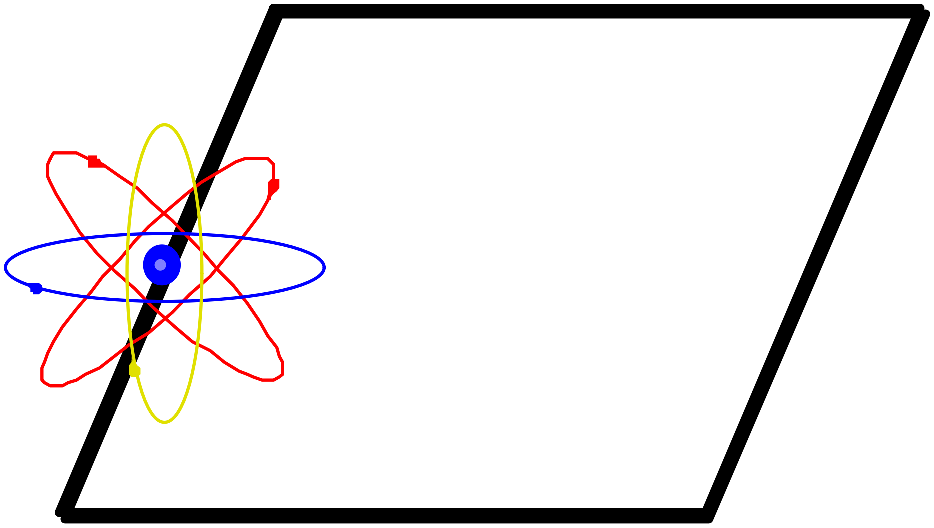
United States
Environmental Protection
Agency

Office of Air and Radiation
Office of Solid Waste and
Emergency Response
Washington, DC 20460

EPA 402-R-96-017
November 1996

Technology Screening Guide for Radioactively Contaminated Sites



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TECHNOLOGY SCREENING GUIDE FOR RADIOACTIVELY CONTAMINATED SITES

Prepared for

U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Radiation and Indoor Air
Radiation Protection Division
Center for Remediation Technology and Tools

and

U. S. Environmental Protection Agency
Office of Solid Waste and Emergency Response

Prepared Under:

Contract No.
68-D2-0156

DISCLAIMER

ACKNOWEDGEMENTS

Edward Feltcorn of ORIA’s Center for Remediation Technology and Tools was the EPA Work Assignment Manager for this guide. Assistance in production of this guide was provided by Jack Faucett Associates (Barry Riordan - Project Manager) under EPA Contract Number 68-D2-0156.

EPA/ORIA wishes to thank the following individuals for their assistance and technical review comments on the drafts of this report:

Doug Bell, EPA/ Superfund
Dr. Walter Kovalick, Jr., EPA Technology Innovation Office
Paul Giardina, EPA Region 2
Paul Leonard, EPA Region 3
Nancy Morlock, EPA Region 6
Linda Meyer, EPA Region 10
Ed Barth, EPA/ORD Cincinnati
Gregg Dempsey, EPA/ORIA Las Vegas Facility
Sam Windham and Samuel Keith, EPA/ORIA NAREL

EPA/ORIA would like to extend special appreciation to Thomas Sorg of EPA/ORD Cincinnati, without his assistance the section on liquid media would have not been complete.

In addition, the following staff from ORIA’s Remediation Technology and Tools Center assisted in the development, production and review of this document:

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LIST OF EXHIBITS

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LIST OF ACRONYMS

AMU	Atomic Mass Unit
ARAR	Applicable or Relevant and Appropriate Requirements
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (Superfund)
CFR	Code of Federal Register
CWA	Clean Water Act
DOD	Department of Defense
DOE	Department of Energy
DRE	Destruction and Removal Efficiencies
EDTA	Ethylenediamine-tetraacetic acid
EP	Extraction Procedure
GAC	Granular, Activated Carbon
HDPE	High Density Polyethylene
ISV	In-situ Vitrification
LDR	Land Disposal Restrictions
LLRWPAA	Low-level Radioactive Waste Policy Amendments Act of 1985
LLW	Low-level Waste
MCL	Maximum Concentration Level
MR	Millirem
NCP	National Contingency Plan
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NRC	U.S. Nuclear Regulatory Commission
NTIS	National Technical Information Service
O&M	Operations and Maintenance
ORIA	Office of Radiation and Indoor Air
ORNL	Oak Ridge National Laboratory
RCRA	Resource Conservation and Recovery Act
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
S/S	Solidification/Stabilization
SVOC	Semivolatile Organic Compound
TCLP	EPA Toxicity Characteristic Leaching Procedure
TRU	Transuranic Waste
VOC	Volatile Organic Compound

EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA), Office of Radiation and Indoor Air, Radiation Protection Division's Center for Remediation Technology and Tools, produced this Technology Screening Guide for Radioactively Contaminated Sites (Guide) to help identify and screen technologies that may effectively treat radioactively contaminated sites. The Guide is designed to give easy access to critical information on applied technologies that address radioactive contamination in solid and liquid media. The solid media includes soils, sediment, sludge, and solid waste, but does not include buildings and structures. The liquid media include groundwater, surface water, and waste water. This information is presented in technology profiles that can be used to screen and compare technologies for site-specific application.

The profiles include 17 applied technologies (technologies in use at contaminated sites) viable for response actions at such sites. There are 12 technologies associated with contaminated solid media and are grouped into five categories: containment, solidification/stabilization, chemical separation, physical separation, and vitrification. There are 5 technologies associated with contaminated liquid media and are grouped into two categories: chemical separation and physical separation.

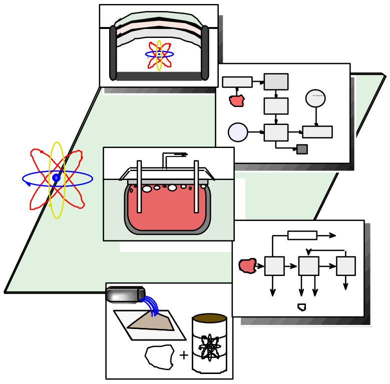
This Guide builds on significant efforts by EPA, the Department of Energy, the Department of Defense, and other agencies to facilitate remedy selection. This Guide also updates information on each technology's operating and performance data. This Guide has been distributed as a draft document to a large and diverse group of peer reviewers, whose comments have been addressed in this final version of the Guide.

Profiles for each technology include a basic description, contaminants addressed, technology operating characteristics, and site characteristics that affect performance. Each profile describes how the technology has performed against the following seven of the nine National Contingency Plan (NCP) evaluation criteria:

- protection of human health and the environment;
- compliance with applicable or relevant and appropriate requirements (ARARs);
- long-term effectiveness;
- reduction of toxicity, mobility, or volume through treatment;
- short-term effectiveness;
- implementability; and
- cost.

