - 222 Emanation Fraction in sand	Fraction Passing #200 Mesh (75 µm)	Fraction of Pond Area with less than 1 m deep	Average Pond Depth for Areas Greater than 1 m deep	Ra - 226 Activity Concentration in Ponding Water (pCi/l)	Effective Stagnant Water Transport coefficient (m^2/s)
647	4	0.22	0.15	0.379	0.19	2.43	578	3.00E-07

Zone - Specific Tailings Properties

Tailings Zone	Surface Area (m^2)	Bulk Density (g/cm^3)	Porosity	Moisture Contents (dry wt_%)	Fraction Passing #200 Mesh (75 µm)	Rn - 222 Effective Diffusion Coefficient (m^2/s)
Submerged	60182	1.12	0.57	Saturated	0.72	5.08E-10
Saturated	60182	1.28	0.39	Saturated	0.36	1.03E-09
Unsaturated	0	1.44	0.39	15	0.05	3.53E-05

Radon Flux Results pCi/m^2s
5.05

Uranium Mill Tailings Radon Flux Calculations

Input Data / 80% Water Cover / 0% Unsaturated

Tailings Data

Ra - 226 Activity Concentrations in Tailings (pCi/g)	Ra - 226 Activity Ratio in slimes vs. sand	Ra - 222 Emanation Fraction in slimes	Ra - 222 Emanation Fraction in sand	Fraction Passing #200 Mesh (75 µm)	Fraction of Pond Area with less than 1 m deep	Average Pond Depth for Areas Greater than 1 m deep	Ra - 226 Activity Concentration in Ponding Water (pCi/l)	Effective Stagnant Water Transport coefficient (m^2/s)
647	4	0.22	0.15	0.379	0.142	2.9	578	3.00E-07

Zone - Specific Tailings Properties

Tailings Zone	Surface Area (m^2)	Bulk Density (g/cm^3)	Porosity	Moisture Contents (dry wt_%)	Fraction Passing #200 Mesh (75 µm)	Rn - 222 Effective Diffusion Coefficient (m^2/s)
Submerged	96292	1.12	0.57	Saturated	0.72	5.08E-10
Saturated	24073	1.28	0.39	Saturated	0.36	1.03E-09
Unsaturated	0	1.44	0.39	15	0.05	3.53E-05

Radon Flux Results pCi/m^2s
3.27

Uranium Mill Tailings Radon Flux Calculations

Input Data / 100% Water Cover / 0% Unsaturated

Tailings Data

Ra - 226 Activity Concentrations in Tailings (pCi/g)	Ra - 226 Activity Ratio in slimes vs. sand	Ra - 222 Emanation Fraction in slimes	Ra - 222 Emanation Fraction in sand	Fraction Passing #200 Mesh (75 μm)	Fraction of Pond Area with less than 1 m deep	Average Pond Depth for Areas Greater than 1 m deep	Ra - 226 Activity Concentration in Ponding Water (pCi/l)	Effective Stagnant Water Transport coefficient (m^2/s)
647	4	0.22	0.15	0.379	0.2	3.05	578	3.00E-07

Zone - Specific Tailings Properties

Tailings Zone	Surface Area (m^2)	Bulk Density (g/cm^3)	Porosity	Moisture Contents (dry wt_%)	Fraction Passing #200 Mesh (75 μm)	Rn - 222 Effective Diffusion Coefficient (m^2/s)
Submerged	120365	1.12	0.57	Saturated	0.72	5.08E-10
Saturated	0	1.28	0.39	Saturated	0.36	1.03E-09
Unsaturated	0	1.44	0.39	15	0.05	3.53E-05

Radon Flux Results pCi/m^2s
2.62

APPENDIX B

DETAILS OF RADON FLUX CALCULATIONS FOR ALLOWABLE UNSATURATED TAILINGS EXPOSURE

Uranium Mill Tailings Radon Flux Calculations

Input Data / 0% Water Cover / 5% Unsaturated

Tailings Data

Ra - 226 Activity Concentrations in Tailings (pCi/g)	Ra - 226 Activity Ratio in slimes vs. sand	Ra - 222 Emanation Fraction in slimes	Ra - 222 Emanation Fraction in sand	Fraction Passing #200 Mesh (75 µm)	Fraction of Pond Area with less than 1 m deep	Average Pond Depth for Areas Greater than 1 m deep	Ra - 226 Activity Concentration in Ponding Water (pCi/l)	Effective Stagnant Water Transport coefficient (m^2/s)
647	4	0.22	0.15	0.379	1	0	578	3.00E-07

Zone - Specific Tailings Properties

Tailings Zone	Surface Area (m^2)	Bulk Density (g/cm^3)	Porosity	Moisture Contents (dry wt_%)	Fraction Passing #200 Mesh (75 µm)	Rn - 222 Effective Diffusion Coefficient (m^2/s)
Submerged	0	1.12	0.57	Saturated	0.72	5.08E-10
Saturated	114347	1.28	0.39	Saturated	0.36	1.03E-09
Unsaturated	6018	1.44	0.39	15	0.05	3.53E-05

Radon Flux Results pCi/m^2s
10.57

Uranium Mill Tailings Radon Flux Calculations

Input Data / 0% Water Cover / 10% Unsaturated

Tailings Data

Ra - 226 Activity Concentrations in Tailings (pCi/g)	Ra - 226 Activity Ratio in slimes vs. sand	Ra - 222 Emanation Fraction in slimes	Ra - 222 Emanation Fraction in sand	Fraction Passing #200 Mesh (75 μm)	Fraction of Pond Area with less than 1 m deep	Average Pond Depth for Areas Greater than 1 m deep	Ra - 226 Activity Concentration in Ponding Water (pCi/l)	Effective Stagnant Water Transport coefficient (m^2/s)
647	4	0.22	0.15	0.379	1	0	578	3.00E-07

Zone - Specific Tailings Properties

Tailings Zone	Surface Area (m^2)	Bulk Density (g/cm^3)	Porosity	Moisture Contents (dry wt_%)	Fraction Passing #200 Mesh (75 μm)	Rn - 222 Effective Diffusion Coefficient (m^2/s)
Submerged	0	1.12	0.57	Saturated	0.72	5.08E-10
Saturated	108329	1.28	0.39	Saturated	0.36	1.03E-09
Unsaturated	12036	1.44	0.39	15	0.05	3.53E-05

Radon Flux Results pCi/m^2s
13.7

Uranium Mill Tailings Radon Flux Calculations

Input Data / 0% Water Cover / 20% Unsaturated

Tailings Data

Ra - 226 Activity Concentrations in Tailings (pCi/g)	Ra - 226 Activity Ratio in slimes vs. sand	Ra - 222 Emanation Fraction in slimes	Ra - 222 Emanation Fraction in sand	Fraction Passing #200 Mesh (75 µm)	Fraction of Pond Area with less than 1 m deep	Average Pond Depth for Areas Greater than 1 m deep	Ra - 226 Activity Concentration in Ponding Water (pCi/l)	Effective Stagnant Water Transport coefficient (m^2/s)
647	4	0.22	0.15	0.379	1	0	578	3.00E-07

Zone - Specific Tailings Properties

Tailings Zone	Surface Area (m^2)	Bulk Density (g/cm^3)	Porosity	Moisture Contents (dry wt_%)	Fraction Passing #200 Mesh (75 µm)	Rn - 222 Effective Diffusion Coefficient (m^2/s)
Submerged	0	1.12	0.57	Saturated	0.72	5.08E-10
Saturated	96292	1.28	0.39	Saturated	0.36	1.03E-09
Unsaturated	24073	1.44	0.39	15	0.05	3.53E-05

Radon Flux Results pCi/m^2s
19.95

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Kennecott Uranium Company
Sweetwater Uranium Project
Radon Flux from Tailings Impoundment Pools

Pool	Radium-226 Activity		Radon Emanation Coefficient	Radon-222 Activity in	LAACC Number	Water	Pool	Placed		Retrieved		Charcoal	Measured Flux	Barometric Pressure During Test		Temperature During Test (Two (2) Meters above Ground Surface)		Ratio of Radon-222 Activity in picoCuries per liter to Flux in picoCuries per meter2-second
Name	Fluid	Sediment	Sediment	Fluid		Temperature	Depth	Date	Time	Date	Time	Moisture		Minimum	Maximum	Minimum	Maximum	
	(pCi/L)	(pCi/gr)	(Percent)	(pCi/L)		(Degrees Centigrade)	(Inches)					(Percent)	(pCi/M2-sec)	Millimeters of Mercury	Millimeters of Mercury	Degrees Centrigrade	Degrees Centrigrade	
1-E	26	10.2	23.1	570	116	19.5	16	8/10/2010	11:24	8/11/2010	12:53	3.1	0.83	765.075	766.677	9.902	27.555	0.0015
1-E	26	10.2	23.1	570	117	19.5	18	8/10/2010	11:27	8/11/2010	12:54	2.0	0.82	765.075	766.677	9.902	27.555	0.0014
1-E	26	10.2	23.1	570	1	15.5	16	8/11/2010	12:53	8/12/2010	13:18	3.1	<0.05	761.976	765.363	12.064	28.311	
1-E	26	10.2	23.1	570	2	15.5	18	8/11/2010	12:54	8/12/2010	13:18	3.1	0.50	761.976	765.363	12.064	28.311	0.0009
5-E	39	8.8	14.3	1750	118	19.5	13	8/10/2010	11:33	8/11/2010	12:57	2.9	0.78	765.075	766.677	9.902	27.555	0.0004
5-E	39	8.8	14.3	1750	119	19.5	10	8/10/2010	11:37	8/11/2010	12:58	2.4	0.78	765.075	766.677	9.902	27.555	0.0004
5-E	39	8.8	14.3	1750	3	15.5	13	8/11/2010	12:57	8/12/2010	13:20	3.0	<0.05	761.976	765.363	12.064	28.311	
5-E	39	8.8	14.3	1750	4	15.5	10	8/11/2010	12:58	8/12/2010	13:22	2.9	0.57	761.976	765.363	12.064	28.311	0.0003
9-W	22	7.3	27.6	772	120	20.3	24	8/10/2010	11:43	8/11/2010	13:01	2.8	0.76	765.075	766.677	9.902	27.555	0.0010
9-W	22	7.3	27.6	772	121	20.3	28	8/10/2010	11:49	8/11/2010	13:03	2.6	0.67	765.075	766.677	9.902	27.555	0.0009
9-W	22	7.3	27.6	772	122	20.3	29	8/10/2010	11:53	8/11/2010	13:04	1.7	0.63	765.075	766.677	9.902	27.555	0.0008
9-W	22	7.3	27.6	772	5	16.7	24	8/11/2010	13:01	8/12/2010	13:25	3.5	0.51	761.976	765.363	12.064	28.311	0.0007
9-W	22	7.3	27.6	772	6	16.7	28	8/11/2010	13:03	8/12/2010	13:27	3.5	0.51	761.976	765.363	12.064	28.311	0.0007
9-W	22	7.3	27.6	772	7	16.7	29	8/11/2010	13:04	8/12/2010	13:27	2.5	0.56	761.976	765.363	12.064	28.311	0.0007
SE Pool	15	18.2	18.7	446	123	19.1	16	8/10/2010	12:00	8/11/2010	13:09	3.6	0.64	765.075	766.677	9.902	27.555	0.0014
SE Pool	15	18.2	18.7	446	124	19.1	15	8/10/2010	12:03	8/11/2010	13:11	2.5	0.61	765.075	766.677	9.902	27.555	0.0014
SE Pool	15	18.2	18.7	446	125	19.1	10	8/10/2010	12:07	8/11/2010	13:12	2.0	0.64	765.075	766.677	9.902	27.555	0.0014
SE Pool	15	18.2	18.7	446	8	17.8	16	8/11/2010	13:09	8/12/2010	13:32	3.3	<0.05	761.976	765.363	12.064	28.311	
SE Pool	15	18.2	18.7	446	9	17.8	15	8/11/2010	13:11	8/12/2010	13:34	3.0	0.51	761.976	765.363	12.064	28.311	0.0011
SE Pool	15	18.2	18.7	446	10	17.8	10	8/11/2010	13:12	8/12/2010	13:33	2.3	0.53	761.976	765.363	12.064	28.311	0.0012

Notes: None of the activated charcoal exceed a moisture content of 3.60% following the test.
None exceeded the 11% limit on moisture described by Dr. Baker.
The test's Lower Limit of Detection (LLD) was 0.5 picoCuries per meter2-sec

Charcoal for this test counted for ten (10) minutes as opposed to five (5) minutes to improve Lower limit of Detection (LLD).
Barometric pressure data is corrected for elevation (corrected to sea level)

Appendix 39

SECTION 6
ALPHA-EMITTING RADIUM ISOTOPES IN DRINKING WATER
METHOD 903.0

1. Scope and Application

1.1 This method covers the measurement of the total soluble alpha emitting radioisotopes of radium, namely radium-223, radium-224 and radium-226 in drinking water. Part 141 of the Interim Primary Drinking Water Regulations, Federal Register, July 9, 1976, has promulgated the maximum contaminant levels of radium-226 plus radium-228 (see Method 904.0) not to exceed 5 pCi/l.

1.2 Although the method does not always give an accurate measurement of the radium-226 content of the sample (when other radium alpha emitters are present), it can be used to screen samples. When the total radium alpha activity of a drinking water sample is greater than 5 pCi/l, then the radium-226 analysis (Method 903.1) is required.

1.3 Since this method provides for the separation of radium from other water dissolved solids in the sample, the sensitivity of the method is a function of sample size, reagent and instrument background, counting efficiency and counting time. The National Interim Primary Drinking Water Regulations (NIPDWR) require a sensitivity of measurement of 1 pCi/l for radium-226. Using a low background alpha counting system, liter or more size sample aliquots, and sufficient counting times, the detection limit of 1 pCi/l can easily be met.

1.4 Absolute measurement can be made by calibrating the alpha detector with standard radium-226 in the geometry obtained with the final precipitate.

2. Summary of Method

2.1 The radium in the drinking water sample is collected by coprecipitation with barium and lead sulfate, and purified by reprecipitation from EDTA solution. Citric acid is added to the drinking water sample to assure that complete interchange occurs before the first precipitation step. The final $BaSO_4$ precipitate which includes radium-226, radium-224 and radium-223 is alpha counted to determine the total disintegration rate of the radium isotopes.

2.2 The radium activities are counted in an alpha counter where efficiency for determining radium-226 has been calibrated with a standard of known radium-226 activity. By making a correction for the ingrowth of alpha activity in radium-226 for the elapsed time after separation, one can determine radium activity in the sample. Since some daughter ingrowth can occur before the separated radium is counted, it is necessary to make activity corrections for the count rate. A table of ingrowth factors for various times after radium separation is provided. (See Sec. 9.2).

3. Sample Handling and Preservation - (See Section 3 - Method 900.0)

4. Interferences

4.1 Inasmuch as the radiochemical yield of the radium activity is based on the chemical yield of the $BaSO_4$ precipitate, the presence of significant natural barium in the sample will result in a falsely high chemical yield.

4.2 Radium isotopes are separated from other alpha emitting radionuclides by this method.

4.3 The alpha count of the separated radium must be corrected for its partially ingrown alpha emitting daughters.

5. Apparatus - See Appendix D for details and specifications.

5.1 Alpha scintillation or a gas-flow proportional alpha particle counting system with low background (< 1 cpm)

5.2 Stainless steel counting planchets

5.3 Electric hot plate

5.4 Drying oven and/or drying lamp

5.5 Glass desiccator

5.6 Analytical balance

5.7 Centrifuge

5.8 Glassware

6. Reagents

6.1 Distilled or deionized water.

6.2 Acetic acid, 17.4$\underline{N}$: glacial CH_3COOH (conc.), sp.gr. 1.05, 99.8%.

6.3 Ammonium Sulfate, 200 mg/ml: Dissolve 20 grams $(NH_4)_2SO_4$ in a minimum of water and dilute to 100 ml.

6.4 Barium carrier, 16 mg/ml, standardized:
Dissolve 2.846g $BaCl_2.2H_2O$ in water, add 0.5 ml 16<u>N</u> HNO_3, and dilute to 100 ml with water.

Standardization: (in triplicate)

Pipette 2.0 ml carrier solution into a centrifuge tube containing 15 ml water. Add 1 ml 18N H_2SO_4 with stirring and digest precipitate in a water bath for 10 minutes. Cool, centrifuge and decant the supernatant. Wash precipitate with 15 ml water. Transfer the precipitate to a tared stainless steel planchet with a minimum of water. Dry under infra-red lamp, store in desiccator and weigh as $BaSO_4$.

6.5 Citric acid, 1M: Dissolve 19.2g $C_6H_8O_7.H_2O$ in water and dilute to 100 ml.

6.6 EDTA reagent, basic, (0.25M): Dissolve 20g NaOH in 750 ml water, heat and slowly add 93g disodium ethylenedinitriloacetate dihydrate ($Na_2C_{10}H_{14}O_8N_2.2H_2O$). Heat and stir until dissolved, filter through course filter paper and dilute to 1 liter.

6.7 Lead carrier, 15 mg/ml: Dissolve 2.4g $Pb(NO_3)_2$ in water, add 0.5 ml 16N HNO_3 and dilute to 100 ml with water.

6.8 Sodium hydroxide, 6N: Dissolve 24g NaOH in 80 ml water and dilute to 100 ml.

6.9 Sulfuric acid, 18N: Cautiously mix 1 volume 36N H_2SO_4 (conc.) with 1 volume of water.

6.10 Sulfuric acid, 0.1N: Mix 1 volume 18N H_2SO_4 with 179 volumes of water.

7. Calibrations

7.1 The counting efficiency for radium alpha particles with barium sulfate carrier present must be determined using a standard (known) radium alpha activity and 32 mg of barium carrier as $BaSO_4$ (same carrier amount used with samples). This is done with spiked distilled water samples and the procedure for regular samples is followed. Note the time of the Ra-$BaSO_4$ precipitation.

7.2 The radium-alpha counting efficiency, E, is calculated as follows:

$$E\ (\text{cpm/dpm}) = \frac{C}{A \times I}$$

where:

C = sample net cpm (gross counts minus background divided by the counting time in minutes).
A = dpm of radium-226 added to sample.
I = ingrowth factor for the elapsed time from Ra-$BaSO_4$ precipitation to mid-point of counting time.

8. Procedure

8.1 To a 1000-ml drinking water sample, add 5 ml 1<u>M</u> $C_6H_8O_7 \cdot H_2O$, 1 ml lead carrier, and 2.0 ml barium carrier, and heat to boiling.