The state and community acceptance NCP criteria are not addressed in the profiles because the assessments of the remedial technologies against these criteria usually are site-specific. Finally, the profiles summarize the key information for each technology.

Section I introduces the Guide and provides background information on general characteristics of radioactive waste at NPL sites. Section II provides profiles for technologies applicable to solid media while section III presents profiles for technologies applicable to liquid media. A quick reference to radiation concepts and glossary of terms is provided in Appendix A. The Bibliography in Appendix B cites general references and categorizes references by technologies. Exhibit ES-1, provides a summary of the information in this Guide, concerning the technologies that have been demonstrated to be applicable to the most commonly found radionuclides at Superfund sites, in three broad classes of media.



SECTION I

INTRODUCTION

1.1 PURPOSE

This Guide is designed to help site managers identify and screen technologies that are potentially effective in cleaning up radioactively contaminated sites. EPA recognizes that site managers fulfill numerous technical, management, and regulatory responsibilities, all driven by the goal of making expedient yet careful decisions about site response actions. While these responsibilities are met at all Superfund and RCRA Corrective Action sites, they are particularly challenging when site managers must deal with the complexity of radioactive contamination.

To make appropriate site response action decisions, site managers must have the pertinent technical information to help guide them. This document is a reference that can be consulted for critical information on radioactive contamination cleanup technologies to screen applications at their site. This Guide updates information from previous EPA publications on applied technologies for solid and liquid media contamination. Each technology profile is presented in two parts. The first part provides process descriptions, operating principles, and other features in a consistent presentation format for each technology. The second part provides an evaluation of this data against the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) evaluation criteria.[1]

The Guide has been written for site managers who have had some Superfund or RCRA experience, although not necessarily with radioactive contamination. In planning and implementing response actions, this document can be used in the Remedial Investigation/ Feasibility Study (RI/FS) Proposed Plan, or Corrective Measures Study (CMS) processes. In

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[1] National Oil and Hazardous Substance Pollution Contingency Plan, 40 CFR Part 300, March 8, 1990, contains the implementing regulations for CERCLA, including the methodology for assessing the range of remedial technologies.

addition, Superfund and RCRA program administrators, EPA site manager counterparts in federal facilities, site managers outside of EPA, EPA Regional Radiation Program staff and technology vendors can use the Guide to evaluate technology options.

1.2 BACKGROUND

Since the passage of CERCLA in 1980, significant efforts have been made to study, develop, and use technologies that can address radioactive contamination. Diverse initiatives have attempted to pinpoint the safest, most thorough, efficient, and cost-effective ways to respond to this type of hazard. The American Nuclear Society, the Commission of the European Communities, and the International Atomic Energy Agency, for example, have examined remediation and waste management options for low-level and high-level radioactive waste in the United States and abroad.[2] In addition, the Department of Energy (DOE) has played a major role in researching potential applications for innovative technologies at Federal Facility Superfund sites.[3] The Department of Defense (DOD) has also helped refine the search for applicable technologies in its work on nonradioactive waste.[4]

EPA had previously compiled information on cleanup technologies for radioactive waste in two documents described below.

- *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites* (1988) discusses remediation technologies for soils contaminated by radioactivity. It identifies the full range of technologies potentially useful in reducing radioactivity levels at hazardous waste sites, describing the technology, its development status, potential application, advantages and disadvantages, and associated information needs.
- *Assessment of Technologies for the Remediation of Radioactively Contaminated Superfund Sites* (1990) rated technologies by examining 29 technologies for cleaning up soil, water, and structures. It also identified information gaps related to assessing the technologies.

Despite EPA and other agencies' efforts, information on radioactive cleanup technologies is scattered; site managers under pressure to make decisions must often sift

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[2] Appendix B, the Bibliography, presents multiple listings of conference proceedings from these organizations.

[3] Readers can consult DOE findings on technology innovations in several sources noted in the bibliography or specific technology profiles in this document. Technical information is available in two key resources. The DOE Environmental Restoration and Waste Management (EM), Office of Technology Development's annual *Technology Catalogue* provides descriptions of the technology and its technical performance, projected performance, waste applicability, status, regulatory considerations, potential commercial applications, baseline technology, and intellectual property rights of site characterization and monitoring, site remediation, and waste management technologies. In addition, the 1993 Oak Ridge National Laboratory (ORNL) *Technology Logic Diagram, Volume 3 Technology Evaluation Data Sheets* cites the following key information on 127 Remedial Action technologies: the ORNL problem to be addressed, problem area/constituents, reference requirements, sub-elements, technology, status, science/technology needs, and implementation needs.

[4] DOD Environmental Technology Transfer Committee, EPA, Dept. of Interior and Dept. Of Energy cooperatively prepared in 1994 the *Remediation Technologies Screening Matrix and Reference Guide* which helps site managers narrow the field of remediation alternatives in the remedy selection process.

through volumes of information, a time-consuming process. Recognizing the ongoing challenge of integrating vast quantities and levels of information into one resource, this document:

- Builds upon EPA's earlier efforts;
- Capitalizes on the work of other researchers; and
- Attempts to bridge the body of technology data and the remedy selection process.

This Guide focuses on technologies that address radioactive waste and are effective for soil and liquid media at radioactively contaminated sites. The solid media includes soils, sediment, sludge, and solid waste; it does not include buildings and structures. The liquid media include groundwater, surface water, and waste water. It does not address radon in air or the decontamination of structures. Sufficient information is provided to screen these technologies for a possible match to the specific site of interest to the user.

To develop this document, a survey of EPA and DOE databases such as VISITT and ER 95 was performed, and documents were reviewed that describe or assess technology applications to radioactively contaminated waste. This information was drawn from government publications and journal articles and formed the basis for the technology characterizations presented in subsequent sections. Also reviewed were CERCLA Records of Decision (RODs) for NPL sites contaminated with radioactive waste. The RODs provided some additional insight into the remedy selection process at Superfund sites with radioactive contamination. They also provided a set of technologies that have been considered or selected for actual cleanup situations using the process required by CERCLA and the NCP.

Finally, this Guide was distributed nationally for peer review and comment. Additional technical research was conducted to address these comments and to update the information with other relevant data sources.

1.3 GENERAL INFORMATION RELATED TO RADIOACTIVELY CONTAMINATED SITES

1.3.1 Types of Sites

Of the radioactively contaminated sites identified, nine general types of sites have been established. These are:[5]

- defense plants
- mill tailings, processing, and disposal sites
- radium and thorium sites
- commercial landfills
- low-level waste disposal sites
- research facilities
- commercial manufacturing
- fuel fabrication and processing
- scrap metal recovery.

1.3.2 Characteristics of Radioactively Contaminated NPL Sites

Experience with Superfund sites demonstrates that waste at radioactively contaminated sites are primarily by-products of four main processes or activities: research, design, or development of nuclear weapons; radioactive waste disposal; mining/processing of radioactive ores; and some forms of manufacturing. As shown in Exhibit 1-1, uranium represents the most prevalent element with respect to radioactively contaminated NPL sites, followed by radium, radon, and thorium.