8.2 Cautiously, with vigorous stirring, add 20 ml 18N H_2SO_4. Digest 5 to 10 minutes and let the mixed $BaSO_4$-$PbSO_4$ precipitate settle overnight. Decant and discard supernate.

8.3 Transfer the precipitate to a centrifuge tube with a minimum amount of 0.1<u>N</u> H_2SO_4. Centrifuge and discard supernate.

8.4 Wash the precipitate twice with 0.1<u>N</u> H_2SO_4. Centrifuge and discard washes.

8.5 Dissolve the precipitate by adding 15 ml basic EDTA reagent; heat in a hot water bath and add a few drops 6<u>N</u> NaOH until solution is complete.

8.6 Add 1 ml $(NH_4)_2SO_4$ (200 mg/ml) and stir thoroughly. Add 17.4<u>N</u> CH_3COOH dropwise until precipitation begins, then add 2 ml extra. Digest 5 to 10 minutes.

8.7 Centrifuge, discard the supernate, and record time.

<u>Note</u>: At this point, the separation of the $BaSO_4$ is complete and the radon (and daughters) ingrowth commences.

8.8 Wash the $BaSO_4$ precipitate with 15 ml water, centrifuge, and discard wash.

8.9 Transfer the precipitate to a tared stainless-steel planchet with a minimum of water, and dry under infra-red lamps.

<u>Note</u>: Drying should be rapid but not too vigorous to minimize any loss of radon-222 that has already grown into the precipitate.

8.10 Cool, weigh, and store in desiccator.

8.11 Count in a gas-flow internal proportional counter or an alpha scintillation counter to determine the alpha activity.

9. Calculation

9.1 Calculate the radium-226 concentration, D, (which would include any radium-224 and radium-223 that is present) in picocuries per liter as follows:

$$D = \frac{C}{2.22 \times EVR \times I}$$

where:

C = net count rate, cpm,
E = counter efficiency for radium-226 in $BaSO_4$ predetermined for this procedure (see Sec. 7.2).
V = liters of sample used,
R = fractional chemical yield,
I = ingrowth correction factor (See Sec. 9.2), and
2.22 = conversion factor from dpm/pCi.

9.2 It is not always possible to count the $BaSO_4$ precipitate immediately after separation, therefore, corrections must be made for the ingrowth of the radium-226 daughters between the time of separation and counting according to the following table:

Hours from separation to counting	Ingrowth correction factor
0	1.00
1	1.02
2	1.04
3	1.06
4	1.08
5	1.10
6	1.12
24	1.49
48	1.91
72	2.25
96	2.54
120	2.78
144	2.99
192	3.29
240	3.51

10. Precision and Accuracy

10.1 Precision and accuracy data for this method is taken from a survey of analyses of radium in water samples in the EMSL-Las Vegas intercomparison program for the period September 1977 to January 1979. Some of the laboratories participating in the EMSL-Las Vegas intercomparison program used this method because it was included in the approved methods and they did not have the capability for analyzing radium-226 by radon-222 emanation, (Method 903.1), which was also an approved method.

10.2 Eleven laboratories participated in from 1 to 7 of 8 intercomparison studies and analyzed 46 test samples for radium-226 by this method. Of the 46 tests, the data for 40 tests (in triplicate, for a total of 120 aliquots) was used for the laboratory performance statistical analysis. Of the 40 tests used, 29 tests (87 aliquots analyzed) gave acceptable results (results within 3 sigma of the known value, with 1 sigma equal to 15% of the known value). The extent of acceptability in the 40 tests (29 acceptable) was 72.5%.

10.3 The 8 intercomparison studies were conducted quarterly from September 1977 to January 1979. Two of the studies were performance studies in which the samples contained other radionuclides. Also, samples in all of the studies contained a known quantity of radium-228 activity (with the thorium-228 and radium-224 daughters partially ingrown).

10.4 Radium-226, radium-228, and radium-224 activities in study samples:

	pCi/l (at separation)		
Study	Radium-226	Radium-228	Radium-224
1	3.5	9.3	0.4
2	10.2	14.6	1.1
3	5.5	16.7	1.7
4 (performance)	6.5	7.9	0.8
5	3.7	5.6	0.7
6	6.8	20.8	3.0
7	9.2	8.9	1.5
8 (performance)	5.0	5.4	0.8

10.5 It can be seen from the above table that the radium-224 was a significant contributor to the alpha activity of precipitated radium activity and therefore the samples were biased high for a radium-226 analysis by this method. A waiting period of 14 days after radium separation and purification before counting for alpha activity would reduce the radium-224 contribution to less than 0.1 of its activity at purification (radium-224 separation from its thorium-228 parent). The count would then need to be corrected for the ingrown radon-222 and its alpha emitting daughters.

10.6 The 72.5% acceptable results obtained by this method, even with the samples biased high, show the method to be an acceptable one for screening drinking water samples for radium-226.

Bibliography

1. Goldin, A.S., Determination of Dissolved Radium, Anal. Chem. 33, 406-409 (March 1961).
2. Kirby, H.W., Decay and Growth Tables for the Naturally Occurring Radioactive Series, Anal. Chem. 26, 1063-1071 (1954).
3. Harley, J.H., ed. EML Procedures Manual, U.S. DOE, Dept. HASL-300, Env. Meas. Lab., U.S. DOE, New York, N. Y. (1972).

METHOD 3050B

ACID DIGESTION OF SEDIMENTS, SLUDGES, AND SOILS

1.0 SCOPE AND APPLICATION

1.1 This method has been written to provide two separate digestion procedures, one for the preparation of sediments, sludges, and soil samples for analysis by flame atomic absorption spectrometry (FLAA) or inductively coupled plasma atomic emission spectrometry (ICP-AES) and one for the preparation of sediments, sludges, and soil samples for analysis of samples by Graphite Furnace AA (GFAA) or inductively coupled plasma mass spectrometry (ICP-MS). The extracts from these two procedures are not interchangeable and should only be used with the analytical determinations outlined in this section. Samples prepared by this method may be analyzed by ICP-AES or GFAA for all the listed metals as long as the detecion limits are adequate for the required end-use of the data. Alternative determinative techniques may be used if they are scientifically valid and the QC criteria of the method, including those dealing with interferences, can be achieved. Other elements and matrices may be analyzed by this method if performance is demonstrated for the analytes of interest, in the matrices of interest, at the concentration levels of interest (See Section 8.0). The recommended determinative techniques for each element are listed below:

FLAA/ICP-AES		GFAA/ICP-MS
Aluminum	Magnesium	Arsenic
Antimony	Manganese	Beryllium
Barium	Molybdenum	Cadmium
Beryllium	Nickel	Chromium
Cadmium	Potassium	Cobalt
Calcium	Silver	Iron
Chromium	Sodium	Lead
Cobalt	Thallium	Molybdenum
Copper	Vanadium	Selenium
Iron	Zinc	Thallium
Lead		
Vanadium		

1.2 This method is not a total digestion technique for most samples. It is a very strong acid digestion that will dissolve almost all elements that could become “environmentally available.” By design, elements bound in silicate structures are not normally dissolved by this procedure as they are not usually mobile in the environment. If absolute total digestion is required use Method 3052.

2.0 SUMMARY OF METHOD

2.1 For the digestion of samples, a representative 1-2 gram (wet weight) or 1 gram (dry weight) sample is digested with repeated additions of nitric acid (HNO_3) and hydrogen peroxide (H_2O_2).

2.2 For GFAA or ICP-MS analysis, the resultant digestate is reduced in volume while heating and then diluted to a final volume of 100 mL.

2.3 For ICP-AES or FLAA analyses, hydrochloric acid (HCl) is added to the initial digestate and the sample is refluxed. In an optional step to increase the solubility of some metals (see Section 7.3.1: NOTE), this digestate is filtered and the filter paper and residues are rinsed, first with hot HCl and then hot reagent water. Filter paper and residue are returned to the digestion flask, refluxed with additional HCl and then filtered again. The digestate is then diluted to a final volume of 100 mL.

2.4 If required, a separate sample aliquot shall be dried for a total percent solids determination.

3.0 INTERFERENCES

3.1 Sludge samples can contain diverse matrix types, each of which may present its own analytical challenge. Spiked samples and any relevant standard reference material should be processed in accordance with the quality control requirements given in Sec. 8.0 to aid in determining whether Method 3050B is applicable to a given waste.

4.0 APPARATUS AND MATERIALS

4.1 Digestion Vessels - 250-mL.

4.2 Vapor recovery device (e.g., ribbed watch glasses, appropriate refluxing device, appropriate solvent handling system).

4.3 Drying ovens - able to maintain 30°C ± 4°C.

4.4 Temperature measurement device capable of measuring to at least 125°C with suitable precision and accuracy (e.g., thermometer, IR sensor, thermocouple, thermister, etc.)

4.5 Filter paper - Whatman No. 41 or equivalent.

4.6 Centrifuge and centrifuge tubes.

4.7 Analytical balance - capable of accurate weighings to 0.01 g.

4.8 Heating source - Adjustable and able to maintain a temperature of 90-95°C. (e.g., hot plate, block digestor, microwave, etc.)

4.9 Funnel or equivalent.

4.10 Graduated cylinder or equivalent volume measuring device.

4.11 Volumetric Flasks - 100-mL.

5.0 REAGENTS

5.1 Reagent grade chemicals shall be used in all tests. Unless otherwise indicated, it is intended that all reagents shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society, where such specifications are available. Other grades may be used, provided it is first ascertained that the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination. If the purity of a reagent is questionable, analyze the reagent to determine the level of impurities. The reagent blank must be less than the MDL in order to be used.

5.2 Reagent Water. Reagent water will be interference free. All references to water in the method refer to reagent water unless otherwise specified. Refer to Chapter One for a definition of reagent water.

5.3 Nitric acid (concentrated), HNO_3. Acid should be analyzed to determine level of impurities. If method blank is < MDL, the acid can be used.

5.4 Hydrochloric acid (concentrated), HCl. Acid should be analyzed to determine level of impurities. If method blank is < MDL, the acid can be used.

5.5 Hydrogen peroxide (30%), H_2O_2. Oxidant should be analyzed to determine level of impurities. If method blank is < MDL, the peroxide can be used.

6.0 SAMPLE COLLECTION, PRESERVATION, AND HANDLING

6.1 All samples must have been collected using a sampling plan that addresses the considerations discussed in Chapter Nine of this manual.

6.2 All sample containers must be demonstrated to be free of contamination at or below the reporting limit. Plastic and glass containers are both suitable. See Chapter Three, Section 3.1.3, for further information.

6.3 Nonaqueous samples should be refrigerated upon receipt and analyzed as soon as possible.

6.4 It can be difficult to obtain a representative sample with wet or damp materials. Wet samples may be dried, crushed, and ground to reduce subsample variability as long as drying does not affect the extraction of the analytes of interest in the sample.

7.0 PROCEDURE

7.1 Mix the sample thoroughly to achieve homogeneity and sieve, if appropriate and necessary, using a USS #10 sieve. All equipment used for homogenization should be cleaned according to the guidance in Sec. 6.0 to minimize the potential of cross-contamination. For each digestion procedure, weigh to the nearest 0.01 g and transfer a 1-2 g sample (wet weight) or 1 g sample (dry weight) to a digestion vessel. For samples with high liquid content, a larger sample size may be used as long as digestion is completed.

> NOTE: All steps requiring the use of acids should be conducted under a fume hood by properly trained personnel using appropriate laboratory safety equipment. The use of an acid vapor scrubber system for waste minimization is encouraged.

7.2 For the digestion of samples for analysis by GFAA or ICP-MS, add 10 mL of 1:1 HNO_3, mix the slurry, and cover with a watch glass or vapor recovery device. Heat the sample to 95°C ± 5°C and reflux for 10 to 15 minutes without boiling. Allow the sample to cool, add 5 mL of concentrated HNO_3, replace the cover, and reflux for 30 minutes. If brown fumes are generated, indicating oxidation of the sample by HNO_3, repeat this step (addition of 5 mL of conc. HNO_3) over and over until no brown fumes are given off by the sample indicating the complete reaction with HNO_3. Using a ribbed watch glass or vapor recovery system, either allow the solution to evaporate to approximately 5 mL without boiling or heat at 95°C ± 5°C without boiling for two hours. Maintain a covering of solution over the bottom of the vessel at all times.

NOTE: Alternatively, for direct energy coupling devices, such as a microwave, digest samples for analysis by GFAA or ICP-MS by adding 10 mL of 1:1 HNO_3, mixing the slurry and then covering with a vapor recovery device. Heat the sample to 95°C ± 5°C and reflux for 5 minutes at 95°C ± 5°C without boiling. Allow the sample to cool for 5 minutes, add 5 mL of concentrated HNO_3, heat the sample to 95°C ± 5°C and reflux for 5 minutes at 95°C ± 5°C. If brown fumes are generated, indicating oxidation of the sample by HNO_3, repeat this step (addition of 5 mL concentrated HNO_3) until no brown fumes are given off by the sample indicating the complete reaction with HNO_3. Using a vapor recovery system, heat the sample to 95°C ± 5°C and reflux for 10 minutes at 95°C ± 5°C without boiling.

7.2.1 After the step in Section 7.2 has been completed and the sample has cooled, add 2 mL of water and 3 mL of 30% H_2O_2. Cover the vessel with a watch glass or vapor recovery device and return the covered vessel to the heat source for warming and to start the peroxide reaction. Care must be taken to ensure that losses do not occur due to excessively vigorous effervescence. Heat until effervescence subsides and cool the vessel.

NOTE: Alternatively, for direct energy coupled devices: After the Sec. 7.2 "NOTE" step has been completed and the sample has cooled for 5 minutes, add slowly 10 mL of 30% H_2O_2. Care must be taken to ensure that losses do not occur due to excessive vigorous effervesence. Go to Section 7.2.3.

7.2.2 Continue to add 30% H_2O_2 in 1-mL aliquots with warming until the effervescence is minimal or until the general sample appearance is unchanged.

NOTE: Do not add more than a total of 10 mL 30% H_2O_2.

7.2.3 Cover the sample with a ribbed watch glass or vapor recovery device and continue heating the acid-peroxide digestate until the volume has been reduced to approximately 5 mL or heat at 95°C ± 5°C without boiling for two hours. Maintain a covering of solution over the bottom of the vessel at all times.

NOTE: Alternatively, for direct energy coupled devices: Heat the acid-peroxide digestate to 95°C ± 5°C in 6 minutes and remain at 95°C ± 5°C without boiling for 10 minutes.

7.2.4 After cooling, dilute to 100 mL with water. Particulates in the digestate should then be removed by filtration, by centrifugation, or by allowing the sample to settle. The sample is now ready for analysis by GFAA or ICP-MS.

7.2.4.1 Filtration - Filter through Whatman No. 41 filter paper (or equivalent).

7.2.4.2 Centrifugation - Centrifugation at 2,000-3,000 rpm for 10 minutes is usually sufficient to clear the supernatant.

7.2.4.3 The diluted digestate solution contains approximately 5% (v/v) HNO_3. For analysis, withdraw aliquots of appropriate volume and add any required reagent or matrix modifier.

7.3 For the analysis of samples for FLAA or ICP-AES, add 10 mL conc. HCl to the sample digest from 7.2.3 and cover with a watch glass or vapor recovery device. Place the sample on/in the heating source and reflux at 95^oC ± 5°C for 15 minutes.

NOTE: Alternatively, for direct energy coupling devices, such as a microwave, digest samples for analysis by FLAA and ICP-AES by adding 5 mL HCl and 10 mL H_2O to the sample digest from 7.2.3 and heat the sample to $95^oC \pm 5°C$, Reflux at $95^oC \pm 5°C$ without boiling for 5 minutes.

7.4 Filter the digestate through Whatman No. 41 filter paper (or equivalent) and collect filtrate in a 100-mL volumetric flask. Make to volume and analyze by FLAA or ICP-AES.

NOTE: Section 7.5 may be used to improve the solubilities and recoveries of antimony, barium, lead, and silver when necessary. These steps are optional and are not required on a routine basis.

7.5 Add 2.5 mL conc. HNO_3 and 10 mL conc. HCl to a 1-2 g sample (wet weight) or 1 g sample (dry weight) and cover with a watchglass or vapor recovery device. Place the sample on/in the heating source and reflux for 15 minutes.

7.5.1 Filter the digestate through Whatman No. 41 filter paper (or equivalent) and collect filtrate in a 100-mL volumetric flask. Wash the filter paper, while still in the funnel, with no more than 5 mL of hot (~95°C) HCl, then with 20 mL of hot (~95°C) reagent water. Collect washings in the same 100-mL volumetric flask.

7.5.2 Remove the filter and residue from the funnel, and place them back in the vessel. Add 5 mL of conc. HCl, place the vessel back on the heating source, and heat at 95°C ± 5°C until the filter paper dissolves. Remove the vessel from the heating source and wash the cover and sides with reagent water. Filter the residue and collect the filtrate in the same 100-mL volumetric flask. Allow filtrate to cool, then dilute to volume.

NOTE: High concentrations of metal salts with temperature-sensitive solubilities can result in the formation of precipitates upon cooling of primary and/or secondary filtrates. If precipitation occurs in the flask upon cooling, do not dilute to volume.

7.5.3 If a precipitate forms on the bottom of a flask, add up to 10 mL of concentrated HCl to dissolve the precipitate. After precipitate is dissolved, dilute to volume with reagent water. Analyze by FLAA or ICP-AES.

7.6 Calculations

7.6.1 The concentrations determined are to be reported on the basis of the actual weight of the sample. If a dry weight analysis is desired, then the percent solids of the sample must also be provided.

7.6.2 If percent solids is desired, a separate determination of percent solids must be performed on a homogeneous aliquot of the sample.

8.0 QUALITY CONTROL

8.1 All quality control measures described in Chapter One should be followed.

8.2 For each batch of samples processed, a method blank should be carried throughout the entire sample preparation and analytical process according to the frequency described in Chapter One. These blanks will be useful in determining if samples are being contaminated. Refer to Chapter One for the proper protocol when analyzing method blanks.

8.3 Spiked duplicate samples should be processed on a routine basis and whenever a new sample matrix is being analyzed. Spiked duplicate samples will be used to determine precision and bias. The criteria of the determinative method will dictate frequency, but 5% (one per batch) is recommended or whenever a new sample matrix is being analyzed. Refer to Chapter One for the proper protocol when analyzing spiked replicates.