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[5] US EPA (1993), *Environmental Characteristics of EPA, NRC, and DOE Sites Contaminated with Radioactive Sutstances*, U.S. EPA, Air and Radiation, EPA 402-R-93-011, March 1993.

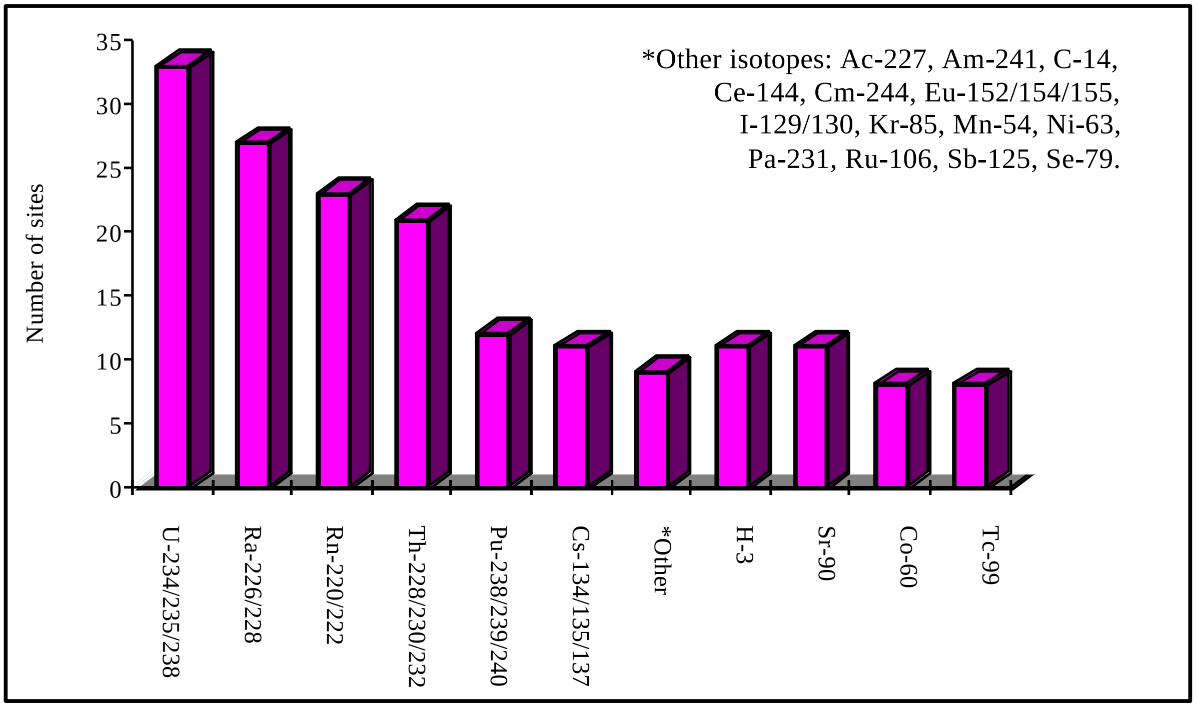

Exhibit 1-1: Isotope Distribution at Radioactively Contaminated NPL Sites*

*Source: US EPA (1993), *Environmental Pathway Models - Groundwater Modeling in Support of Remedial Decision-Making at Sites Contaminated with Radioactive Materials*, EPA 402-R-93-009.

EPA's 1990 study of some radioactively contaminated NPL sites found that most sites were characterized by “soils contaminated with Radium, Thorium, and/or Uranium” (92%) or “water contaminated with Radium, Thorium, and/or Uranium” (80%). Exhibit 1-2 illustrates how the sites in the 1990 study were dispersed with respect to contaminants present and media affected.

Exhibit 1-2: NPL Sites by Media and Contaminants*

CONTAMINANT	SOILS	WATER	STRUCTURES
Radium/Thorium/Uranium	23	20	8
Other Radionuclides	6	5	2
Mixed Waste	11	12	3

*Source: *Assessment of Technologies for the Remediation of Radioactively Contaminated Superfund Sites*, EPA (1990).

Exhibit 1-3 provides more specific information about the media impacted and radionuclides detected at the sites.

Exhibit 1-3: NPL Sites and Radionuclides Detected*

SUPERFUND SITE	MEDIA IMPACTED	RADIONUCLIDES PRESENT
Austin Avenue Radiation Site	Soil, Debris	Ra-226, Th-230, U-238
Agrico Chemical Co.	Groundwater	U-238, Ra-226, Ra-228, gross alpha, gross beta
Denver Radium Site	Soil, Debris, Groundwater, Air	Ra (Soil); U-234, U-238, Th-230, Ra-226, Rn-222 present
Feed Materials Production Center (DOE)	Debris	U-238, U-234, U-235, U-238, Th-230, Th-232, Th-228, Ra-226, Ra-228, Cs-137
Glen Ridge Radium Site	Soil	Rn-222 (Gas); Ra-226, U-234, Th (Soil)
Hanford 100-Area (DOE)	Solid and Liquid Waste, Groundwater, Surface Water	U, Pu-238, Pu-239, Pu-240, Cs-137, Sr-90, Co-60, Ni-63, Eu-152, Eu-154, Eu-155, Tritium
Hanford 200-Area (DOE)	Solid and Liquid Waste, Groundwater, Surface Water	U, Pu-239, Pu-240, Cs-137, Sr-90, Co-60, I-129, Tritium
Hanford 300-Area (DOE)	Solid and Liquid Waste, Groundwater, Surface Water	U, Pu-238, Pu-239, Pu-240, Cs-137, Sr-90, Co-60, Pr-147
Homestake Mining Company	Soil, Tailings, Groundwater, Air	Rn-222 (Air); Ra (Tailings); U (GW)
Idaho National Engineering Lab (DOE)	Sediment, Soil, Solid Waste	Cs-137, Co-60, Strontium, Plutonium, Uranium, Th-230, Americium
Kerr-McGee (Kress Creek)	Sediment, Soil, Tailings	Thorium
Kerr-McGee (Reed Keppler)	Groundwater, Soil, Air	Th-232, Ra-226 (GW); Th-232 (Soil)
Kerr-McGee (Residential)	Soil, Tailings	Th-232
Kerr-McGee (Sewage Treatment Plant)	Soil, Groundwater	Th-232 (Soil), Th-232, Th-230, Ra-226 (GW)
Lansdowne Radiation Site	Soil, Sewer Lines, Building Materials	Ra-226, Th-230, Ac-227 (Soil); Rn-222, Rn-220, Ra-226, Th-230, Ac-227, Pa-231(Sewer, Bldg.)
Lincoln Park	Groundwater	Ra-226, U-234, U-238
Lodi Municipal Well	Groundwater	U-238
Maxey Flats Nuclear Disposal	Soil, Groundwater, Surface Water, Sediment, Air	Ra, U, Th, H-3, Cs-137, Co-60 (Soil); Ra-226, U, H-3, Sr-90, Pu-239 (GW); Ra-226, H-3 (SW); Ra-226, Sr-90, Pu-239, Cs-137, H-3 (Sediment); H-3 (Air)
Maywood Chemical Co.	Groundwater, Soil, Sediment	Rn-222 (GW); Th-232, Ra-226, U-238 (Soil); Th-232, Ra-226, U-238 (Sediment)

Exhibit 1-3: NPL Sites and Radionuclides Detected* (Cont.)