8.4 Limitations for the FLAA and ICP-AES optional digestion procedure. Analysts should be aware that the upper linear range for silver, barium, lead, and antimony may be exceeded with some samples. If there is a reasonable possibility that this range may be exceeded, or if a sample's analytical result exceeds this upper limit, a smaller sample size should be taken through the entire procedure and re-analyzed to determine if the linear range has been exceeded. The approximate linear upper ranges for a 2 gram sample size:

Ag	2,000 mg/kg
As	1,000,000 mg/kg
Ba	2,500 mg/kg
Be	1,000,000 mg/kg
Cd	1,000,000 mg/kg
Co	1,000,000 mg/kg
Cr	1,000,000 mg/kg
Cu	1,000,000 mg/kg
Mo	1,000,000 mg/kg
Ni	1,000,000 mg/kg
Pb	200,000 mg/kg
Sb	200,000 mg/kg
Se	1,000,000 mg/kg
Tl	1,000,000 mg/kg
V	1,000,000 mg/kg
Zn	1,000,000 mg/kg

NOTE: These ranges will vary with sample matrix, molecular form, and size.

9.0 METHOD PERFORMANCE

9.1 In a single laboratory, the recoveries of the three matrices presented in Table 2 were obtained using the digestion procedure outlined for samples prior to analysis by FLAA and ICP-AES. The spiked samples were analyzed in duplicate. Tables 3-5 represents results of analysis of NIST Standard Reference Materials that were obtained using both atmospheric pressure microwave digestion techniques and hot-plate digestion procedures.

10.0 REFERENCES

1. Rohrbough, W.G.; et al. Reagent Chemicals, American Chemical Society Specifications, 7th ed.; American Chemical Society: Washington, DC, 1986.

2. 1985 Annual Book of ASTM Standards, Vol. 11.01; "Standard Specification for Reagent Water"; ASTM: Philadelphia, PA, 1985; D1193-77.

3. Edgell, K.; USEPA Method Study 37 - SW-846 Method 3050 Acid Digestion of Sediments, Sludges, and Soils. EPA Contract No. 68-03-3254, November 1988.

4. Kimbrough, David E., and Wakakuwa, Janice R. Acid Digestion for Sediments, Sludges, Soils, and Solid Wastes. A Proposed Alternative to EPA SW 846 Method 3050, Environmental Science and Technology, Vol. 23, Page 898, July 1989.

5. Kimbrough, David E., and Wakakuwa, Janice R. Report of an Interlaboratory Study Comparing EPA SW 846 Method 3050 and an Alternative Method from the California Department of Health Services, Fifth Annual Waste Testing and Quality Assurance Symposium, Volume I, July 1989. Reprinted in Solid Waste Testing and Quality Assurance: Third Volume, ASTM STP 1075, Page 231, C.E. Tatsch, Ed., American Society for Testing and Materials, Philadelphia, 1991.

6. Kimbrough, David E., and Wakakuwa, Janice R. A Study of the Linear Ranges of Several Acid Digestion Procedures, Environmental Science and Technology, Vol. 26, Page 173, January 1992. Presented Sixth Annual Waste Testing and Quality Assurance Symposium, July 1990.

7. Kimbrough, David E., and Wakakuwa, Janice R. A Study of the Linear Ranges of Several Acid Digestion Procedures, Sixth Annual Waste Testing and Quality Assurance Symposium, Reprinted in Solid Waste Testing and Quality Assurance: Fourth Volume, ASTM STP 1076, Ed., American Society for Testing and Materials, Philadelphia, 1992.

8. NIST published leachable concentrations. Found in addendum to certificate of analysis for SRMs 2709, 2710, 2711 - August 23, 1993.

9. Kingston, H.M. Haswell, S.J. ed., Microwave Enhanced Chemistry, Professional Reference Book Series, American Chemical Society, Washington, D.C., Chapter 3, 1997.

TABLE 1

STANDARD RECOVERY (%) COMPARISON FOR METHODS 3050A AND 3050B[a]

Analyte	METHOD 3050A[a]	METHOD 3050B w/option[a]
Ag	9.5	98
As	86	102
Ba	97	103
Be	96	102
Cd	101	99
Co	99	105
Cr	98	94
Cu	87	94
Mo	97	96
Ni	98	92
Pb	97	95
Sb	87	88
Se	94	91
Tl	96	96
V	93	103
Zn	99	95

[a] All values are percent recovery. Samples: 4 mL of 100 mg/mL multistandard; n = 3.

TABLE 2

PERCENT RECOVERY COMPARISON FOR METHODS 3050A AND 3050B

	Percent Recovery[a,c]							
Analyte	Sample 4435		Sample 4766		Sample HJ		Average	
	3050A	3050B	3050A	3050B	3050A	3050B	3050A	3050B
Ag	9.8	103	15	89	56	93	27	95
As	70	102	80	95	83	102	77	100
Ba	85	94	78	95	b	b	81	94
Be	94	102	108	98	99	94	99	97
Cd	92	88	91	95	95	97	93	94
Co	90	94	87	95	89	93	89	94
Cr	90	95	89	94	72	101	83	97
Cu	81	88	85	87	70	106	77	94
Mo	79	92	83	98	87	103	83	98
Ni	88	93	93	100	87	101	92	98
Pb	82	92	80	91	77	91	81	91
Sb	28	84	23	77	46	76	32	79
Se	84	89	81	96	99	96	85	94
Tl	88	87	69	95	66	67	74	83
V	84	97	86	96	90	88	87	93
Zn	96	106	78	75	b	b	87	99

a - Samples: 4 mL of 100 mg/mL multi-standard in 2 g of sample. Each value is percent recovery and is the average of duplicate spikes.

b - Unable to accurately quantitate due to high background values.

c - Method 3050B using optional section.

Table 3
Results of Analysis of Nist Standard Reference Material 2704 “River Sediment” Using Method 3050B (µg/g ± SD)

Element	Atm. Pressure Microwave Assisted Method with Power Control	Atm. Pressure Microwave Assisted Method with Temperature Control (gas-bulb)	Atm. Pressure Microwave Assisted Method with Temperature Control (IR-sensor)	Hot-Plate	NIST Certified Values for Total Digestion (µg/g ±95% CI)
Cu	101 ± 7	89 ± 1	98 ± 1.4	100 ± 2	98.6 ± 5.0
Pb	160 ± 2	145 ± 6	145 ± 7	146 ± 1	161 ± 17
Zn	427 ± 2	411 ± 3	405 ± 14	427 ± 5	438 ± 12
Cd	NA	3.5 ± 0.66	3.7 ± 0.9	NA	3.45 ± 0.22
Cr	82 ± 3	79 ± 2	85 ± 4	89 ± 1	135 ± 5
Ni	42 ± 1	36 ± 1	38 ± 4	44 ± 2	44.1 ± 3.0

NA - Not Available

Table 4
Results of Analysis of NIST Standard Reference Material 2710 “Montana Soil (Highly Elevated Trace Element Concentrations)” Using Method 3050B (µg/g ± SD)

Element	Atm. Pressure Microwave Assisted Method with Power Control	Atm. Pressure Microwave Assisted Method with Temperature Control (gas-bulb)	Atm. Pressure Microwave Assisted Method with Temperature Control (IR-sensor)	Hot-Plate	NIST Leachable Concentrations Using Method 3050	NIST Certified Values for Total Digestion (µg/g ±95% CI)
Cu	2640 ± 60	2790 ± 41	2480 ± 33	2910 ± 59	2700	2950 ± 130
Pb	5640 ± 117	5430 ± 72	5170 ± 34	5720 ± 280	5100	5532 ± 80
Zn	6410 ± 74	5810 ± 34	6130 ± 27	6230 ± 115	5900	6952 ± 91
Cd	NA	20.3 ± 1.4	20.2 ± 0.4	NA	20	21.8 ± 0.2
Cr	20 ± 1.6	19 ± 2	18 ± 2.4	23 ± 0.5	19	39*
Ni	7.8 ± 0.29	10 ± 1	9.1 ± 1.1	7 ± 0.44	10.1	14.3 ± 1.0

NA - Not Available

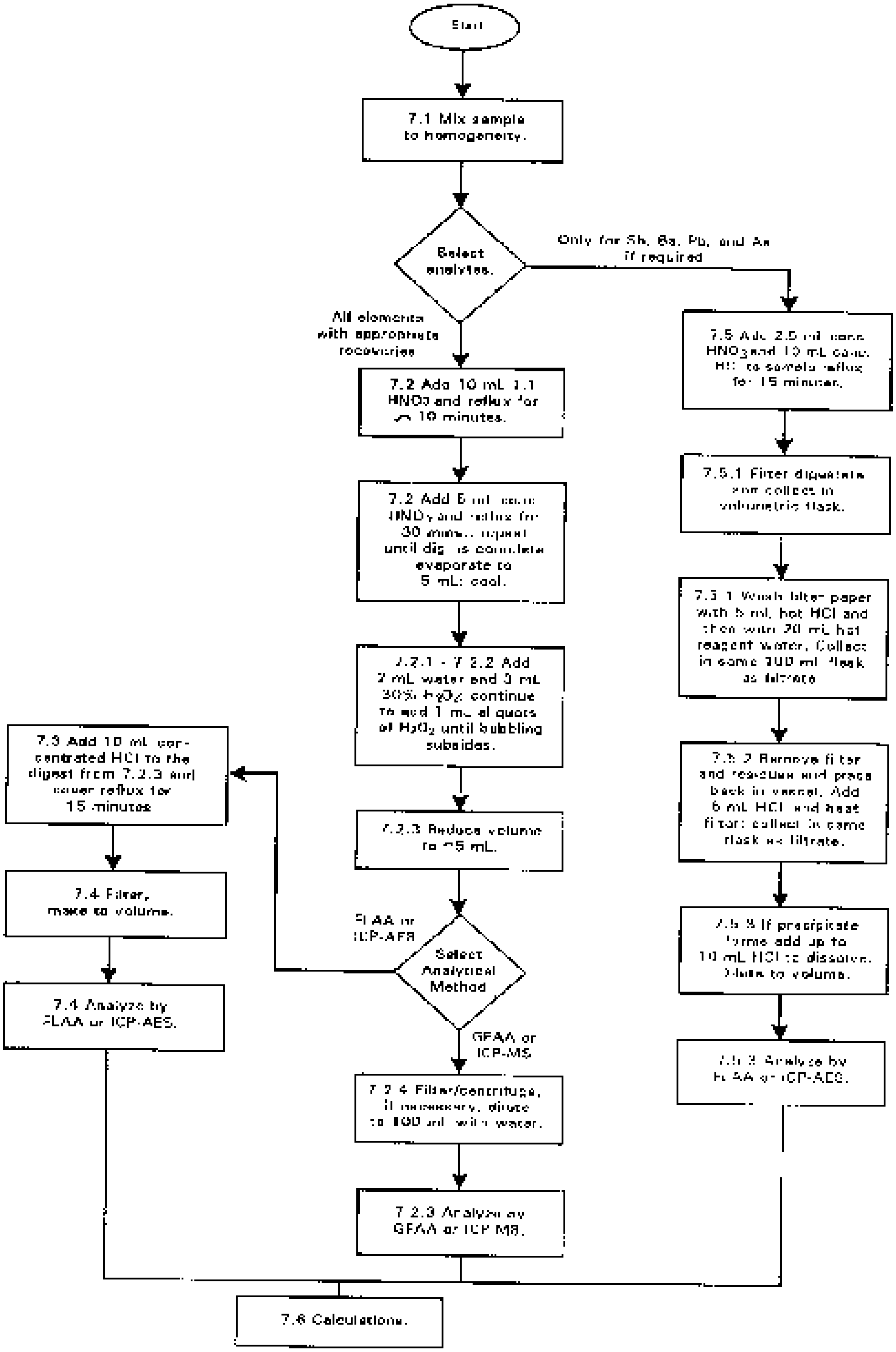
* Non-certified values, for information only.

Table 5
Results of Analysis of NIST Standard Reference Material 2711 "Montana Soil (Moderately Elevated Trace Element Concentrations)" Using Method 3050B
(µg/g ± SD)

Element	Atm. Pressure Microwave Assisted Method with Power Control	Atm. Pressure Microwave Assisted Method with Temperature Control (gas-bulb)	Atm. Pressure Microwave Assisted Method with Temperature Control (IR-sensor)	Hot-Plate	NIST Leachable Concentrations Using Method 3050	NIST Certified Values for Total Digestion (µg/g ±95% CI)
Cu	107 ± 4.6	98 ± 5	98 ± 3.8	111 ± 6.4	100	114 ± 2
Pb	1240 ± 68	1130 ± 20	1120 ± 29	1240 ± 38	1100	1162 ± 31
Zn	330 ± 17	312 ± 2	307 ± 12	340 ± 13	310	350.4 ± 4.8
Cd	NA	39.6 ± 3.9	40.9 ± 1.9	NA	40	41.7 ± 0.25
Cr	22 ± 0.35	21 ± 1	15 ± 1.1	23 ± 0.9	20	47*
Ni	15 ± 0.2	17 ± 2	15 ± 1.6	16 ± 0.4	16	20.6 ± 1.1

NA - Not Available
* Non-certified values, for information only.

METHOD 3050B
ACID DIGESTION OF SEDIMENTS, SLUDGES, AND SOILS



RELATIONSHIPS OF RADON DIFFUSION COEFFICIENT WITH SATURATED HYDRAULIC CONDUCTIVITY, FINES CONTENT AND MOISTURE SATURATION OF RADON/INFILTRATION BARRIERS FOR THE UMTRA PROJECT

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ABSTRACT

The release of ^{222}Radon to the atmosphere from uranium-mill tailings is controlled by the rate of its gas transport through earthen materials. Of the many soil-related parameters, the radon diffusion coefficient is the key parameter that characterizes this transport. We compared the laboratory measured radon diffusion coefficients for the UMTRA Project with simple empirical correlations developed by others. The empirical correlations predict the radon diffusion coefficient based on the fraction of moisture saturation and porosity. One of the more recent correlations agrees reasonably well with the laboratory measurements. In addition, by using a series of correlation curves, we studied the empirical relationships of the radon diffusion coefficient with the saturated hydraulic conductivity, the fines content, and the moisture saturation in soil. The results reveal that a reliable determination of the long-term moisture and porosity is essential in the design of an adequate radon barrier with respect to the radon diffusion coefficient.

INTRODUCTION

The U.S. Department of Energy administers the Uranium Mill Tailings Remedial Action (UMTRA) Project. The UMTRA Project involves the design and construction of disposal embankments to isolate and stabilize abandoned uranium mill tailings at 24 sites in ten states. A prime component of these disposal embankments is a radon/infiltration barrier consisting of soil material. This barrier is designed to control radon flux levels and infiltration of water. Diffusion theory is used to determine the thickness of the radon barrier required to attenuate radon flux to meet the standards set by the U.S. Environmental Protection Agency in 40 CFR 192. The radon diffusion coefficient is the key parameter that characterizes the radon movement through soils. The modeling equation for the radon diffusion mechanism is given by:

$$D \frac{d^2C}{dX^2} - \lambda C + R\rho E\lambda/p = 0 \qquad \text{(Eq.1) (1)}$$

where D = diffusion coefficient for radon in the pore space (cm^2/s)
p = total porosity of the material (dimensionless)
λ = decay constant of radon (2.1×10^{-6} s^{-1})
C = radon concentration in the total pore space (pCi/cm^3)
R = radium-226 content of the dry material (pCi/g)
ρ = dry bulk density of the material (g/cm^3)
E = radon emanation coefficient (dimensionless)

The saturated hydraulic conductivity is the other parameter that is important in the selection and evaluation of a radon/infiltration barrier. As a typical practice during the design phase for the radon/infiltraion barrier, a series of laboratory tests are performed to determine the radon diffusion coefficients and the saturated hydraulic conductivities, together with the basic characterization properties such as the fines contents and compaction characteristics.

Because of the significance of the radon diffusion coefficient in designing an adequate radon barrier, predictive equations relating the radon diffusion coefficient to moisture saturation and porosity was proposed by Rogers et al (1) and most recently by Rogers and Nielson (2). The UMTRA Project has provided an opportunity for the collection of a sizable data base consisting of radon diffusion coefficients, saturated hydraulic conductivities and other characteristics. Therefore, the primary purpose of this paper is to compare the measured radon diffusion coefficients developed for the UMTRA Project with the published predictive equations. Our objective is to verify if the predictive equations will give reasonably accurate diffusion coefficients for use when specific measurements on the soils of interest are not available. Secondly, this paper attempts to study if there is any relationship among the saturated hydraulic conductivity, radon diffusion coefficient, fines content and moisture saturation by developing a series of correlation curves among these parameters.

MATERIAL DATA AND METHODS

Material Data Aquisition

During the design of radon/infiltration barriers for seventeen UMTRA Project sites, 113 samples were tested for radon diffusion coefficients at various moisture saturation fractions. Typically, candidate radon/infiltration barrier materials were local deposits of soils. The nature of the material in each deposit varied greatly, and included local outcroppings, exposed strata, general topsoil or overburden. The samples were compacted mostly in the range of 93 to 100 percent per ASTM D698. Test results from the samples have produced a data base of 545 radon diffusion coefficient measurements. Table 1 tabulates the site designation and soil type/classification of the radon/infiltration barrier soil samples, and the pertinent parameters including the percentage of fines (material passing the No. 200 sieve), the saturated hydraulic conductivity, maximum dry density and compaction level.

[PLACE TABLE I HERE]

All tests to determine radon diffusion coefficients for the UMTRA Project were performed by Rogers and Associates Engineering Corporation, Salt Lake City, Utah. The radon diffusion coefficients were measured by the transient diffusion method at different moisture saturations. The conceptual basis of the experimental meaurements as reported by Rogers and Associates is as follows: a column containing the soil to be tested is exposed on one end at time zero to a large volume of air containing a known high radon concentration; a continuous alpha particle detector is sealed to the opposite end of the column to measure the alpha activity from radon and its daughters; as radon diffuses through the soil, the measured alpha activity increases to a constant maximum level which corresponds to an equilibrium radon distribution throughout the soil; the measured alpha activity buildup curve is then compared to theoretical curves calculated for various diffusion coefficients, and the actual diffusion coefficient is inferred from the best fit.

Saturated hydraulic conductivities were performed by several soil laboratories and measured using either one of the three conventional testing methods: the triaxial, the falling head, or the constant head permeability tests.

It should be noted that the radon/infiltration barriers for some UMTRA Project sites are bentonite-amended, and radon diffusion coefficients were tested with bentonite mixed in the samples. To maintain a compatible data base, these bentonite-amended radon diffusion coefficient measurements were not included in this study.

Predictive Correlations of Radon Diffusion Coefficients

1. Overview - It is often desirable to estimate the diffusion coefficient of materials under varying conditions for which measured values are not available. This can be accomplished with either complex models based upon physical characteristics of the soils, or with empirical correlations based upon measured values of radon diffusion coefficients. For a given soil, the soil moisture, compaction and pore size distribution are important factors controlling the value of the diffusion coefficient.