SUPERFUND SITE	MEDIA IMPACTED	RADIONUCLIDES PRESENT
Montclair Radium Site	Soil	Ra, Th, U (Soil); Rn-222 (Gas)
Monticello Radioactivity Contaminated Properties	Tailings	U-238, U-236, Ra-226, Th-230, Rn-222, Ra-226
Oak Ridge Reservation (Lower Watts Bar Reservoir) (DOE)	Solid Waste, Groundwater, Sludge, Soil	Cs-137, Co-60, Sr-90, Ra-226, Cm-244, Th-230, Th-232, Pu-238, Pu-239, U-234, U-235, U-238
Paducah Gaseous Diffusion Plant (DOE)	Liquid waste, Groundwater	Tc-99, Np-237, Th-230, U-234, U-235, U-238
Radioactive Waste Management Complex	Debris	Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Americium, Th-232, U-234, U-235, K-40
Rocky Flats Plant (DOE)	Soil, Sediment, Wastewater Impoundments	Pu, Tritium
Savannah River Site (DOE)	Soil, Sludge, Groundwater	Radium, Chromium
Schpack Landfill	Soil and Groundwater	Ra-226, U-238, U-234 (Soil); Rn-222 (GW); K-40, Th-228, Th-230 present
Teledyne Wah Chang	Sludge, Groundwater	Ra-226, Th, U (Sludge); Ra-228 (GW)
U.S. Radium Corporation	Soil	Ra-226, U-238
United Nuclear Corporation	Groundwater, Surface Water, Tailings	Ra-226, Ra-228, Th-230 (GW); Ra-226, Ra-228, Th-230, Th-277(SW); U-238, Th-230, Ra-226, Rn-222 (Tailings)
Uravan Uranium	Groundwater, Air, Tailings, Surface Water	Rn-222, U-234, U-238, Th-230, Ra-226
W.R. Grace & Co. Inc. (DOE)	Soil, Groundwater, Surface Water, Sediment	Th-232, Ra-226, Ra-228 (Soil, GW, SW, Sediment); Ra-222, Ra-220
Weldon Spring Quarry (DOE)	Soil, Groundwater, Air, Sediment (Raffinate Pits)	Ra, U, Th (Soil); U (GW, SW); Rn (Air); Ra-226, Ra-228, U-238, U-234, U-235, Th-230, Th-232 (Sediment)

*Source: *Assessment of Technologies for the Remediation of Radioactively Contaminated Superfund Sites*,EPA (1990) and EPA Records of Decision, Office of Emergency and Remedial Response, through Fiscal Year 1995.

1.3.3 General Remedial Response Actions

The special characteristics represented by radioactivity in a waste stream constrain the response options available to site managers. This is because unlike nonradioactive hazardous waste, which contain chemicals alterable by physical, chemical, or biological processes that can reduce or destroy the hazard itself, radioactive waste cannot be similarly altered or destroyed. (For an explanation of the nature and source of radioactive material, refer to Appendix A.)

Since destruction of radioactivity is not an option, response actions at radioactively contaminated sites the concepts of "Time, Distance and Shielding" are the concepts used in radiation protection. Time allows the natural decay of the radionuclide to take place, resulting in reduction in risk to human health and the environment. Distance and shielding from the radioactive material rapidly reduces the risk from all forms of radiation by reduction of the intensity of the imparted energy. Therefore all remediation solutions involve either removing and disposing of radioactive waste, or immobilizing and isolating radioactive material to protect human health and the environment. Radioactive material can be extracted from soil and water and converted to a form for disposal at an approved location. Alternatively, radioactively contaminated soil can be immobilized, preventing the radioactive components from migrating from the site and causing harm. Associated with immobilization are measures to isolate (shield) radioactive material while it decays to site specific levels, thus ensuring that people are protected from direct exposure to the radiation by inhalation, ingestion or contact.

The selection of response actions is influenced by such considerations as site characteristics (soil properties, hydrogeology, etc.), the half-life and radiations of the radioactive material(s) (Alpha, Beta or Gamma), proximity of the waste to populations, available resources, handling and level of personal protective equipment, and treatment costs. As part of the selection process, disposal of extracted and concentrated radioactive material should be considered. Disposal requirements and options for transporting such waste materials to licensed facilities[6] vary, depending on the nature of the contaminant and the containment technology used.

This Guide presumes that a succession of remedial measures, commonly referred to as a "treatment train," would be employed at most sites to respond to various types of site contamination. Treatment trains can reduce the volume of materials that need further treatment and/or remediate multiple contaminants within a single medium. A treatment train, for example, might include soil washing, followed by solidification and stabilization measures, and land encapsulation.

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[6] Commercial sites licensed to receive low-level radioactive waste exist at Barnwell, SC; Hanford, WA; and Beatty, NV. Actions are currently underway to move the repository operations at Barnwell, SC, to a site in North Carolina.

1.4 TECHNICAL APPROACH USED

1.4.1 Technologies Presented

To provide a concise guide to a variety of treatment alternatives that may be viable for response actions at specific sites, 17 applied technologies have been selected for evaluation in this Guide. These technologies address contamination of solid and liquid media. These were selected for two reasons: 1) the technology had been considered and/or selected at a Superfund site with radioactive contamination, or 2) there was sufficient data available from field scale testing and other research that demonstrated the technology's potential application to an actual cleanup of radioactive contamination. Many more technologies were reviewed but not presented due to insufficient data and/or unreliable sources of data. The technologies in this Guide are:

- **Solid Media:**
    - Capping
    - Land Encapsulation
    - Cryogenic Barrier
    - Vertical Barriers
    - Cement Solidification/Stabilization
    - Chemical Solidification/Stabilization
    - Solvent/Chemical Extraction
    - Dry Soil Separation
    - Soil Washing
    - Flotation
    - In-situ Vitrification
    - Ex-situ Vitrification.

- **Liquid Media:**
    - Ion Exchange
    - Chemical Precipitation
    - Membrane Filtration
    - Carbon Adsorption
    - Aeration.

The determining factor in selecting the technologies presented here is their applicability to radioactive waste, although they also apply to nonradioactive hazardous waste. For example, incineration technologies that treat volatile and semivolatile organic compounds, but which do not affect radioactively contaminated media, are excluded. This Guide also excludes technologies to specifically remediate radon contamination in air or contaminated structures. Finally, this Guide addresses waste disposal options only to the extent of identifying technologies for sites that contain radioactively contaminated media. For more complete information for supporting site-specific decisions, the bibliography cites references for readers who wish to explore the technology in greater detail.

1.4.2 Approach To Evaluating Technologies

Profiles of selected technologies are designed to provide pertinent information in a consistent format. Because numerous information sources are available on these technologies, only key data concerning technology and site characteristics are included. Data categories are based on the information useful in evaluating NCP criteria. Each technology profile addresses the relevant information under three main sections: 1) Technology Characterization, 2) NCP Criteria Evaluation, and 3) Summary. The following is a detailed discussion about how profiles are organized and what information they include.

1) Technology Characterization

The technology characterization summarizes current information about the technology as it has been tested or applied.

- Description: This Section describes basic principles and methodologies of each technology. Descriptions focus on the features relevant to making criteria evaluations and comparisons with other technologies. Profiles describe the overall effects of the technology on the contaminated materials rather than operating procedures, process outcomes, and reagents.
- Target Contaminant Groups: This segment of the profile lists individual contaminants or contaminant groups addressed by the technology.
- Technology Operating Characteristics: This segment discusses various aspects of operating the technology for example, removal efficiencies, generation of residuals, process times, or high energy demands. The operating characteristics may influence site managers' decisions about selecting an appropriate treatment technology.
- Site Conditions: This discussion addresses important site conditions that may affect the technology's viability or implementation at a particular site, including for example, topography, depth to groundwater, and soil types.

2) NCP Criteria Evaluation

This Section evaluates the technology's performance according to the NCP criteria established for Superfund sites. Two of the criteria, community acceptance and state acceptance, are not presented in the profiles, since site managers must evaluate these on a site-specific basis. Exhibit 1-4 briefly explains the seven remaining evaluation criteria, in relation to a response action.

Exhibit 1-4: NCP Evaluation Criteria Included in Technology Profiles

Protection of human health and the environment

How the response action will...

- through treatment, engineering, controls and/or institutional controls,***** provide adequate protection of human health and the environment by eliminating, reducing, or controlling significant risks posed through each site-specific pathway
- reduce risk exposure levels to protective ARAR levels or to within the EPA-acceptable risk range for carcinogenic risk or below the Hazard Index of 1 for noncarcinogenic risks
- not pose unacceptable short-term risks or cross-media risks.

**** Note:*** *Institutional controls alone may not be sufficient response actions for radioactively contaminated sites.*

Compliance with Applicable or Relevant and Appropriate Requirements (ARARs)

- Whether and how the response action will comply with all federal ARARs and any more stringent state ARARs, or if/how the response justified an ARAR waiver.
- If no requirements are applicable, then site decision-makers must consider relevant and appropriate requirements.

Long-term effectiveness and permanence

- How the response action will maintain reliable protection of human health and the environment over time, once cleanup levels have been met.

Reduction of toxicity, mobility, or volume through treatment

How the treatment will...

- address the principal threats at the site, reducing the hazards posed by those threats
- destroy, reduce the quantity of, or immobilize contaminants so that they do not leave the site via exposure pathways
- affect toxicity, mobility, or volume reduction with respect to residuals, the risks posed by residuals, and effects of treatment reversibility.

Short-term effectiveness

- Time elapsed until the response action effectively protects human health and the environment.
- Prior to attaining cleanup levels, whether any adverse impacts may occur
- How/whether the response action will adversely affect the community and workers and impact the environment during operations.

Implementability

- Ease of construction and operation of the response action and availability of services and materials required to perform the proposed remedial action
- Ability to satisfy permitting or administrative requirements for the technology and monitor its effectiveness, and the availability of necessary equipment, utilities, and operation specialists
- Response action's fit with site-specific characteristics
- Technical considerations, such as treatment reliability and the possible effect on future remedial action.

Exhibit 1-4: NCP Evaluation Criteria Included in Technology Profiles (Cont.)

Cost

- Estimated present worth, capital, and operation and maintenance costs.

  NOTE: Costs are typically driven by the cost of purchasing/leasing and operating treatment equipment; the volume of waste requiring treatment; and costs associated with waste transport, residuals storage and/or disposal. In addition, for radioactively contaminated sites, costs of remediation could include cost of shielding and protective equipment from external exposure to remediation workers. Specific cost data are not available for all technologies and those stated in this Guide should be considered broad estimates.

3) Summary

This Section summarizes the essential information presented in each profile. A matrix presents a composite view of pertinent performance or site characteristics and how they relate to the evaluation criteria.

Profiles are designed to enable cross-comparisons with other profiles to screen technologies for further consideration. To make the final selection from the screened technology(ies), many site-specific factors, such as hydrogeology and soil porosity, and factors related to the implementation of each technology, such as materials handling, must be considered.

1.4.3 Summary of Technologies Selected

A table summarizing each of the technologies is presented in Exhibit 1-5. This table describes which media are addressed by the technology and the radioactive contaminants for which the technology is applicable or demonstrated. In addition, the Table includes special considerations that may affect whether a technology is appropriate for a specific site and general results and/or limitations on how well the technology has performed.

Exhibit 1-5: Summary of Solid and Liquid Media Technologies

TECHNOLOGY	CONTAMINANT	MEDIUM	CONSIDERATIONS *
Containment			
Capping (In-situ process)	Applicable for all classes of radioactive waste	Soils, mine tailings, sediments, bulk waste	• Inappropriate where water table is high • Maintenance requires ensuring against development, surface erosion, vegetative growth, and wildlife activity in cap area • Reduces vertical but not horizontal mobility • Does not remove or remediate contaminated media
Land Encapsulation (Ex-situ process)	Applicable for low-level, mixed and commercial radioactive wastes	Soil, sediment, bulk waste	• Stringent siting and construction requirements • Transportation risks exist for offsite facilities • Does not remediate contaminated media
Cryogenic Barrier (In-situ process)	Applicable to all classes of radioactive waste	Soils, sediment, bulk waste, groundwater	• Optimal soil moisture must be maintained • Refrigeration unit must continue to operate • Remote sites may require electrical power and utility installation • Heat from high-level radioactive waste may increase electrical power needs and maintenance costs • Does not remove or remediate contaminated media

Exhibit 1-5: Summary of Solid and Liquid Media Technologies (Cont.)