Empirical correlations for predicting radon diffusion coefficients have the advantage of being simple and easy to use, with a minimal amount of information needed. Rogers et al (3) developed the early correlations relating diffusion coefficients to the wet weight-percent moisture in the soil. Subsequently, the development of the model revealed that the moisture saturation fraction, m, was the primary fundamental parameter characterizing diffusion coefficient. The widely used correlation (1) as a function of the parameter, m, is given by:

$$D = 0.07 \exp[-4(m - mp^2 + m^5)] \qquad \text{(Eq.2)}$$

where m = moisture saturation fraction
p = total porosity

The exponential argument in the correlation is a simple power series in m. The first term defines the general downward slope, while the second term contains the porosity influence and also causes a more gradual decrease with moisture in the pore filling region of the soil. The final term in the exponential argument accounts for major pore blockage near saturation and causes the more rapid decreases needed in this region.

Rogers et al (1) further stated that the correlation, based on their data base of about 200 elements, has a geometric standard deviation of 2.0. However, individual estimates for a particular soil at a given moisture may be uncertain by as much as an order of magnitude, especially for high values of m.

A most recent correlation equation, based on a data base of 1,073 diffusion coefficient measurements on natural soils, was developed (2) to update the correlation given by equation (2). The new correlation is given by:

$$D = D_0 \, p \exp(-6mp - 6m^{14p}) \qquad \text{(Eq.3)}$$

where D_0 = radon diffusion coefficient in air (0.11 cm^2/s)

The porosity term (p) preceding the exponential argument approximates the effect of tortuosity, with a higher compaction causing a lower value for p. The higher compaction causes a more tortuous pathway for radon diffusion and thus accordingly a lower diffusion coefficient, even at low fractions of moisture saturation. The first term in the exponential argument dominates the moisture-dependence of D for $m \leq 0.5$. It accounts for the effect that a greater mass of water is stored at high porosity than at low porosity at a given moisture saturation fraction. The extra water blocks a larger fraction of the small pores in the high-porosity material, thus causing a greater relative decrease in D for the high-porosity material. The second term in the exponential accounts for the relatively rapid decrease in diffusion coefficient at high moisture saturations, when most of the pores are blocked by water. In general, soils with high porosities tend to have more uniform-sized particles, giving a narrower pore size distribution. Consequently, fewer pores are totally filled with water until the moisture content approaches saturation. This causes the diffusion coefficient of high-porosity soils to remain higher with increasing water above m = 0.6, and then to decrease more rapidly as m approaches unity. Low-porosity soils tend to have a wider particle size distribution and a larger fraction of small pores. Their small pores fill with water at lower fractions of saturation, blocking radon migration and resulting in a lower D for moisture saturation m greater than 0.6, and a less steep decrease near saturation. The porosity term in the exponential argument partially acounts for this dependence as m approaches saturation. The coefficient of six(6) on the last term defines the value of D at saturation.

2. Comparison - The 545 measured radon diffusion coefficients developed for the UMTRA Project radon/infiltration barriers (Table 1) were used to compare with and verify the two predictive correlations described above. The porosities of the samples range from 0.26 to 0.61, with an average of 0.39. The comparisons were made by plotting all the measured data points and the predictive equation lines using the upper and lower measured porosities as shown in Figures 1 and 2 respectively. The function lines using the average porosity were also plotted.

[PLACE FIG. 1 HERE]
[PLACE FIG. 2 HERE]

Relationships Among Radon Diffusion Coefficient, Saturated Hydraulic Conductivity and Moisture Saturation

The saturated hydraulic conductivity is a well-established and commonly used parameter. It is therefore desirable to determine what relationship may exist between saturated hydraulic conductivity (k) and radon diffusion coefficient (D) at various fractions of moisture saturation (m). In order to do so, the authors have attempted to develop a series of radon diffusion coefficient vs. moisture saturation curves for the range of saturated hydraulic conductivity values given in Table 1. Firstly, for each moisture saturation fraction at which diffusion coefficients were tested, D was plotted against the corresponding k for that particular sample. Then a best fit of D vs. k was obtained. A typical D vs. k plot is shown in Figure 3. This plot provided the interpolated or extrapolated D values at the designated saturated hydraulic conductivity (k) of 10^{-5}, 10^{-6}, 10^{-7}, and 10^{-8} cm/s. Finally, based on all the D vs. k plots, variations of diffusion coefficient with moisture saturation plots (D vs. m) were developed for k values of 10^{-5}, 10^{-6}, 10^{-7}, and 10^{-8} cm/s, and the best fit correlation curves were constructed. Figure 4 shows the D-k-m correlation curves.

[PLACE FIG. 3 HERE]
[PLACE FIG. 4 HERE]

Relationships Among Radon Diffusion Coefficient, Fines Content and Moisture Saturation

The relationship between diffusion coefficient and fines content (material passing the No. 200 sieve) at various moisture saturation fractions was evaluated because the fines content parameter is a convenient way to classify soils. A similar procedure described in the previous section for developing D-k-m relationships was employed. Firstly, plots of D vs. fines content (F_{cm}) were developed based on the data in Table 1 for each tested moisture saturation fraction. A typical D vs. F_{cm} plot with the best fit line is shown in Figure 5. Interpolated or extrapolated D values at the designated fines contents of 20%, 40%, 60% and 80% were then obtained. Finally, variations of diffusion coefficient with moisture saturation plots (D vs. m) were developed for fines content values of 20%, 40%, 60% and 80%, and the best fit correlation curves were constructed. Figure 6 shows the D-F_{cm}-m correlation curves.

[PLACE FIG. 5 HERE]
[PLACE FIG. 6 HERE]

RESULTS AND DISCUSSIONS

Comparison of Measured Radon Diffusion Coefficients with Published Predictive Equations

Figure 1 illustrates the comparison of the body of radon diffusion coefficient measurements with the earlier correlation function by equation (2), using the upper, average and lower measured porosities obtained from the data base for the function. For intermediate moisture saturation fractions ($0.3 \leq m \leq 0.8$), the correlation by equation (2) was found to agree fairly well with the measurements. However, at lower moisture saturation ($m < 0.3$), the correlation function tends to over-estimate the radon diffusion coefficients. The majority of the data points in this region lie below the function lines. At high moisture saturation ($m > 0.8$), the function also tends to estimate higher diffusion coefficients as it lies above the majority of the data points. However, at high moistures relatively small errors in sample moisture content, density, or specific gravity estimates from which the saturation, m, is estimated may result in large apparent errors in diffusion coefficients. Therefore, the predicted D values might be acceptable in order to provide a reasonable degree of conservatism to account for these errors.

A comparison of the measured radon diffusion coefficients with the recently proposed correlation by Rogers and Nielson (2) is illustrated by Figure 2. The correlation, given by equation (3) using the upper and lower measured porosities, was found to agree well with the measured data points over the whole range of moisture saturation at which diffusion coefficient measurements were made. Therefore, this new correlation provides a more reliable and accurate prediction of D than the previous correlation.

Relationships Among Radon Diffusion Coefficient, Saturated Hydraulic Conductivity and Moisture Saturation

Correlation curves among the diffusion coefficient (D), saturated hydraulic conductivity (k), and moisture saturation (m) were developed as shown in Figure 4. An apparent trend was observed. At a given moisture saturation, m, of the radon barrier material, the diffusion coefficient decreases as the saturated hydraulic conductivity decreases. This trend is agreeable with the general notion that both D and k have direct relations with the common parameter, p, the porosity. The more tortuous the radon pathway, which is defined by the tortuosity, τ, the lower is the radon diffusion coefficient (4). The tortuosity is a function of the soil porosity. For a soil of approximately uniform pore size distribution, the relationship of τ with p is given by:

$$\tau = \{1+[3(1-p)/2\pi]^{2/3}\}^{-1} \quad \text{(Eq. 4)} \quad (5)$$

Thus, a lower porosity gives a lower τ, that is, a more tortuous radon pathway and accordingly a lower diffusion coefficient.

The satuated hydraulic conductivity is also related to the porosity as given by the well-known Kozeny-Carmen equation (6), which takes the form:

$$k = (\rho g/\mu)[p^3/(1-p)^2](d_m^2/180) \qquad \text{(Eq.5)}$$

where ρ = fluid density
μ = fluid viscosity
d_m = representative grain size

Thus, a lower porosity gives a lower saturated hydraulic conductivity, k.

The magnitude of the variation in D, however, is not as prominent as the corresponding variation in k, as indicated by the narrow width of variations of D with k as shown in Figure 4.

The sources of uncertainties of the correlation between D, k, and m include the potential errors in obtaining the D values for the designated k from the D vs. k plot for each m, and also the potential errors in obtaining a fit curve based on the interpolated/extrapolated data points. These uncertainties increase at high moisture saturation (m > 0.8) due to the lack of adequate reliable data points.

Relationships Among Radon Diffusion Coefficient, Fines Content and Moisture Saturation

Correlation curves among the radon diffusion coefficient (D), fines content (F_{cm}) and moisture saturation (m) were developed as shown in Figure 6. It was observed that diffusion coefficients decrease slightly as fines contents increase from 20% to 60%, but the decrease becomes indistinquishable as fines contents increase from 60% to 80%. The small variations of D with fines contents may imply that the effect of the fines content on the value of the radon diffusion coefficient D of a soil is not very significant. Soil characteristics like the pore size distribution and the porosity appear to have a greater influence on the diffusion coefficient. According to Nielson et al (7), for soils with the same median pore radius, the diffusion coefficient may vary as much as an order of magnitude when the geometric standard deviation (GSD) of the pore size distribution is varied from GSD = 1 to GSD = 5.

The sources of uncertainties of this correlation also include the potential errors in obtaining the D values for the designated fines content F_{cm} from the D vs. F_{cm} plot for each m, and also the potential errors in obtaining a fit curve based on the interpolated/extrapolated data points. These uncertainties increase at high moisture saturation ($m > 0.8$) due to the lack of adequate reliable data points.

CONCLUSIONS

The recently published (2) predictive correlation of diffusion coefficient given by equation (3) agrees with the UMTRA Project measurements better than the previous correlation (1) as given by equation (2). The previous correlation tends to over-estimate diffusion coefficients at low moistures ($m < 0.3$) and high moistures ($m > 0.8$). The UMTRA radon barriers are often designed for relatively low long-term moisture content, for example the 15-bar moisture content for conservatism. Additional unnecessary conservatism in the estimation of the diffusion coefficient at the low moisture saturation region may result in a more costly radon barrier design.

From the study of the relationships of radon diffusion coefficients with saturated hydraulic conductivities, an apparent trend was observed. Diffusion coefficients, D, tend to decrease with saturated hydraulic conductivities, k, with the rate of the variation of k being more prominent than the rate of variation of D. From the study of the relationships between radon diffusion coefficients and the fines contents, F_{cm}, it was found that there was only a slight dependency of the diffusion coefficient on the fines content. Diffusion coefficients decrease slightly as fines contents increase from 20% to 60%. The variation in D is almost minimal as F_{cm} increase from 60% to 80%. Therefore, in designing an adequate radon barrier, reliable determinations of the long-term moisture and the porosity are more important and essential than the simple classification of the soil type by fines content.

REFERENCES

1. V.C. ROGERS, K.K. NIELSON, D.C. RICH, G.M. SANDQUIST, AND M.L. MAUCH, "Radon Attenuation with Earthen Covers, 1982 Annual Report to the U.S. Department of Energy on UMTRAP Technology Development," RAE-33-14, Rogers and Associates Engineering Corp., Salt Lake City, Utah (1982).
2. V.C. ROGERS AND K.K. NIELSON, "Correlations for Predicting Air Permeabilities and ^{222}Rn Diffusion Coefficients of Soils," Health Physics, Vol. 61, No. 2 (August 1991).
3. V.C. ROGERS, R.F. OVERMYER, AND K.K. NIELSON, "Radon Attenuation Through Cover Materials," Uranium Mill Tailings Management - II, Ft. Collins: Colorado State University, p. 145 - 156 (November 1979).

4. F.R. TROEH, J.D. JABRO, AND D. KIRKHAM, "Gaseous diffusion equations for porous materials", Geoderma 27:239-253 (1982).
5. K.K. NIELSON, AND V.C. ROGERS, "A Mathematical Model for Radon Diffusion in Earthen Materials". NUREG/CR-2765, U.S. Nuclear Regulatory Commission, Washington, D. C. (1982a).
6. J. BEAR, "Dynamics of Fluids in Porous Media," American Elsevier, New York (1972).
7. K.K. NIELSON, V.C. ROGERS, AND G.W. GEE, "Diffusion of Radon through Soils: A Pore Distribution Model," Soil Science Soc. Am. J. 48:482-487 (1984).

TABLE I
UMTRA PROJECT RADON/INFILTRATION BARRIER MATERIAL DATA
(Sheet 1 of 5)

Site	Sample No.	Unified Soil Classification	Maximum Dry Density$^{(1)}$ (pcf)	As Compacted		Percent Fines (%)	Porosity (P)	Specific Gravity (Gs)	Saturated Hydraulic Conductivity (k) (cm/s)	No. of Diffusion Coefficient Measurements
				Percent Compaction	Dry Density (pcf)					
Ambrosia Lake, New Mexico	AMB-518	CH	100.0	95%	95.0	88	0.45	2.78	2.0E-07	8
	AMB-519	CH	102.5	95%	97.4	84	0.43	2.74	N/A	8
	AMB-517	SC	102.3	95%	97.2	48	0.426	2.72	2.0E-07	8
	AMB-516	CL	115.0	95%	109.3	53	0.34	2.67	N/A	8
	1-RAD	SM-SC	110.6	95%	105.4	37	0.38	2.71	9.1E-07	2
	3-RAD	CL	100.6	95%	95.6	73	0.446	2.78	8.2E-07	2
	5-RAD	CL	99.7	95%	95.0	55	0.45	2.78	7.0E-07	2
Belfield/ Bowman, N. Dakota	BOW 01-8	CL	100.5	95%	96.4	95	0.43	2.71	2.5E-08	4
	BOW 01-6	CL	100.5	95%	96.4	96	0.45	2.78	6.3E-09	4
	BOW 01-11	CL	99.8	95%	94.8	99	0.45	2.77	8.4E-09	4
	#2 (16-40")	CH	98.2	95%	93.3	99	0.45	2.73	1.4E-09	5
	#6 (30-42")	CL-CH	103.4	100%	103.4	99	0.39	2.74	4.9E-09	5
Durango, Colorado	WPRB-1	N/A	107.7	95%	102.3	N/A	0.39	2.70	N/A	5
	WPRB-3	N/A	107.7	95%	102.3	N/A	0.39	2.70	N/A	5
	WPRB-4	N/A	107.1	95%	101.7	N/A	0.398	2.70	N/A	5
	WPRB-6	N/A	106.3	95%	101.0	N/A	0.4	2.70	N/A	5
	WPRB-7	N/A	106.2	100%	106.2	N/A	0.37	2.70	N/A	5
	WPRB-8	N/A	103.8	95%	98.6	N/A	0.42	2.70	N/A	5
	BCRB-9	N//A	108.1	95%	102.7	N/A	0.39	2.70	N/A	5
	BCRB-11	N/A	106.7	95%	101.3	N/A	0.4	2.70	N/A	5
	BCRB-14	N/A	113.0	95%	107.3	N/A	0.36	2.70	N/A	5
Falls City, Texas	TP-15	SC	77.0	95%	73.2	44	0.53	2.5	2.2E-08	5
	FCT-11	CH	78.6	95%	74.7	90	0.565	2.76	3.7E-08	8
	FCT-03	CH	77.6	95%	73.7	97	0.565	2.67	N/A	8
	TP-12B	CH	80.5	95%	76.5	65	0.522	N/A	1.6E-09	5
	TP12A	OH	78.7	95%	74.9	57.5	0.53	2.57	6.2E-08	5
	TP-11	SM	102.8	95%	97.7	45	0.39	N/A	1.1E-07	5
	TP-14	OH	97.8	95%	92.9	54	0.434	2.65	1.7E-08	5
	FCT-05	CH	77.4	95%	73.5	96	0.56	2.68	1.9E-08	8

TABLE I
UMTRA PROJECT RADON/INFILTRATION BARRIER MATERIAL DATA
(Sheet 2 of 5)

Site	Sample No.	Unified Soil Classification	Maximum Dry Density$^{(1)}$ (pcf)	As Compacted		Percent Fines (%)	Porosity (P)	Specific Gravity (Gs)	Saturated Hydraulic Conductivity (k) (cm/s)	No. of Diffusion Coefficient Measurements
				Percent Compaction	Dry Density (pcf)					
Grand Junction, Colorado	TP-123	SC	114.3	95%	108.6	49	0.37	2.788	4.7E-07	5
	TP-125	CL	109.66	95%	104.3	88	0.395	2.768	3.9E-07	6
	TP-127	CL	117.5	95%	111.7	67	0.352	2.772	4.7E-08	5
	TP-130	CL	110.6	95%	105.1	64	0.39	2.767	4.0E-07	5
	TP-131	CL	114.9	95%	109.2	66	0.364	2.762	1.2E-07	5
	TP-136	CL	114.9	95%	109.2	88	0.372	2.788	2.4E-07	5
Gunnison, Colorado	SX-4	SC	115.5	95%	109.7	48	0.346	2.71	1.4E-07	5
	SX-5	CL	107.0	95%	101.7	71	0.394	2.71	1.0E-07	5
	SX-8	CL	113.0	82%	92.7	63	0.45	2.71	3.9E-06	5
	SX-1	SC-SM	120.0	82%	98.4	24	0.422	2.71	4.8E-06	5
	SX-4B	SC	115.5	82%	94.7	48	0.44	2.71	2.2E-06	5
Mexican Hat,Utah/ Monument Valley, Airzona	RB407408	N/A	114.5	100%	114.5	24	0.3	2.63	5.1E-05	3
	RB402404	N/A	117.5	100%	117.5	N/A(~36)	0.29	2.66	2.1E-05	3
	RB702	SP-SM	121.0	100%	121.0	16	0.263	2.63	1.9E-04	3
	RB702705	N/A	111.5	100%	111.5	14	0.323	2.65	1.0E-04	3
Lakeview, Oregon	LKV02-802	GM	95.6	95%	91.4	30	0.43	2.58	7.9E-07	9
	LKV02-805	ML	64.5	93%	60.2	84	0.61	2.50	3.2E-07	11
Lowman, Idaho	TP-1 (3-5)	SM-SC	122.3	95%	116.2	20	0.292	2.65	N/A	6
	TP-1 (7-9)	SM	121.1	95%	115.0	17	0.3	2.66	4.5E-06	6
	TP-2 (3-5)	SM-SC	121.0	95%	115.0	34	0.3	2.64	1.7E-06	6
	TP-3 (5-7)	SM	121.5	95%	115.4	29	0.315	2.7	2.1E-06	6
	TP-4 (3-5)	SM	120.5	95%	114.5	18	0.32	2.7	N/A	6
	TP-4 (7-9)	SM	119.5	95%	113.5	17	0.313	2.64	N/A	6