TECHNOLOGY	CONTAMINANT	MEDIUM	CONSIDERATIONS *
Solidification/Stabilization			
Cement Solidification/ Stabilization (In-situ or ex-situ process)	Applicable to all classes of radioactive waste	Soils, buried waste	• The chemical form or the presence of other contaminants may inhibit cementation • Best suited to highly porous, coarse-grained low-level radioactive waste in impermeable matrices • Not suitable if masses are thin, discontinuous, and at or near the surface • Debris may interfere with solidification process • Does not remediate contaminated media
Chemical Stabilization/ Solidification (In-situ or ex-situ process)	Applicable to all classes of radioactive waste	Soils, sediments, sludges	• Better suited to fine-grained soil with small pores • Presence of some contaminants may inhibit chemical effectiveness • Does not remediate contaminated media

Exhibit 1-5: Summary of Solid and Liquid Media Technologies (Cont.)

TECHNOLOGY	CONTAMINANT	MEDIUM	CONSIDERATIONS *
Chemical Separation			
Solvent/Chemical Extraction (Ex-situ process)	Demonstrated on various radionuclides including radium, thorim, and uranium. Also, radioisotopes of cobalt, iron, chromium, uranium, and plutonium.	Soils, sediment, sludge	• Ex-situ processes that require disposal of separated waste and some residuals in medium • Multiple reagents may be used for mixed contaminants; careful treatability studies required • Radioactive contaminant removal ranges from 13% to 100% depending on the contaminant, solvent type, and conditions • Not practical for soil with more than 6.7% organic material
Ion Exchange (Ex-situ process)	Demonstrated for radium, uranium and strontium	Groundwater, surface water, wastewater, liquid waste	• Most effective when the waste stream is in ionic form • The presence of more than one radioactive contaminant may require more than one treatment process • Pretreatment may be necessary for removing solids, modifying pH, or removing competing ions • Reported removal rates for radium and uranium are 65 to 97% and 65 to 99%, respectively

Exhibit 1-5: Summary of Solid and Liquid Media Technologies (Cont.)

TECHNOLOGY	CONTAMINANT	MEDIUM	CONSIDERATIONS *
Chemical Precipitation	Demonstrated for uranium	Groundwater, surface water, wastewater, liquid waste	• Most effective with optimum pH levels within a relatively narrow range • Study demonstrated removal of 80 to 95% uranium from pond water, depending on pH, reagent, and reagent dosage
Physical Separation			
Dry Soil Separation	Demonstrated for thorium, uranium, Pu-239, Am-241, Ra-222, Cs-137 and Co-60	Soil, sludge, crushed asphalt or concrete	• Soil must first be excavated, therefore poses a health and safety risk to workers and the local community • Soil residuals will requires further treatment and/or disposal • The volume of contaminated soils can be reduced by >90%
Soil Washing (Ex-situ process)	Demonstrated for thorium, uranium, cesium, radium, and plutonium	Soil, slurry	• Appropriate where radioactive contaminants are closely associated with fine soil particles (size between 0.25 and 2 mm) • Soil character, moisture content, particle size distribution, contaminant concentrations and solubilities affect efficiency/operability of soil washer • Process may not work for humus soil • Technology is not yet fully demonstrated for radioactive contamination

Exhibit 1-5: Summary of Solid and Liquid Media Technologies (Cont.)			
TECHNOLOGY	**CONTAMINANT**	**MEDIUM**	**CONSIDERATIONS ***
Flotation (Ex-situ process)	Demonstrated for uranium and plutonium	Soil, sediment	• Effectiveness varies with soil characteristics • Most effective at separating soil particles in the size range of 0.1 to 0.01mm • Has not been fully demonstrated for radioactive contamination • Testing showed reduced radium concentrations in uranium mill tailings from 290 -300 pCi/g to 50-60 pCi/g
Microfiltration	Demonstrated for uranium, americium, and plutonium	Groundwater, surface water, slurry, wastewater	• Best suited for separating very fine particles (0.1 to 0.001 microns) from liquid media • Removal efficiencies were greater than 99% for uranium, plutonium, americium
Reverse Osmosis	Demonstrated for uranium	Groundwater, surface water, slurry, wastewater	• Affected by the size and charge of the ion being treated • Aqueous waste stream must be treated or disposed of • Reduced uranium concentrations in groundwater by 99%
Carbon Adsorption	Demonstrated for uranium, Co-60, and Ru-106	Groundwater, surface water, slurry, wastewater	• Presence of iron may promote fouling of carbon • Effective in reducing groundwater uranium concentrations from 26-100 ug/l to <1 ug/l

Exhibit 1-5: Summary of Solid and Liquid Media Technologies (Cont.)

TECHNOLOGY	CONTAMINANT	MEDIUM	CONSIDERATIONS *
Aeration	Demonstrated for radon	Groundwater, surface water, slurry, wastewater	• Primarily used in radon removal • Radon removal efficiency ranged from 90% to 99.6% in water
Vitrification			
In-Situ Vitrification	Demonstrated for most radioactive waste	Soil, sludge, sediment, mine tailings	• High moisture/salt content in soil can increase electrical needs/cost • Plan for void volumes/percentages of metals, rubble, combustible organics • Requires off-gas control systems • Volatile radionuclides trapped during the process require further treatment and/or disposal • Does not affect radioactivity
Ex-Situ Vitrification	Demonstrated for most radioactive waste including low-level and transuranic wastes	Soils, debris, sediment, buried waste, metals	• Fixed and rotating hearth applications are available • Requires off-gas control systems • Volatile radionuclides trapped during the process require further treatment and/or disposal • Has not been fully demonstrated • Costs are considered high • Does not affect radioactivity

* These considerations are general in nature; please refer to profiles for a complete discussion of each technology

1.5 ORGANIZATION AND USE OF THIS GUIDE

The remainder of this Guide contains the following components:

Section II provides treatment technologies for solid media grouped under five categories:

- **Containment** - technologies that provide barriers between contaminated and uncontaminated media to prevent contaminant migration and shield potential receptors from radiation
- **Solidification/Stabilization -** technologies that add material to the contaminated waste and soil to produce a leach-resistant media, which binds the waste
- **Chemical Separation -** technologies that use the contaminants' chemical properties to separate contaminants from the contaminated media
- **Physical Separation -** technologies that rely on the contaminants' physical properties to separate contaminants from the contaminated media.
- **Vitrification -** a technology that heats contaminated media sufficiently to liquefy the media and its contaminants and, upon cooling, traps the contaminants in a glass matrix.

Exhibit 1-6 highlights the five types of solid media technologies discussed.