TABLE I
UMTRA PROJECT RADON/INFILTRATION BARRIER MATERIAL DATA
(Sheet 3 of 5)

Site	Sample No.	Unified Soil Classi-fication	Maximum Dry Density$^{(1)}$ (pcf)	As Compacted		Percent Fines (%)	Porosity (P)	Specific Gravity (Gs)	Saturated Hydraulic Conductivity (k) (cm/s)	No. of Diffusion Coefficient Measurements
				Percent Compac-tion	Dry Density (pcf)					
Naturita, Colorado	MCT-5	CL	109.6	95%	104.1	80	0.376	2.68	5.4E-08	5
	MCT-7	CL	105.8	95%	100.5	85	0.41	2.73	1.8E-08	5
	MCT-10-11	CL-SM	109.5	95%	104.0	65	0.38	2.70	2.8E-08	6
	MCT-15	OL	107.6	95%	102.2	72	0.38	2.67	2.0E-08	6
	MCT-16	CL	113.1	95%	107.4	74	0.357	2.69	1.2E-08	6
	NAT-502	SC	115.9	9%	109.9	45	0.34	2.68	5.5E-07 2.6E-07 1.2E-05	8
	NAT-506	N/A	105.9	95%	100.6	N/A	0.43	2.83	N/A	8
	NAT-509	N/A	111.2	95%	105.6	N/A	0.37	2.70	N/A	8
Rifle, Colorado	MET-8B	SC-CL	110.5	95%	105.0	50	0.368	2.66	N/A	4
	MEB-8	SC	119.0	95%	113.1	34	0.32	2.66	4.9E-07	4
	MET-5	SC	113.5	95%	107.8	48	0.35	2.68	4.7E-07	4
Salt Lake City, Utah	SLC-02-021	N/A	105.1	95%	99.8	N/A	0.43	2.79	N/A	2
	SLC-02-022	N/A	105.1	95%	99.8	N/A	0.415	2.76	N/A	2
	SLC-02-023	N/A	103.8	95%	98.6	N/A	0.415	2.68	N/A	2
	SLC-02-024	N/A	103.5	95%	98.3	N/A	0.41	2.66	N/A	2
	SLC-02-025	N/A	104.1	95%	98.9	N/A	0.41	2.69	N/A	2
	SLC-02-026	N/A	103.1	95%	98.0	N/A	0.42	2.69	N/A	2
	SLC-02-027	N/A	106.4	95%	101.1	N/A	0.4	2.68	N/A	2
	SLC-02-028	N/A	101.8	95%	96.7	N/A	0.42	2.66	N/A	2
	SLC-02-029	N/A	103.8	95%	98.6	N/A	0.46	2.63	N/A	2
	SLC-02-030	N/A	103.8	95%	98.6	N/A	0.4	2.75	N/A	2
	SLC-02-031	N/A	103.8	95%	98.6	N/A	0.4	2.65	N/A	2
	SLC-02-032	N/A	102.5	95%	97.3	N/A	0.41	2.66	N/A	2
	SLC-02-033	N/A	100.5	95%	95.5	N/A	0.44	2.73	N/A	2
	SLC-02-034	N/A	103.8	95%	98.6	N/A	0.39	2.6	N/A	2

TABLE I
UMTRA PROJECT RADON/INFILTRATION BARRIER MATERIAL DATA
(Sheet 4 of 5)

Site	Sample No.	Unified Soil Classi-fication	Maximum Dry Density (pcf)	As Compacted		Percent Fines (%)	Porosity (P)	Specific Gravity (Gs)	Saturated Hydraulic Conductivity (k) (cm/s)	No. of Diffusion Coefficient Measurements
				Percent Compac-tion	Dry Density (pcf)					
Salt Lake City, Utah (Continued)	SLC-02-035	N/A	109.4	95%	103.9	N/A	0.375	2.68	N/A	2
	SLC-02-036	N/A	105.8	95%	100.5	N/A	0.39	2.63	N/A	2
	SLC-02-037	N/A	98.9	95%	93.9	N/A	0.44	2.69	N/A	2
	SLC-02-038	N/A	103.8	95%	98.6	N/A	0.415	2.69	N/A	2
	SLC-02-039	N/A	104.4	95%	99.2	N/A	0.4	2.67	N/A	2
	SLC-02-040	N/A	109.0	95%	103.6	N/A	0.375	2.66	N/A	2
	SLC-303(4-8)	N/A	92.1	93%	85.7	N/A	0.51	2.83	N/A	11
	SLC-303(10.5-13)	N/A	112.5	94%	105.8	N/A	0.4	2.83	N/A	10
	SLC-303(4-8)	N/A	92.1	95%	87.5	N/A	0.51	2.83	N/A	6
	SLC-306(0-3)	N/A	97.0	95%	92.2	N/A	0.45	2.71	N/A	12
Shiprock, New Mexico	#1(0-2.5')	SM	114.3	95%	108.6	24	0.3	2.498	N/A	6
	#2(2-7.5')	ML	114.6	95%	108.9	73	0.34	2.654	2.7E-05	6
	#3(7-11')	SM	118.8	95%	112.9	40	0.35	2.796	1.9E-07	6
	#3(11-15')	ML	117.9	95%	112.0	75	0.28	2.478	N/A	6
	#4(1-10')	ML	116.0	95%	110.2	86	0.33	2.617	N/A	7
	#8(Shale)	GC	121.3	95%	115.2	23	0.35	2.82	2.0E-09	6
	Devils Wash #2	ML	115.9	95%	110.1	75	0.34	2.67	N/A	6
Slickrock, Colorado	RB-2(0-3)	CL	111.0	95%	105.5	65	0.39	2.67	N/A	3
	RB-2(3-9)	SC	118.0	95%	112.1	38	0.32	2.67	7.3E-08	3
	RB-4(2-4)	CL	111.5	95%	105.9	71	0.387	2.8	N/A	3
	RB-4(6-8)	CL	110.5	95%	105.0	56	0.4	2.8	4.1E-08	3
	RB-6(0-3)	SC	118.5	95%	112.6	30	0.35	2.8	5.6E-07	3
	RB-6(6-9)	CL	109.5	95%	104.0	63	0.403	2.8	1.4E-8	3

TABLE I
UMTRA PROJECT RADON/INFILTRATION BARRIER MATERIAL DATA
(Sheet 5 of 5)

Site	Sample No.	Unified Soil Classi-fication	Maximum Dry Density[1] (pcf)	As Compacted		Percent Fines (%)	Porosity (P)	Specific Gravity (Gs)	Saturated Hydraulic Conductivity (k) (cm/s)	No. of Diffusion Coefficient Measurements
				Percent Compac-tion	Dry Density (pcf)					
Tuba City, Arizona	MK150 0-3	SW-SM	114.8	100%	114.8	10	0.31	2.66	1.7E-08	3
	MK152 0-6	SC	110.8	100%	110.8	34	0.34	2.73	4.89E-09	3
	MK154 0-8	SC	111.7	100%	111.7	27	0.33	2.68	1.9E-08	3
	MK156 0-4	SW-SM	115.7	100%	115.7	17	0.31	2.7	1.5E-08	3
	MK158 0-6	SC	108.1	100%	108.1	28	0.36	2.68	1.0E-08	3
	MK160 0-4	CL	101.3	100%	101.3	50	0.41	2.74	6.7E-09	3
	MK163 0-4	SC	110.5	100%	110.5	36	0.35	2.72	7.1E-09	3
	MK165 0-5	SM	113.6	100%	113.6	28	0.32	2.7	2.9E-09	3
	MK167-0-2	SC	113.7	100%	113.7	33	0.32	2.69	3.1E-09	3
	TP-41 1-3	SC	111.8	100%	111.8	44	0.38	2.73	5.0E-07	9
	TP-42 1-7	SM-SC	113.6	100%	113.6	22	0.38	2.81	6.5E-08	9
	TP-44 0-8.5	SM	114.8	100%	114.8	22	0.32	2.71	7.8E-08	9
	TP-46 0-8	SM-SC	109.5	1005	109.5	32	0.39	2.75	2.0E-06	9

[1] As per ASTM D698 (Standard Proctor Test).
N/A = Data Not Available.

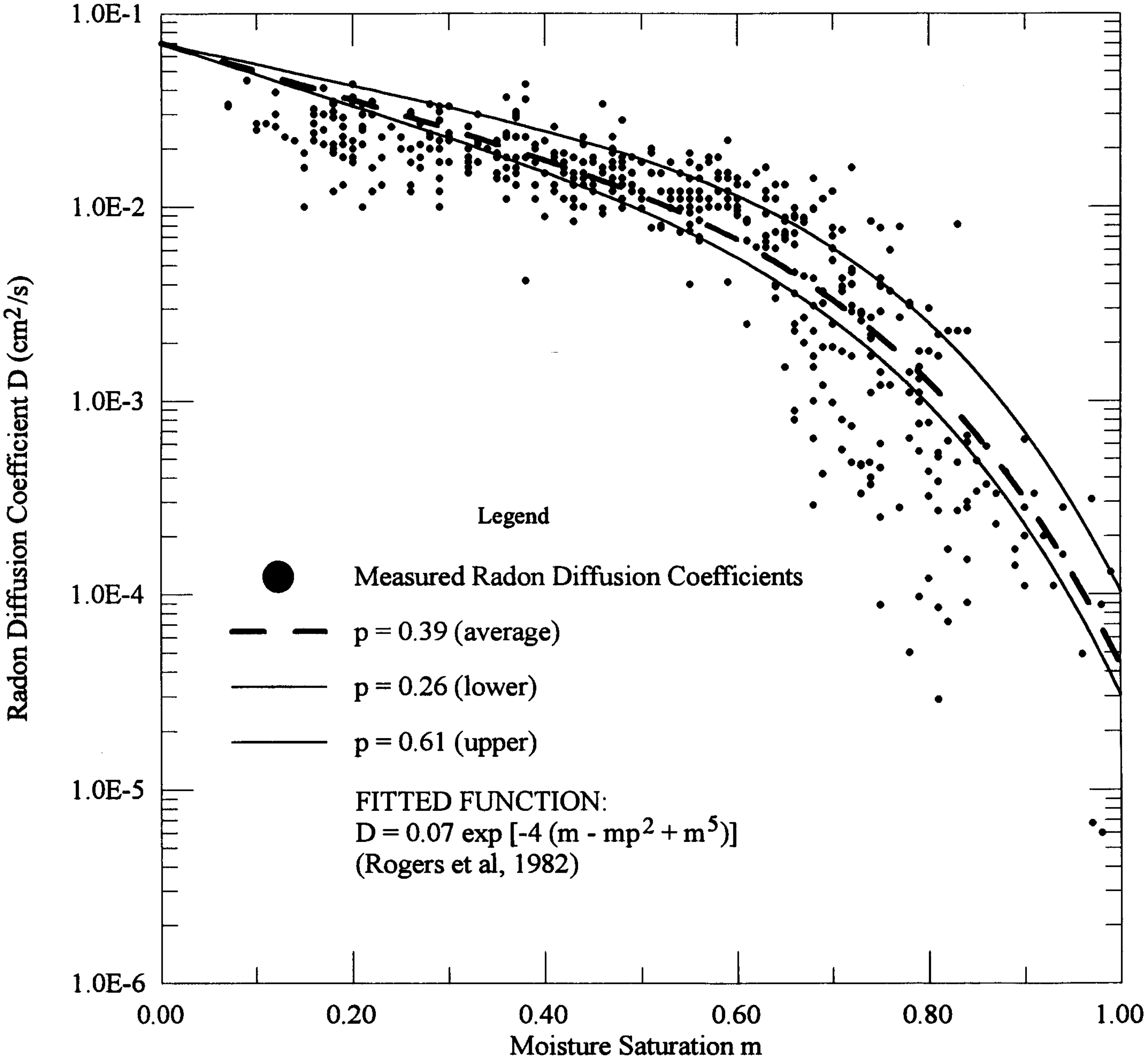

FIG. 1 Comparison of measured radon diffusion coefficients with predictive correlation by Rogers et al. (1982) (1)

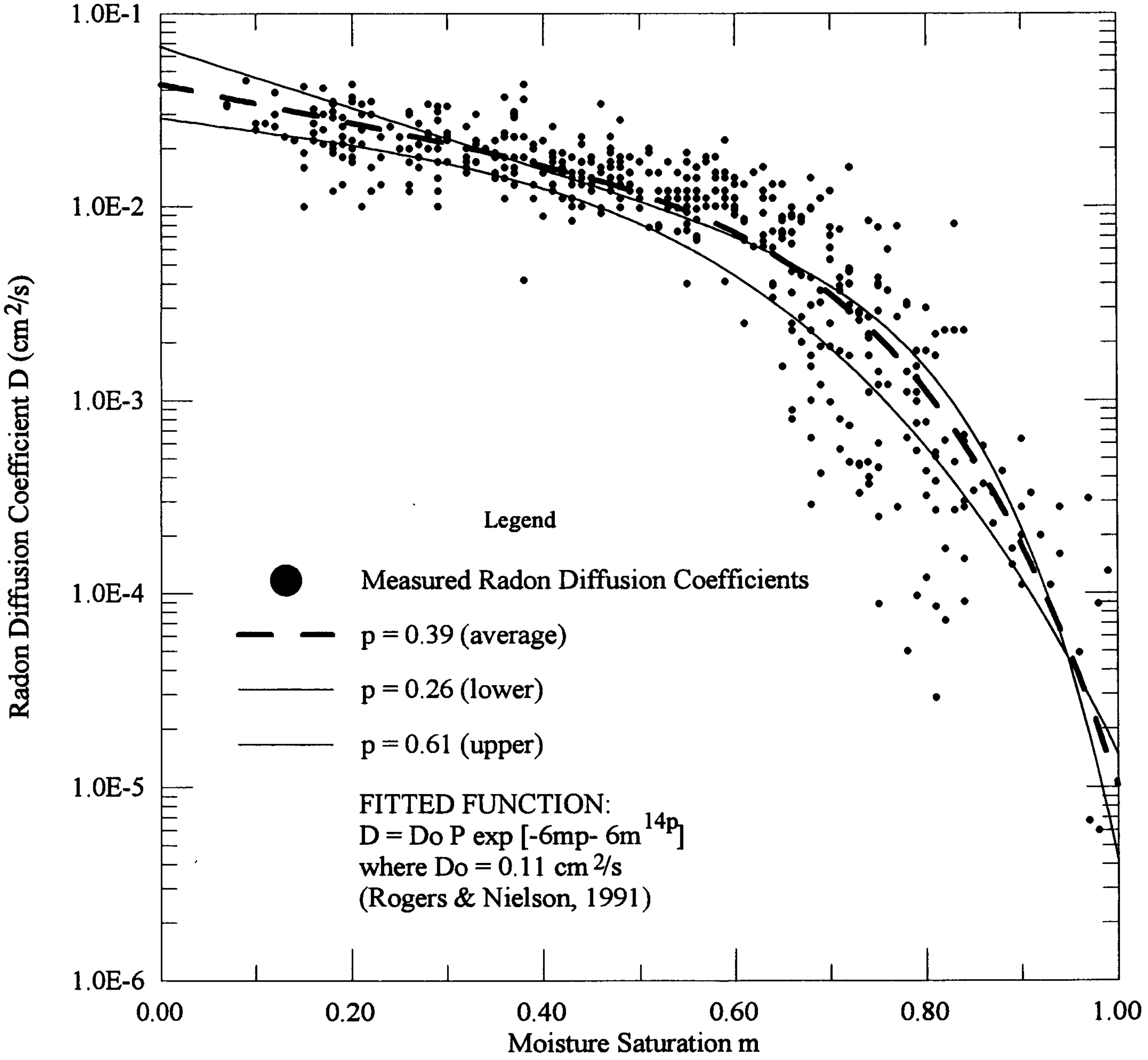

FIG. 2 Comparison of measured radon diffusion coefficients with predictive correlation by Rogers and Nielson (1991) (2)

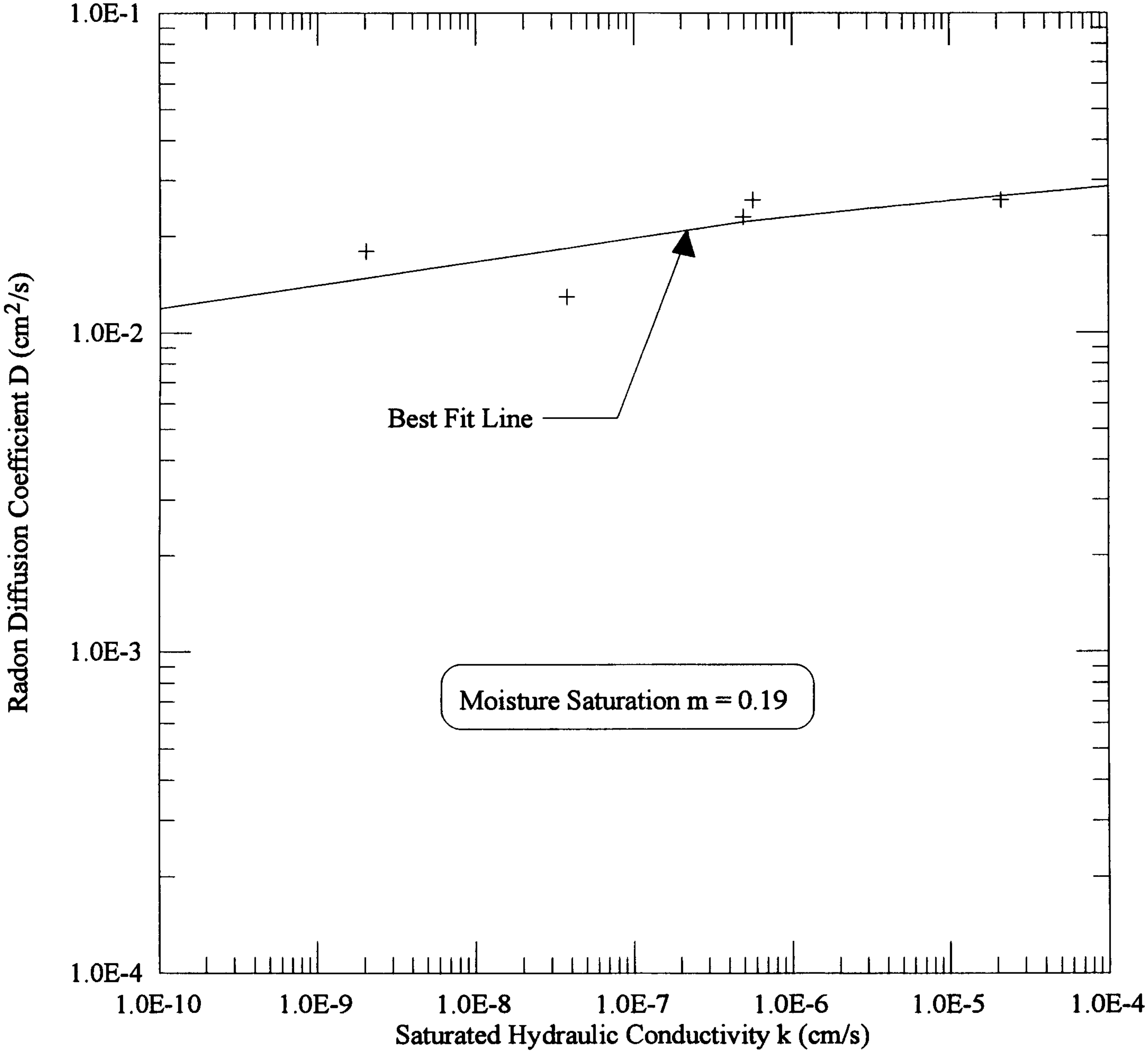

FIG. 3 Typical plot of radon diffusion coefficient vs. saturated hydraulic conductivity

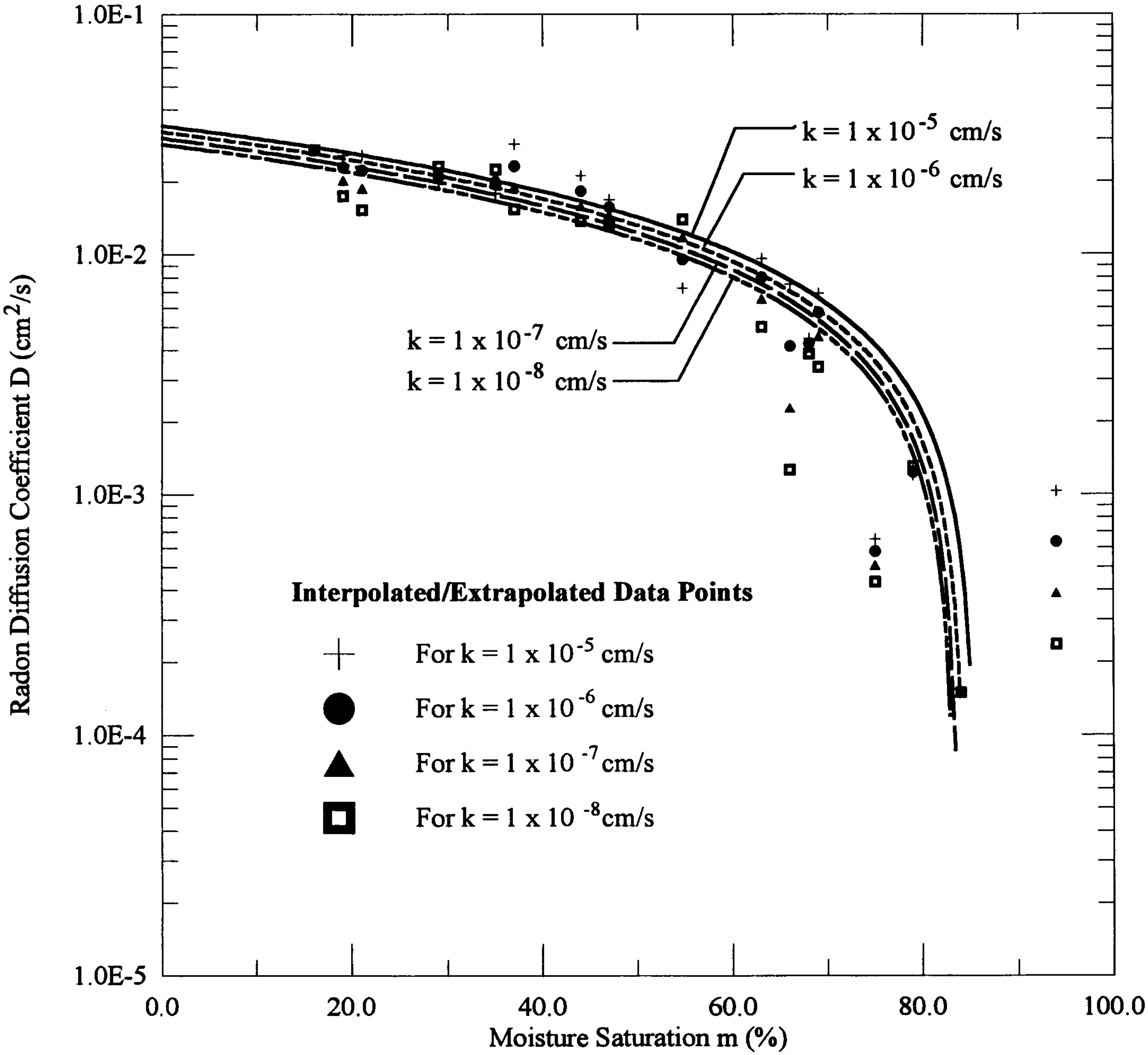

FIG. 4 Variation of radon diffusion coefficient - moisture curve with saturated hydraulic conductivity

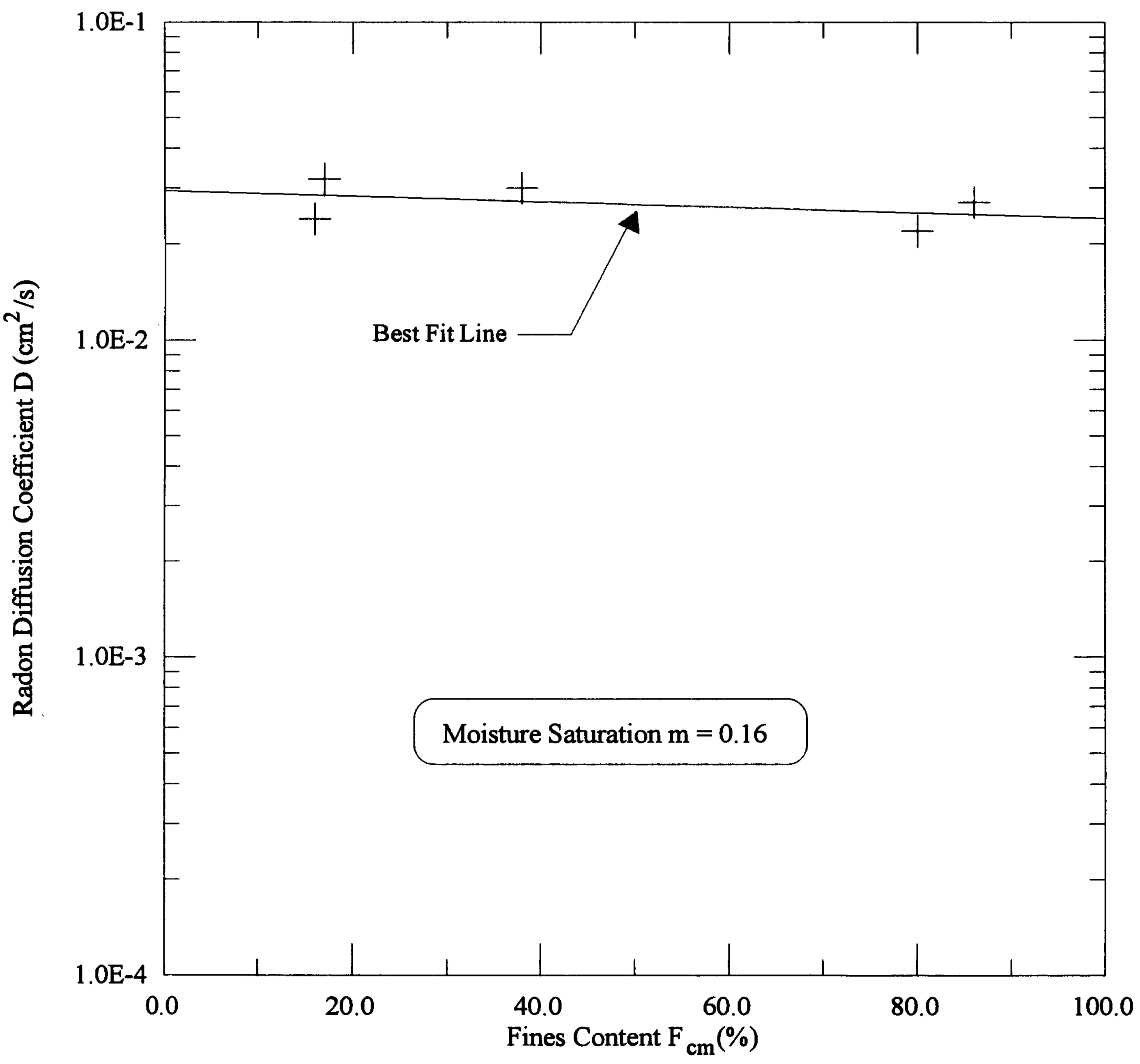

FIG. 5 Typical plot of radon diffusion coefficient vs. fines content

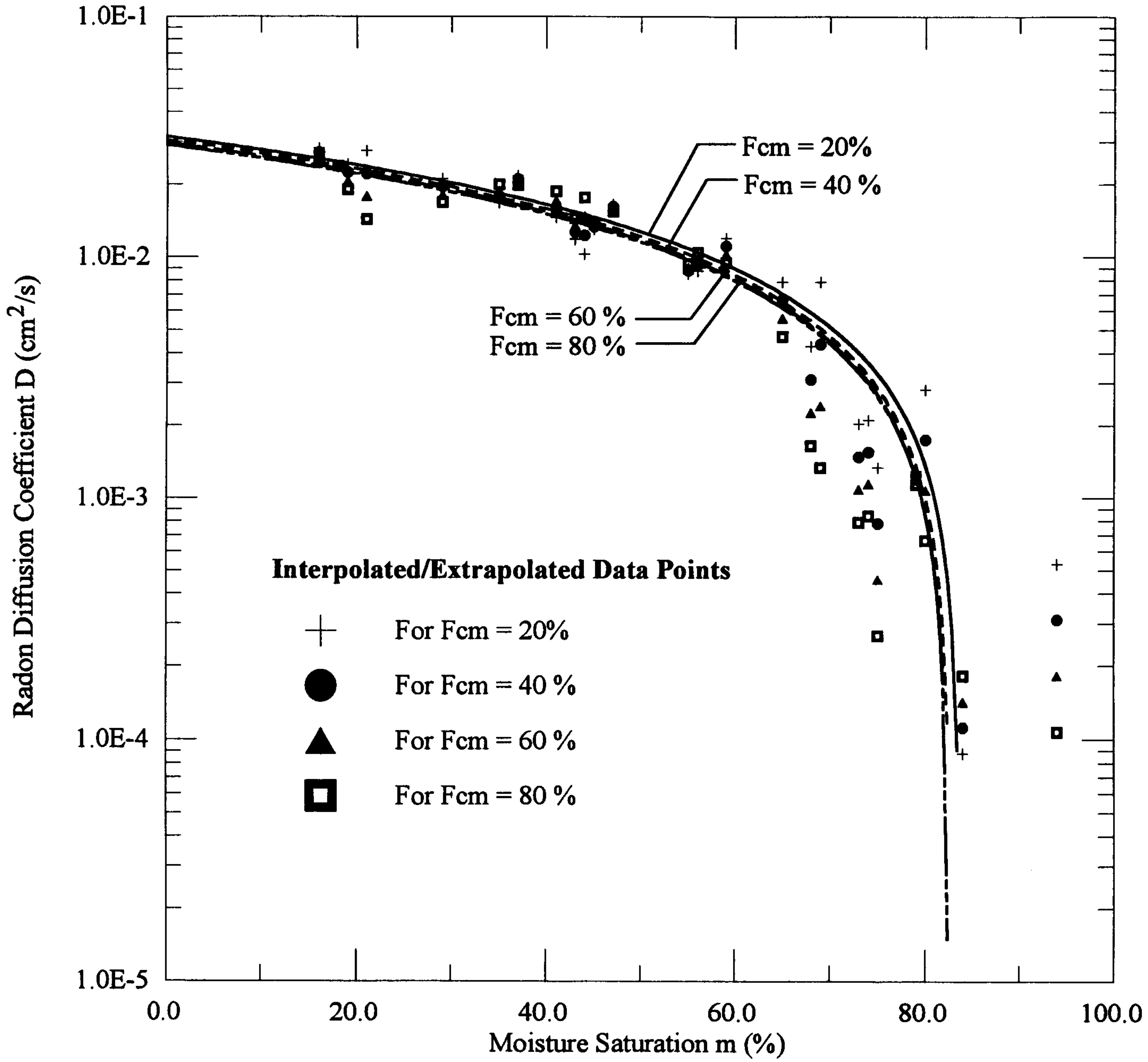

FIG. 6 Variation of radon diffusion coefficient - moisture curve with fines content

Designation: D 5072 – 92

Standard Test Method for Radon in Drinking Water[1]

This standard is issued under the fixed designation D 5072; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the measurement of radon in drinking water in concentrations above 0.04 Bq/L.

1.2 This test method may be used for absolute measurements by calibrating with a radium-226 standard or for relative measurements by comparing the measurements made with each other.

1.3 *This standard does not purport to address the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 1129 Terminology Relating to Water[2]

D 1193 Specification for Reagent Water[2]

D 2777 Practice for Determination of Precision and Bias of Methods of Committee D-19[2]

D 3370 Practices for Sampling Water[2]

2.2 *U.S. EPA Reports:*

EPA 520/5-83-027 Methods and Results of EPA's Study of Radon in Drinking Water[3]

EPA 600/2-87/082 Two Test Procedures for Radon in Drinking Water[4]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, refer to Terminology D 1129 and to other published glossaries.

4. Summary of Test Method

4.1 This test method is based on the scintillation counting of radon-222 and its daughters, a gaseous daughter product of radium-226.

4.2 An aliquot of unaerated water is drawn into a syringe, then gently injected beneath 10 mL of liquid scintillation mix that does not contain an emulsifier. The vials are capped, shaken, and allowed to stand 3 h prior to counting. A commercial liquid scintillation counter is used to count the sample.

5. Significance and Use

5.1 The most prevalent of the radon isotopes in ground water is radon-222. This isotope presents the greatest health risk compared to the other naturally occurring radon isotopes if ingested via the water pathway.

6. Interferences

6.1 Other radionuclides soluble in the scintillation mix may interfere. Water that is contaminated with high energy beta/gamma emitters, even though they are not soluble in the scintillation mix, may also interfere. These interferences would be rare in drinking water samples but may be observed in some cases.

7. Apparatus

7.1 *Sampling Funnel.*

7.2 *Tube,* with standard faucet fitting.

7.3 *Disposable Syringe,* 12 mL capacity, with 20 gage, 1½ in. (38 mm) hypodermic needle.

7.4 *Glass Liquid Scintillation Vials,* 20 mL capacity with polyethylene inner seal glass.

7.5 *Liquid Scintillation Counter.*

7.6 *Scintillation Cocktail Mix,* without emulsifier. Toluene based mix is acceptable.

8. Reagents and Materials

8.1 *Purity of Reagents*—Reagent grade chemicals shall be used in all tests. Unless otherwise indicated, it is intended that all reagents shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society, where such specifications are available.[5] Other grades may be used, provided it is first ascertained that the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination.

8.2 *Purity of Water*—Unless otherwise indicated, referenced to water shall be understood to mean conforming to Specification D 1193, Type III.

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[1] This test method is under the jurisdiction of ASTM Committee D-19 on Water and is the direct responsibility of Subcommittee D19.04 on Methods of Radiochemical Analysis.

Current edition approved Mar. 15, 1992. Published May 1992.

[2] *Annual Book of ASTM Standards,* Vol 11.01.

[3] Published December 1983. For availability, contact the Superintendent of Documents, U.S. Government Printing Office, North Capital and "H" Sts., NW, Washington, DC 20401.

[4] Published March 1989. For availability, contact the Superintendent of Documents, U.S. Government Printing Office, North Capital and "H" Sts., NW, Washington, DC 20401.

[5] "Reagent Chemicals, American Chemical Society Specification," Am. Chemical Soc., Washington, DC. For suggestions on the testing of reagents not listed by the American Chemical Society, see "Analar Standards for Laboratory Chemicals," Poole, Dorset, U.K., and the "United States Pharmacopeia."

8.3 *Radioactive Purity*—Radioactive purity shall be such that the measured radioactivity of blank samples does not exceed the calculated probable error of measurements.

8.4 *Radium-226 Solution Standard,* traceable to the National Institute of Standards and Technology (NIST).

9. Sampling

Note 1—Refer to Practices D 3370 for applicable sampling instructions. Also see U.S. Governmental Protection Agency reports EPA 520 and EPA 600.

9.1 Attach the sampling funnel and tube to a faucet with the standard faucet fitting.

9.2 Slowly turn on the water and allow a steady stream to flow out of the funnel for approximately 2 min. This purges the tube and ensures a fresh sample.

9.3 Reduce the flow of water and invert the funnel. The flow should be adjusted to a level that does not cause turbulence in the pool of water contained in the funnel. Allow excess water to spill over one edge of the funnel.

9.4 Examine the hose connection and tubing for air bubbles or pockets. If these are visible, raise or lower the funnel until they are removed.

10. Calibration and Standardization

10.1 Add a known quantity of traceable NIST radium-226 standard solution to a known volume of water.

10.2 Combine a 10 mL aliquot of the radium-226 standard solution with 10 mL of scintillation mix in a 20 mL glass scintillation vial.

10.3 Allow approximately 30 days for buildup of radon (that is, secular equilibrium with radium-226).

10.4 Shake vial to transfer nearly all the radon to the scintillation mix phase (radon is highly soluble in the scintillation mix). The radium-226 remains in the aqueous phase and, therefore, does not contribute significantly to the count rate.

10.5 Allow the buildup of the radon short-lived progeny by waiting 3 h before counting.

10.6 Count the standard and background samples for 50 min or longer.

11. Procedure

11.1 Collect unaerated sample in accordance with Section 9.

11.2 Clean scintillation vials with alcohol and add 10 mL of scintillation mix.

11.3 Place the tip of the hypodermic needle approximately 3 cm under the surface of the water in the funnel and withdraw a few millilitres of water and eject this water. Using this procedure, rinse the syringe and hypodermic needle two or three more times.