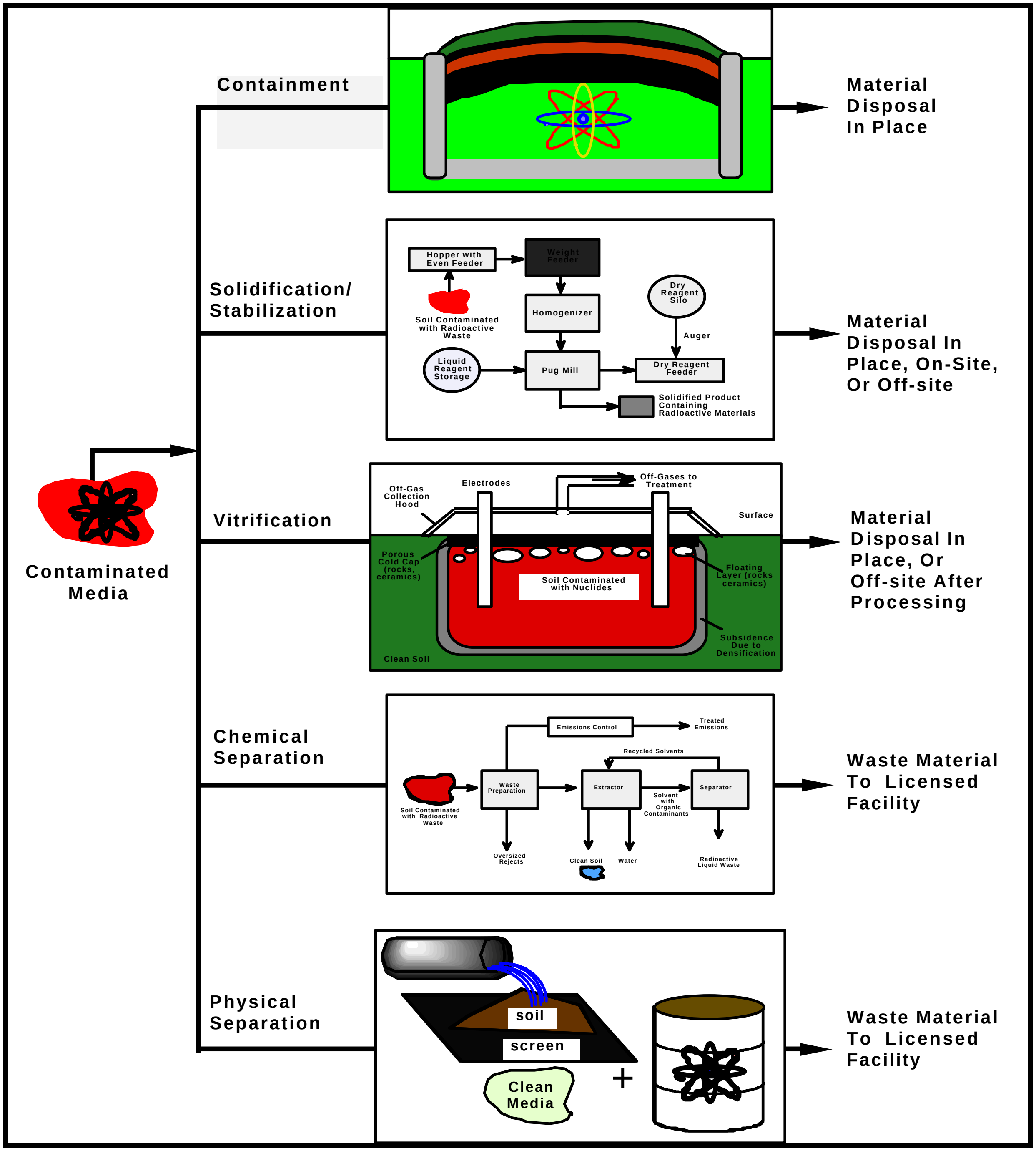


Exhibit 1-6: Solid Media Technology Categories

Section III which describes five treatment technologies for contaminated liquid media, grouped under chemical and physical separation categories:

- **Chemical Separation** - technologies that use chemical reagents or exchange mechanisms to bind up or immobilize radionuclides based on their chemical properties.
- **Physical Separation** - technologies that rely on physical properties such as size or volatility to separate and immobilize radionuclides.

Following sections II and III are the Appendices, containing a discussion of radioactivity concepts, glossary of terms, and a bibliography of general references for those readers who wish to research the technologies further.

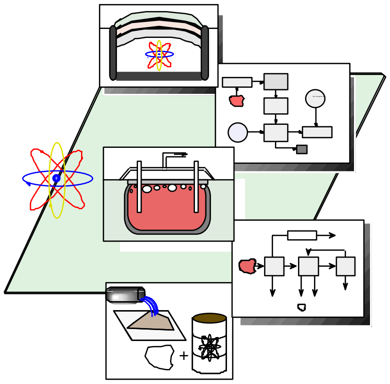
Exhibit 1-7 suggests how the profiles in this Guide can be used to identify potential treatment technologies for their sites.

Exhibit 1-7: Using the Technology Profiles

To locate information in the profiles, take the following steps...

- Note which contaminants and media the technology addresses.
- Note any distinctive operating or site characteristics that influence the technology's effectiveness; consider whether these circumstances permit or rule out this technology. Note special factors to be considered, for example, cost, safety of nearby populations, or topography, if they significantly influence the choice of appropriate technologies.
- Identify all relevant technologies using the first two steps.
- Assess how those technologies have performed according to the NCP criteria.
- Identify technologies to evaluate further. Consult your Regional Decision Team and additional resources identified in the Technology Profiles.

You are encouraged to provide feedback for future updates to this guide in the form of comments, suggestions and new sources of information to the address on page v.



SECTION II

SOLID MEDIA TECHNOLOGY PROFILES

CONTAINMENT TECHNOLOGIES

Containment technologies are designed to isolate contaminated materials in order to prevent exposure to humans and the environment. Often, volume reduction or other treatment technologies are applied to radioactive waste prior to containment. Regardless of the technologies applied, however, there is generally a portion of the radioactive material that requires long-term disposal. Exceptions include radionuclides with relatively short half-lives (e.g. Cobalt-60), in which case containment for shorter periods of time may be appropriate. Because most radionuclides require long-term disposal, remedies for radioactively contaminated sites usually employ containment technologies. Some containment technologies are designed to prevent horizontal contaminant migration, some to prevent vertical migration, and others to prevent any form of migration. To achieve the necessary level of isolation, different containment technologies are often used in conjunction with one another.

The following containment technologies used to isolate radioactive waste are discussed in this section: capping (containment in place); land encapsulation (excavation and disposal, on-site or off-site); cryogenic barriers (containment in place); vertical barriers (containment in place).

2.1 CAPPING

2.1.1 Technology Characterization

Description

Capping is a containment technology that forms a barrier between the contaminated media and the surface, thereby shielding humans and the environment from radiation effects. Capping radioactive waste involves covering the contaminated media with a cap sufficiently thick and impermeable to minimize the migration of waste to the surface and to control windblown contamination. A cap must also restrict surface water infiltration into the contaminated subsurface to reduce the potential for contaminants to leach from the site. Capping does not prevent horizontal migration of contaminants due to groundwater flow, however, it can be used in conjunction with vertical walls to produce an essentially complete structure surrounding the waste mass.[7] A cap can be placed over a large, discrete contaminated area or it can be a continuous cover over several smaller contaminated areas close together. A cap must extend a few feet beyond the perimeter of the contaminated area to prevent lateral infiltration of rain.