11.4 Again, place the tip of the needle approximately 3 cm below the surface of the water and withdraw approximately 12 mL.

Note 2—The water should be pulled into the syringe slowly to avoid extreme turbulence and collection of air bubbles. If large air bubbles are noticed in the syringe, the sample should be rejected and redrawn.

TABLE 1 Radon Precision Data

Bq/L	s(o)	s(t)
60	82	131
604	553	1644
2454	1820	7783

TABLE 2 Radon Bias Data

Amount Added Bq/L	Amount found Bq/L	% Bias
60	58	−2.6
604	578	−4.7
2454	2308	−6.0

11.5 Invert the syringe and slowly eject any small air bubbles and extra water. Retain precisely 10 mL of water in the syringe.

11.6 Remove the cap from a vial and carefully place the tip of the needle into the bottom of the liquid scintillation solution. Slowly eject the water from the syringe into the vial.

Note 3—The water is injected under the liquid scintillation solution to prevent loss of radon from the sample. If the water is forced out of the syringe with much pressure, it will cause turbulence in the solution and could result in loss of radon.

11.7 Carefully withdraw the hypodermic needle from the vial and replace the cap. The cap should be tightly secured to prevent leakage. Shake and allow 3 h before counting.

11.8 Repeat the previous steps to obtain two separate aliquots from each sample.

11.9 Count drinking water samples for 50 min in the liquid scintillation counter.

11.10 Count a background sample, consisting of 10 mL of water and 10 mL of scintillation solution and a standard radium-226 solution sample for 50 min at the beginning of counting and after every ten drinking water samples.

12. Calculation

12.1 Calculate the becquerels per litre of radon in the sample by using the following equation:

$$A = \frac{(C_S - C_B)\,(1000\text{ mL})}{(CF)\,(D)\,(10\text{ mL})\,(1\text{ L})}$$

where:

A = becquerals of radon per litre of sample,

C_S = sample counts per second (cps),

C_B = background cps,

CF = cps/dps (disintegrations per second) conversion factor,

D = decay correction $D = \exp\left(-\frac{0.693(T)}{t_{1/2}}\right)$,

T = time in days from collection time to midpoint of counting time, and

$t_{1/2}$ = radiological half-life of radon, 3.82 days.

13. Precision and Bias[6]

13.1 The collaborative test conducted on this test method

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[6] Supporting data on the precision and bias of this test method have been filed at ASTM Headquarters Request RR: D19-1142.

METHOD 115-MONITORING FOR RADON-222 EMISSIONS

This appendix describes the monitoring methods which must be used in determining the radon-222 emissions from underground uranium mines, uranium mill tailings piles, phosphogypsum stacks, and other piles of waste material emitting radon.

1. Radon-222 Emissions from Underground Uranium Mine Vents.

1.1 Sampling Frequency and Calculation of Emissions. Radon-222 emissions from underground uranium mine vents shall be determined using one of the following methods:

1.1.1 Continuous Measurement. These measurements shall be made and the emissions calculated as follows:

(a) The radon-222 concentration shall be continuously measured at each mine vent whenever the mine ventilation system is operational.

(b) Each mine vent exhaust flow rate shall be measured at least 4 times per year.

(c) A weekly radon-222 emission rate for the mine shall be calculated and recorded weekly as follows:

$$A_w = C_1Q_1T_1 + C_2Q_2T_2 + \ . \ . \ . + C_iQ_iT_i$$

where:

A_w = Total radon-222 emitted from the mine during week (C_i)

C_i = Average radon-222 concentration in mine vent i(Ci/m^3)

Q_i = Volumetric flow rate from mine vent i(m^3/hr)

T_i = Hours of mine ventilation system operation during week for mine vent i(hr)

(d) The annual radon-222 emission rate is the sum of the weekly emission rates during a calendar year.

1.1.2 Periodic Measurement. This method is applicable only to mines that continuously operate their ventilation system except for extended shutdowns. Mines which start up and shut down their ventilation system frequently must use the continuous measurement method describe in Section 1.1.1 above. Emission rates determined using periodic measurements shall be measured and calculated as follows:

(a) The radon-222 shall be continuously measured at each mine vent for at least one week every three months.

(b) Each mine vent exhaust flow rate shall be measured at least once during each of the radon-222 measurement periods.

(c) A weekly radon-222 emission rate shall be calculated for each weekly period according to the method described in Section 1.1.1. In this calculation T=168 hr.

(d) The annual radon-222 emission rate from the mine should be calculated as follows:

$$A_y = \frac{52 - W_s}{n} \, (A_{w1} + A_{w2} + . . . + A_{wi})$$

where:

A_y = Annual radon-222 emission rate from the mine(C_i)

A_{wi} = Weekly radon-222 emission rate during the measurement period i (C_i)

n = Number of weekly measurement periods per year

W_s = Number of weeks during the year that the mine ventilation system is shut down in excess of 7 consecutive days, i.e., the sum of the number of weeks each shut down exceeds 7 days

1.2 Test Methods and Procedures

Each underground mine required to test its emissions, unless an equivalent or alternative method has been approved by the Administrator, shall use the following test methods:

1.2.1 Test Method 1 of appendix A to part 60 shall be used to determine velocity traverses. The sampling point in the duct shall be either the centroid of the cross section or the point of average velocity.

1.2.2 Test Method 2 of appendix A to part 60 shall be used to determine velocity and volumetric flow rates.

1.2.3 Test Methods A-6 or A-7 of appendix B, Method 114 to part 61 shall be used for the analysis of radon-222. Use of Method A - 7 requires prior approval of EPA based on conditions described in appendix B.

1.2.4 A quality assurance program shall be conducted in conformance with the programs described for Continuous Radon Monitors and Alpha Track Detectors in EPA 520/1-89-009. (2)

2. Radon-222 Emissions from Uranium Mill Tailings Piles.

2.1 Measurement and Calculation of Radon Flux from Uranium Mill Tailings Piles.

2.1.1 Frequency of Flux Measurement. A single set of radon flux measurements may be made, or if the owner or operator chooses, more frequent measurements may be made over a one year period. These measurements may involve quarterly, monthly or weekly intervals. All radon measurements shall be made as described in paragraphs 2.1.2 through 2.1.6 except that for measurements made over a one year period, the requirement of paragraph 2.1.4(c) shall not apply. The mean radon flux from the pile shall be the arithmetic mean of the mean radon flux for each measurement period. The weather conditions, moisture content of the tailings and area of the pile covered by water existing at the time of the measurement shall be chosen so as to provide measurements representative of the long term radon flux from the pile and shall be subject to EPA review and approval.

2.1.2 Distribution of Flux Measurements. The distribution and number of radon flux measurements required on a pile will depend on clearly defined areas of the pile (called regions) that can have significantly different radon fluxes due to surface conditions. The mean radon flux shall be determined for each individual region of the pile. Regions that shall be considered for operating mill tailings piles are:

(a) Water covered areas,
(b) Water saturated areas (beaches),
(c) Dry top surface areas, and
(d) Sides, except where earthen material is used in dam construction.

For mill tailings after disposal the pile shall be considered to consist of only one region.

2.1.3 Number of Flux Measurements. Radon flux measurements shall be made within each region on the pile, except for those areas covered with water. Measurements shall be made at regularly spaced locations across the surface of the region, realizing that surface roughness will prohibit measurements in some areas of a region. The minimum number of flux measurements considered necessary to determine a representative mean radon flux value for each type of region on an operating pile is:

(a) Water covered area-no measurements required as radon flux is assumed to be zero,
(b) Water saturated beaches-100 radon flux measurements,
(c) Loose and dry top surface-100 radon flux measurements,
(d) Sides-100 radon flux measurements, except where earthern material

is used in dam construction.

For a mill tailings pile after disposal which consists of only one region a minimum of 100 measurements are required.

2.1.4 Restrictions to Radon Flux Measurements. The following restrictions are placed on making radon flux measurements:

(a) Measurements shall not be initiated within 24 hours of a rainfall.

(b) If a rainfall occurs during the 24 hour measurements period, the measurement is invalid if the seal around the lip of the collector has washed away or if the collector is surrounded by water.

(c) Measurements shall not be performed if the ambient temperature is below 35°F or if the ground is frozen.

2.1.5 Areas of Pile Regions. The approximate area of each region of the pile shall be determined in units of square meters.

2.1.6 Radon Flux Measurement. Measuring radon flux involves the adsorption of radon on activated charcoal in a large-area collector. The radon collector is placed on the surface of the pile area to be measured and allowed to collect radon for a time period of 24 hours. The radon collected on the charcoal is measured by gamma-ray spectroscopy. The detailed measurement procedure provided in appendix A of EPA 520/5-85-0029(1) shall be used to measure the radon flux on uranium mill tailings, except the surface of the tailings shall not be penetrated by the lip of the radon collector as directed in the procedure, rather the collector shall be carefully positioned on a flat surface with soil or tailings used to seal the edge.

2.1.7 Calculations. The mean radon flux for each region of the pile and for the total pile shall be calculated and reported as follows:

(a) The individual radon flux calculations shall be made as provided in appendix A EPA 86 (1). The mean radon flux for each region of the pile shall be calculated by summing all individual flux measurements for the region and dividing by the total number of flux measurements for the region.

(b) The mean radon flux for the total uranium mill tailings pile shall be calculated as follows.

$$J_s = \frac{J_1A_1 + J_2A_2 + ... + J_iA_i}{A_t}$$

where:

J_s = Mean flux for the total pile (pCi/m^2-s)
J_i = Mean flux measured in region i (pCi/m^2-s)
A_i = Area of region i (m^2)
A_t = Total area of the pile (m^2)

2.1.8 Reporting. The results of individual flux measurements, the approximate locations on the pile, and the mean radon flux for each region and the mean radon flux for the total stack shall be included in the emission test report. Any condition or unusual event that occurred during the measurements that could significantly affect the results should be reported.

3.0 Radon-222 Emissions from Phosphogypsum Stacks.

3.1 Measurement and Calculation of the Mean Radon Flux. Radon flux measurements shall be made on phosphogypsum stacks as described below:

3.1.1 Frequency of Measurements. A single set of radon flux measurements may be made after the phosphogypsum stack becomes inactive, or if the owner or operator chooses, more frequent measurements may be made over a one year period. These measurements may involve quarterly, monthly or weekly intervals. All radon measurements shall be made as described in paragraphs 3.1.2 through 3.1.6 except that for measurements made over a one year period, the requirement of paragraph 3.1.4(c) shall not apply. For measurements made over a one year period, the radon flux shall be the arithmetic mean of the mean radon flux for each measurement period.

3.1.2 Distribution and Number of Flux Measurements. The distribution and number of radon flux measurements required on a stack will depend on clearly defined areas of the stack (called regions) that can have significantly different radon fluxes due to surface conditions. The mean radon flux shall be determined for each individual region of the stack. Regions that shall be considered are:

(a) Water covered areas,
(b) Water saturated areas (beaches),
(c) Loose and dry top surface areas,
(d) Hard-packed roadways, and
(e) Sides.

3.1.3 Number of Flux Measurements. Radon flux measurements shall be made within each region on the phosphogypsum stack, except for those areas covered with water. Measurements shall be made at regularly spaced locations across the surface of the region, realizing that surface roughness will prohibit measurements in some areas of a region. The minimum number of flux measurements considered necessary to determine a representative mean radon flux value for each type of region is:

(a) Water covered area-no measurements required as radon flux is assumed to be zero,
(b) Water saturated beaches-50 radon flux measurements,
(c) Loose and dry top surface-100 radon flux measurements,
(d) Hard-packed roadways-50 radon flux measurements, and
(e) Sides-100 radon flux measurements.

A minimum of 300 measurements are required. A stack that has no water cover can be considered to consist of two regions, top and sides, and will require a minimum of only 200 measurements.

3.1.4 Restrictions to Radon Flux Measurements. The following restrictions are placed on making radon flux measurements:

(a) Measurements shall not be initiated within 24 hours of a rainfall.
(b) If a rainfall occurs during the 24 hour measurement period, the measurement is invalid if the seal around the lip of the collector has washed away or if the collector is surrounded by water.
(c) Measurements shall not be performed if the ambient temperature is below 35 °F or if the ground is frozen.

3.1.5 Areas of Stack Regions. The approximate area of each region of the stack shall be determined in units of square meters.

3.1.6 Radon Flux Measurements. Measuring radon flux involves the adsorption of radon on activated charcoal in a large-area collector. The radon collector is placed on the surface of the stack area to be measured and allowed to collect radon for a time period of 24 hours. The radon collected on the charcoal is measured by gamma-ray spectroscopy. The detailed measurement procedure provided in appendix A of EPA 520/5-85-0029(1) shall be used to measure the radon flux on phosphogypsum stacks, except the surface of the phosphogypsum shall not be penetrated by the lip of the radon collector as directed in the procedure, rather the collector shall be carefully positioned on a flat surface with soil or phosphogypsum used to seal the edge.

3.1.7 Calculations. The mean radon flux for each region of the phosphogypsum stack and for the total stack shall be calculated and reported as follows:

(a) The individual radon flux calculations shall be made as provided in appendix A EPA 86 (1). The mean radon flux for each region of the stack shall be calculated by summing all individual flux measurements for the region and dividing by the total number of flux measurements for the region.

(b) The mean radon flux for the total phosphogypsum stack shall be calculated as follows.

$$J_s = \frac{J_1A_1 + J_2A_2 + ... + J_iA_i}{A_t}$$

where:

J_s = Mean flux for the total stack (pCi/m^2-s)
J_i = Mean flux measured in region i (pCi/m^2-s)
A_i = Area of region i (m^2)
A_t = Total area of the stack

3.1.8 Reporting. The results of individual flux measurements, the approximate locations on the stack, and the mean radon flux for each region and the mean radon flux for the total stack shall be included in the emission test report. Any condition or unusual event that occurred during the measurements that could significantly affect the results should be reported.

4.0 Quality Assurance Procedures for Measuring Rn-222 Flux.

A. Sampling Procedures

Records of field activities and laboratory measurements shall be maintained. The following information shall be recorded for each charcoal canister measurement:

(a) Site
(b) Name of pile
(c) Sample location
(d) Sample ID number
(e) Date and time on
(f) Date and time off
(g) Observations of meteorological conditions and comments

Records shall include all applicable information associated with determining the sample measurement, calculations, observations, and comments.

B. Sample Custody

Custodial control of all charcoal samples exposed in the field shall be maintained in accordance with EPA chain-of-custody field procedures. A control record shall document all custody changes that occur between the field and laboratory personnel.

C. Calibration Procedures and Frequency

The radioactivity of two standard charcoal sources, each containing a carefully determined quantity of radium-226 uniformly distributed through 180g of activated charcoal, shall be measured. An efficiency factor is computed by dividing the average measured radioactivity of the two standard charcoal sources, minus the background, in cpm by the known radioactivity of the charcoal sources in dpm. The same two standard charcoal sources shall be counted at the beginning and at the end of each day's counting as a check of the radioactivity counting equipment. A background count using unexposed charcoal should also be made at the beginning and at the end of each counting day to check for inadvertent contamination of the detector or other changes affecting the background. The unexposed charcoal comprising the blank is changed with each new batch of charcoal used.

D. Internal Quality Control Checks and Frequency

The charcoal from every tenth exposed canister shall be recounted.
ive percent of the samples analyzed shall be either blanks (charcoal having no radioactivity added) or samples spiked with known quantities of radium-226.

E. Data Precision, Accuracy, and Completeness

The precision, accuracy, and completeness of measurements and analyses shall be within the following limits for samples measuring greater than 1.0 pCi/m_2 -s.

(a) Precision: 10%

(b) Accuracy: ±10%
(c) Completeness: at least 85% of the measurements must yield useable results.

5.0 References.

(1) Hartley, J.N. and Freeman, H.D., "Radon Flux Measurements on Gardinier and Royster Phosphogypsum Piles Near Tampa and Mulberry, Florida," U.S. Environmental Protection Agency Report, EPA 520/5-85-029, January 1986.
(2) Environmental Protection Agency, "Indoor Radon and Radon Decay Product Measurement Protocols", EPA 520/1-89-009, U.S. Environmental Protection Agency, Washington, DC. (1989).

[38 FR 8826, Apr. 6, 1973]

2.0 TEST PROCEDURES

Ten Kennecott Uranium Company tailing samples collected by SMI personnel were delivered to the ELI-Casper Branch on April 22, 1997. The tailing samples were accepted under ELI's NRC Source and Byproduct Materials License (Attachment A), and Chain-of-Custody request. Per the Chain-of-Custody request, samples were to be analyzed for ^{226}Ra concentration and Radon-222 (^{222}Rn) ECs. A testing protocol was derived and found acceptable to the client (Kennecott Uranium Company), the consultant (SMI), the laboratory (ELI), and review staff of the NRC. A protocol based on Rogers and Nielsons work referenced in NRC Regulatory Guide 3.64, *Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers* was derived and delivered to ELI on December 17, 1996. The balance of this report paraphrases the protocol and explains how the various ECs were derived.

2.1 Sample Drying and Splitting

The entire sample was removed from the delivered plastic bags, weighed wet, and placed in disposable aluminum drying pans. The samples were then dried at 105°C from 16:15 on April 22, 1997, to 07:00 on April 24, 1997. The dried sample, in its entirety, was reweighed to determine moisture percentage and then ground to - 100 mesh with a plate pulverizer and thoroughly mixed. A sample quantity of 300 grams was placed in a small plastic bag and deionized water was added to restore either the initial moisture content or 10%, whichever was greater. The moisture and tailings were thoroughly blended in the bag and the contents were used to completely fill 125 cm^3 steel cans of the identical geometry to ELI's National Institute of Standards and Technologies (NIST) traceable radium standards. Table 1 lists derived moisture percentages, grinding times of the samples, and net weight of the tailings contents.

Table 1. Derived Moisture Percentages, Grinding Times, and Net Weights of Tailing Contents

Tailings Sample ID	*ELI Laboratory ID*	*Drying Start Date*	*Drying Finish Date*	*Sample Grinding Date*	*Sample Grinding Time*	*Moisture % Determined*	*Moisture % Added*	*Net Mass of Unsealed Cans*
BH-1 19-21'	97-22555	04/22/97	04/24/97	04/24/97	07:20	18.01	18.01	231.3
BH-1 21-23'	97-22556	04/22/97	04/24/97	04/24/97	07:25	23.53	23.53	228.4
BH-3 4-6'	97-22557	04/22/97	04/24/97	04/24/97	07:30	14.88	14.88	209.1
BH-3 2-4'	97-22558	04/22/97	04/24/97	04/24/97	07:35	7.26	10.0	185.0
BH-4 14-16'	97-22559	04/22/97	04/24/97	04/24/97	07:45	37.92	37.92	198.3
BH-4 2-4'	97-22560	04/22/97	04/24/97	04/24/97	07:50	18.52	18.52	220.2
BH-7 12-14'	97-22561	04/22/97	04/24/97	04/24/97	07:55	22.77	22.77	201.6
BH-7 2-4'	97-22562	04/22/97	04/24/97	04/24/97	07:58	13.39	13.39	190.7
BH-9 10-11.3'	97-22563	04/22/97	04/24/97	04/24/97	08:00	30.34	30.34	234.5
BH-9 11.3-15'	97-22564	04/22/97	04/24/97	04/24/97	08:05	26.31	26.31	252.7

Three samples were prepared in duplicate and two splits of Tailings Samples BH-1 21-23', BH-9 10-11.3' and BH-9 11.3-15' were prepared to demonstrate potential differences in can sealing techniques.

2.2 Can Sealing Techniques and Testing

The material selected for sample sealing was hot glue applied by a commercial glue gun and rubberized paint. These seals effectively withstood the hot water test for a 10 minute period and the hot glue had the added advantage of being easily removed by partially freezing the sealed can. Under these conditions, the glue became brittle and could, with some force applied, be removed allowing can opening and deemanation. In tests, the rubberized paint seal was actually more effective and easier to remove for deemanation. Sample canning and sealing were completed between 08:00 and 09:00 on April 24, 1997. All cans were leak tested by immersion in 120°F water for a period of not less than ten minutes. As expected, all cans were found to be leak free.

The question of radon leakage and its effect on ECs may be overstated. The quantity of radon gas generated in radium bearing test samples would be so minute as to never create a partial pressure exceeding ambient atmospheric pressure. Additionally, at full equilibrium, the radon gas is decaying to particulate matter as fast as the gas is being generated. To demonstrate this, three cans were prepared and sealed only with electrical tape, one of the sealants known to leak under extreme conditions. ECs for these three samples (97-22556, 97-22563 and 97-22564) were amongst the highest of the samples (0.400, 0.390, and 0.376) on the second deemanation and were higher than their fully sealed and tested duplicates.

The sealed samples were allowed to rest undisturbed until May 22, 1997, a period of 28 days, following the initial count.

2.3 Initial Gamma Counts: January 9, 1997

Following a four-hour delay to allow unsupported radon daughters to disintegrate, during which the samples were sealed and leak tested, initial gamma counting was initiated at 11:26 on April 24, 1997. All samples were counted on a Nucleus Gamma Spectrometer system consisting of a 2" Sodium Iodide (NaI) Crystal Detector and a Multi Channel Analyzer (MCA). Samples were counted for five minutes. Due to the large number of samples, count time was minimized to prevent radon ingrowth from compromising data results. All counts in each selected window exceeded background by a minimum of a factor of three.

Three energy windows were selected for initial and deemanated counting. These included the ^{214}Pb 295KeV peak (46 channels, 272.2-317.8), ^{214}Pb 352KeV peak (50 channels, 329.2-379.3), and the ^{214}Bi 609KeV peak (75 channels, 568.1-643.1). An energy calibration was performed prior to setting the three regions of interest (ROI). A NIST traceable standard was counted four times during the three + hour initial count period and an acid leached sand blank was counted five times with the standard. This was performed to identify any drift in the counting system. Standard and blank counts were stable and repeatable for the duration of the test counting. Prepared laboratory control standards were also repeatedly counted and yielded recoveries of 101.1% and 89.7% after correcting counts to known radium concentrations.

A concern over Compton Scatter into the two ^{214}Pb channels from the ^{214}Bi gamma was addressed. A pure ^{137}Cs source (661.7KeV) was used to identify potential Compton Bleed into these two energy regions as the gamma energy is similar to that of the ^{214}Bi. It was experimentally determined that a 12.5% bleed occurred at the ^{214}Pb 295KeV peak and a 14.7% bleed occurred at the ^{214}Pb 352 KeV region. These values were used to adjust background corrected counts for the two ^{214}Pb energy peaks for initial and subsequent counting.

2.4 Calculation of Deemanation Coefficient #1: February 5, 1997

The first set of deemanation coefficient counts was made on May 22, 1997, beginning at 10:32. At this point, the sealed samples had ingrown for a period of 28 days or 7.25 ^{222}Rn half lives. This ingrowth period represents an ~ 99% ^{222}Rn ingrowth from ^{226}Ra, assuming no radon or daughters were present at the inception of ingrowth.

Counting was conducted in an identical manner to the initial counts following an energy calibration and selection of the appropriate ^{214}Pb and ^{214}Bi channels.

Calculations of radon ECs were conducted after performing the following count rate corrections:

(1) ^{214}Pb peak counts were adjusted for background counts and then adjusted for Compton Scatter Bleed from the ^{214}Bi gamma emissions; and

(2) ^{214}Pb and ^{214}Bi counts were normalized to initial counts based on repetitive NIST standard count rates taken during the April 24, 1997 analyses.

Following the count rate corrections, ECs were calculated using the following formula:

$$E = \frac{Ce - Cd}{Ce}$$

where

E = Emanation Coefficient,

Ce = represents the adjusted count rate for the fully ingrown samples at the ^{214}Pb and ^{214}Bi energy regions, and

Cd = represents the net adjusted count rate for the deemanated samples in the same regions of interest.

2.5 Deemanation Technique and Calculation of Coefficient #2

Two techniques for deemanating the samples were presented in SMI's protocol. One technique suggested drying the opened samples at 60°C for 48 hours prior to counting. Previous experience with this technique indicated that, on slime/clay matrix samples, significant changes in counting geometry were encountered due to sample shrinkage. In one test, this led to very low to negative ECs as the remaining activity was concentrated in a much smaller volume and therefore reported to the detector with a greater efficiency.

The second technique involved the use of vacuum deemanation in a device similar to a bell jar (vacuum desiccator with the desiccant removed to avoid sample drying). Following the full equilibrium count, the samples were placed in a freezer for approximately one hour to make the industrial glue brittle and removable. The samples were placed under 24" Hg vacuum at 14:30 May 22, 1997. The samples were deemanated until 11:40 on May 23, 1997. It was assumed that both deemanation and unsupported daughter decay would occur during the 20-hour period.

Sample counting then progressed as previously documented along with all count corrections. All samples had been counted both from the top of the can and from the bottom on the first two gamma measurements. This was done to assure that all samples were homogeneous within the container. No significant difference in count rates were observed at any of the peaks during the initial and full ingrowth counts. Following vacuum deemanation, the inverse geometry count (upside down), which was considerably lower at all three peaks on earlier testing, was not significantly different, and in most cases was higher. The previous hypothesis that, "since the deemanation occurred with the top of the can removed, that radon removal may have been more efficient near the planar exposed surface", appears to be invalid. ECs were calculated as described above for the third count episode.

3.0 EMANATION COEFFICIENT CALCULATIONS: RESULTS AND DISCUSSION

ECs calculated for the ^{214}Pb peaks showed a great deal of variability ranging from 0.046 to 0.396 on the first count and 0.027 to 0.390 on the second. There was extreme variability between original and duplicate samples for the ^{214}Pb ROI. The probable reasons for this include the lower energy measurements are more prone to back-ground variations and to scatter from higher energy gammas such as ^{214}Bi.

Coefficients derived using the ^{214}Bi energy were considerably more consistent with only one of 64 yielding negative results. All collected data is available in spreadsheet form as an attachment to this document.

The mean value for all emanation coefficient results at the 214Bi energy window was 0.254 ± 0.105. Results for the first EC (dried and ground to full ingrowth) was 0.262 ± 0.102 while the second emanation (full ingrowth to vacuum deemanated) showed a mean and standard deviation of 0.246 ± 0.108.

Final gamma counts at the ^{214}Bi window were also used to calculate the total ^{226}Ra activity of the samples. In addition, each sample was chemically analyzed for ^{226}Ra.

Supporting documentation for this data follows as Attachments A and B. Other supporting documentation including ELI-Casper's NRC Byproduct Materials License, raw count data reporting spreadsheets, original testing protocol (as negotiated between SMI, KUC, ELI, and the NRC), and chain-of-custodies follow as Attachments C through E.

Table 2. **Emanation Coefficient (EC) Data and Analysis for the ^{214}Bi Radon Daughter Energy Peak**

TAILINGS SAMPLE ID	*EC-1*	*EC-1 INVERSE GEO.*	*EC-2*	*EC-2 INVERSE GEO*	*MIN. EC*	*MAX EC*	*MEAN EC*
BH-1 19-21	0.298	**0.389**	0.257	**0.284**	0.257	**0.389**	0.307
BH-1 21-23'	0.237	**0.306**	0.296	**0.296**	0.237	**0.414**	0.343
BH-1 21-23' DUP	0.247	**0.271**	0.312	**0.309**			
BH-1 21-23' TAPE	0.270	**0.414**	0.305	**0.400**			
BH-3 4-6'	0.190	**0.270**	0.187	**0.202**	0.187	**0.270**	0.212
BH3-2-4'	0.181	**0.339**	0.064	**0.157**	0.064	**0.339**	0.185
BH-4 14-16'	0.378	**0.435**	0.265	**0.275**	0.265	**0.435**	0.338
BH-4 2-4'	0.270	**0.149**	0.195	**0.085**	0.085	**0.270**	0.175
BH-7 12-14'3'	0.140	**0.299**	0.178	**0.113**	0.113	**0.299**	0.183
BH-7 2-4'	0.091	**0.031**	0.022	**-0.016**	-0.016	**0.091**	0.032
BH-9 10-11.3'	0.289	**0.338**	0.357	**0.340**	0.245	**0.390**	0.317
BH-9 10-11.3' DUP	0.245	**0.298**	0.297	**0.290**			
BH-9 10-11.3'TAPE	0.260	**0.380**	0.324	**0.390**			
BH-9 11.3-15'	0.070	**0.103**	0.162	**0.184**	0.070	**0.402**	0.254
BH-9 11.3-15' DUP	0.244	**0.292**	0.351	**0.295**			
BH-9 11.3-15' TAPE	0.249	**0.402**	0.320	**0.376**			

Appendix 40

2.0 Theoretical Prediction

The model for the radon flux from water surfaces such as evaporation ponds is based on the stagnant-film model for gas air-water exchange (Bolin 1960, Lewis and Whitman 1924, Whitman 1923). This model asserts that the interface between the atmosphere and the water body is broken up into four layers: A) water body, B) stagnant water zone, C) stagnant air zone, and D) atmosphere. Under normal conditions there exists sufficient turbulence to maintain even concentrations of radon in the zones A and D. At a small enough scale, molecular interaction and friction counteract the effects from turbulence (Whitman, 1923). As a result, two stagnant boundaries are theorized to exist; one at the water to air interface (zone B) and the other at the air to water interface (zone C). The transfer of molecules occurs is a stepwise process between each zone in a reversible fashion.

Comment [MHS1]: But summarized(?) in Schwarzenbach.

$$A \leftrightarrow B \leftrightarrow C \leftrightarrow D$$

Step 1. A ↔ B. Transfer of radon from the water body to the stagnant water zone. This transfer occurs via the eddying and turbulent nature of the bulk fluid and is dependent on water movement, wave generation and propagation.

Step 2. B ↔ C. Transfer of radon from stagnant water to stagnant air zone. Due to the stagnant nature of the two zones, the transfer is theorized as a diffusion process. The diffusion gradient (and therefore, diffusion rate) is dependent on the depth of each zone and concentration of radon.

Step 3. C ↔ D. Transfer of radon from stagnant air zone to atmosphere. Similar to step 1, this occurs from the turbulent nature of air plus wind dispersion of radon into the bulk medium.

The thin layer model defines parameters for each step. The overall rate can be calculated from these parameters. (Schwarzenbach, 1993). The resulting equation follows:

$$J = \left(\frac{1}{{z_w}/{D_w} + {z_a}/{D_a k'_{Rn}}} \right) \times \left(C_w - \frac{C_a}{k'_{Rn}} \right) \quad \text{Eq. 3}$$

where
z = the depth of the two stagnant zones (Zone B and Zone C)
D = the diffusion coefficient for the two stagnant zones
C_w = the dissolved gas at equilibrium with the partial pressure in the gas phase
C_a = atmospheric concentration of gas
k' = Unitless Henry's Law Constant

The Henry's Law Constant for radon, k_{Rn} is reported as 106 L · atm mol^{-1} (NIST). This can be expressed as a unitless ratio, k'_{Rn}, using the ideal gas law; $P = (n/V) RT$.

$$k'_{Rn} = \frac{k_{Rn}}{RT} = 4.33 \quad \text{Eq. 2}$$

The first parenthetical term in equation 3 is equal to the total mass transfer velocity (v_{tot}). It can be expressed as the sum of the partial transfer velocities of each of the two stagnant layers:

$$\frac{1}{v_{tot}} = \frac{1}{v_a k'_{Rn}} + \frac{1}{v_w} \qquad \text{Eq. 4}$$

where

$$v_a = \frac{D_a}{z_a} \qquad \text{Eq. 5}$$

$$v_w = \frac{D_w}{z_w} \qquad \text{Eq. 6}$$

In “typical” air and water conditions, the depth of the Stagnant Water Zone, z_w, and Stagnant Air Zone, z_a, can be approximated to be 0.01 cm and 0.1 cm respectively (Schwarzenbach, Whitman). The EPA estimates the diffusivity of radon in water as 10^{-5} cm^2 s^{-1}. This agrees with available estimation methods (Schwarzenbach). V_w therefore is equal to 1 x 10^{-3} cm s^{-1}. In air, D_a is calculated to be 0.11 cm^2 s^{-1} (EPA), and $v_a k'$ is equal to 476 cm s^{-1}. As v_a is much greater than v_w, it is clear that the transfer within the stagnant water layer (zone C) is the rate limiting step. In this model, the atmosphere is assumed to contain negligible radon and to be an ideal radon sink. Therefore, C_a/k' approaches zero, and equation 3 can be simplified to:

$$J = \left(\frac{D_w}{z_w}\right) \times (C_w) \qquad \text{Eq. 7}$$

Examination of equation 7 shows its similarity to Fick’s first law that flux J is equal to the diffusion coefficient D multiplied by the concentration gradient (in this case, C_w/z_w). By taking a concentration of 1 pCi L^{-1} (10^{-3} pCi cm^{-3}) The flux J per pC/L radon is equal to:

$[(10^{-5}\ cm^2\ s^{-1}) / (0.01\ cm)] \times 10^{-3}\ pCi\ cm^{-3} \times 10^4\ cm^2/m^2 = 0.01\ pCi\ m^{-2}\ s^{-1}$

J_{Rn} = 0.01 pCi m^{-2} s^{-1} per pCi L^{-1} of dissolved radon Eq. 8

Empirical data (Dueñas 1986) suggests a relationship of 0.008 (± 0.0011) pCi m^{-2} s^{-1} per pCi L^{-1} of dissolved radon, between 70 - 90% of the calculated value in this model.

The radon flux from ocean surfaces has been of academic interest. Four calculated or measured radon flux values for the Atlantic and Pacific Ocean surfaces range from 6 x 10^{-4} to 3 x 10^{-3} pCi/m^2s (Wilkening, 1975). Ra-226 concentrations in the Atlantic and Pacific Oceans is reported (Broecker, 1967) as approximately 0.04 pCi/liter. Equation 8 would predict a flux of approximately 4 x 10^{-4} pCi/m^2s, which is in good agreement with the lower end of the reported flux numbers.

HMC took a single sample of the water from Evaporation Pond 1 on August 11, 2009 which was analyzed for radium-226 (Ra-226). They also measured the surface water temperature. The data are presented in Table 1.

	Evaporation Pond 1

Radium-226	165 pCi/L
Temperature	20.6 °C

Table 1. Radium and temperature data from HMC Evaporation Pond EP-1.

The resident time of radium in the pond is long enough to create a secular equilibrium between Ra-226 and its decay progeny. In this condition, the concentration of Rn-222 is equal to the Ra-226 concentration. Using equation 8, the radon flux is calculated to be 1.65 pCi m^{-2} s^{-1} in Evaporation Pond 1, where the error is expressed solely from the uncertainty in the Ra-226 concentration.

The flux model is assumed to operate under standard temperature and pressure (1 atm at 25 degrees C) and with constant wind speeds of around 10 mph. The variation in real conditions are mostly negligible and the available empirical data (Duenas 1986) show the model to be a conservative estimate.

6.0 References

Bolin, B. "On exchange of carbon dioxide between the atmosphere and the sea. *Tellus*. Vol 23. 1960.

Broecker, Wallace S., Yuan Hui Li, and John Cromwell. Radium-226 and Radon-222: Concentration in Atlantic and Pacific Oceans. *Science*: Vol. 158. no. 3806, pp. 1307 – 1310. 8 December 1967

Dueñas, C., M. C. Fernandez, M. de la Torre. "Fluxes and exchange rates of radon and oxygen across an air-sea interface." Geochemical Journal, Vol 20. 1986.

Dueñas, C., M. C. Fernandez, M. Perez Martinez. "Radon 222 From the Ocean Surface." *Journal of Geophysical Research.* Vol 88. 1983.

EPA 520/5-85-029 Radon Flux Measurments on Gardinier and Royster Phosphogypsum Piles Near Tampa and Mulberry, Florida. September 1985. J.N. Hartley and H.D. Freeman, Pacific Northwest Laboratory, Richland, Washington.

EPA On-Line Tools for Site Assessment Calculation. http://www.epa.gov/athens/learn2model/part-two/onsite/estdiffusion.htm

Lewis, W. K., W. C. Whitman. "Principles of gas adsorption." *Industrial and Engineering Chemistry.* Vol 17. 1924.

NIST Webbook. http://webbook.nist.gov/chemistry/

Scarpitta, S. C., N. H. Harley. *An Improved* ^{222}*Rn canister using a two-stage charcoal system.* Health Physics, Vol 60, 177-188. 1991.

Schwarzenbach, Rene P., Philip M. Gschwend, and Dieter M. Imboden. *Environmental Organic Chemistry*. 2nd Edition. 2002.

Torgersen, T., Guy Mathieu, R. H. Hesslein, W. S. Broecker. “Gas Exchange Dependency on Diffusion Coefficient: Direct ^{222}Rn and ^{3}He Comparisons in a Small Lake.” *Journal of Geophysical Research.* Vol 87. 1982.

Whitman, W. G., Preliminary Experimental Confirmation of the two-film theory of gas absorption. *Chemical and Metalllurgical Engineering.* Vol 29. 1923.

Wilkening, Marvin H., William E. Clements. “Radon 222 From the Ocean Surface.” *Journal of Geophysical Research.* Vol 80. 1975.

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