Caps can be made of a variety of materials, each of which provides a different degree of protection. Capping materials include synthetic membrane liners such as geomembranes (e.g. high density polyethylene, HDPE), asphalt, cement, and natural low-permeability soils such as clay. A cap is usually a combination of materials layered one on top of the other. A typical cap for containing radioactive media might consist of several feet of compacted filler, a geomembrane, a layer of compacted clay, another geomembrane, and several feet of top soil (see Exhibit 2-1). A layer of ground cover vegetation may be applied to the surface of the cap to reduce soil erosion and limit the potential for precipitation to permeate the cap.

Caps for radium-contaminated sites must be designed to confine gaseous radon until it has essentially decayed. If synthetic membrane liners are not used, the depth of cover required is about 150 cm for radon-222 and 5 cm for radon-220. In addition, approximately 60 cm of soil cover is required for gamma radiation shielding.[8] Long-

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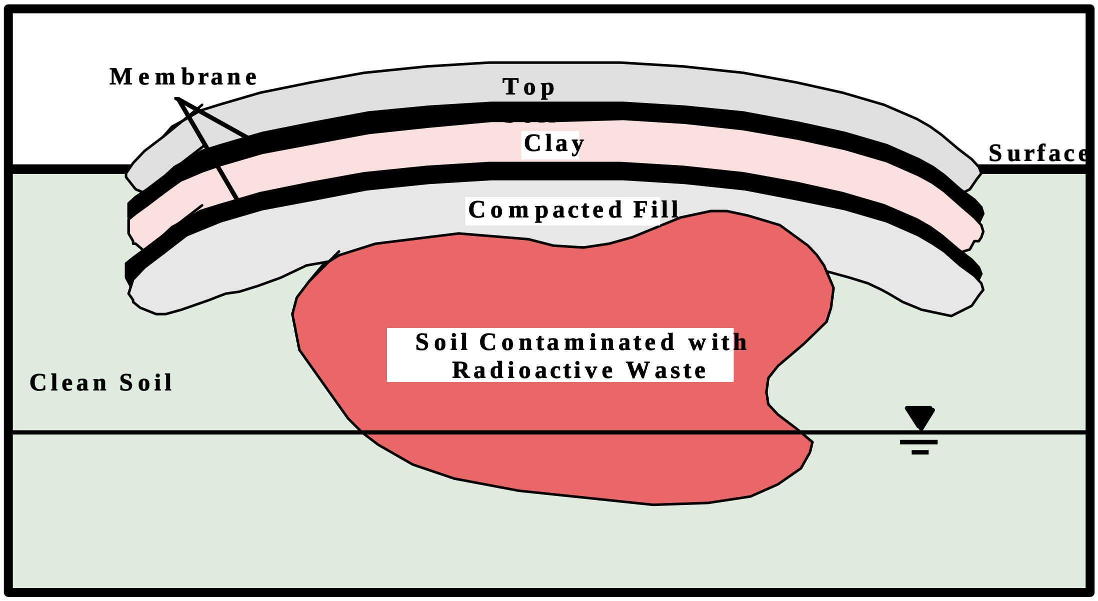
[7] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites,* EPA/540/2-88/002, August 1988.

[8] *Ibid.*

term durability of the cap materials should be considered in order to effectively isolate the radioactive waste. For example, HDPE is susceptible to degradation from sunlight as well as chemical and biological degradation. However, these degradation mechanisms are generally eliminated by burial of the membrane in cover systems that are three meters in depth, thus increasing the longevity of the geomembrane.[9]

Capping is a well-known technology that is relatively easy to implement.[10] Site-specific conditions such as climate need to be considered in determining an appropriate cap design. Many alternatives are possible, depending on the need for water control at the site. Software programs are currently being developed for commercial use to ensure that site managers use the best scientific information on barrier design and performance to select the best remediation practice within the constraints of technical performance, regulatory requirements, and cost.[11]



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[9] Frobel, R. "*Geomembranes in Surface Barriers*," Environmental Restoration Conference, 1995.

[10] Oak Ridge National Laboratory, *Oak Ridge National Laboratory Technology Logic Diagrams, Volume 2, Part B, Remedial Action*, ORNL/M-2751/V2/Pt.B, September 1993.

[11] U.S. Department of Energy, *Decision Support System*, *Technology Catalog*. 1994.

Exhibit 2-1: Capping

Target Contaminant Groups

Capping can be used to contain all types of waste, including radioactive waste materials found in the soil matrix, debris, and radioactively contaminated landfills.

Technology Operating Characteristics

Exhibit 2-2 summarizes the operating characteristics of capping.

Exhibit 2-2: Technical Characteristics of Capping

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	Not Applicable
Emissions: Gaseous and Particulate	Potential for fugitive dust and gas emissions during cap construction. Radon gas collection and treatment systems may be required if buildup occurs once the cap is installed.
Costs: Capital and O&M	Most costs are capital; O&M costs include monitoring and maintenance costs. Cost depends on the type of cap required; typical clay caps are $10 to $15 per square yard, where RCRA caps with multiple layers are $25 to $30 per square yard.
Reliability	Reliable when properly maintained and not impacted by development or other disruptive activities at the site.
Process Time	Objectives are met as soon as cap is in place.
Applicable Media	Soil, mill tailings, sediment, drummed waste, boxed waste and bulk waste
Pretreatment/Site Requirements	Waste may need to be consolidated before cap construction.
Type and Quantity of Residuals	Contaminated media is not processed or removed.
Disposal Needs and Options	Not Applicable
Post-treatment Conditions	Institutional controls, such as deed, site access, and land use restrictions, are usually required.
Ability to Monitor Effectiveness	Radon gas emissions from the subsurface, cap integrity, and the effects of contamination on groundwater can be monitored.

Site Considerations

Site conditions such as fluctuations in air temperature, precipitation, or subsidence may affect the cap's integrity by causing cracking, settling, or erosion. Biological processes such as intrusion of plant roots and burrowing animals can also affect the cap's integrity. These considerations are particularly important for containing radioactive waste because of the long-term isolation required. In order to promote the cap's longevity, infiltration barriers should be covered by a soil layer sufficiently thick to extend below the frost line to accommodate rooting depths of native plants and to extend below the probable depth of animal burrows.[12]

Characterization of soils is not as critical for capping as it is for more complex remedial approaches that depend on soil conditions (e.g. stabilization). In dry and porous soils with high radium concentrations, venting may be required to control radon gas migration and buildup below the ground surface. Such venting may violate applicable emission standards unless the radon is collected and treated.[13] The impact that groundwater flow could have on contaminant migration at the site should be considered. Capping may not be a feasible alternative at sites with low topography, flooding, or a shallow groundwater table; these conditions encourage horizontal migration and decrease the cap's effectiveness.

2.1.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

Capping protects human health by putting a barrier between the radioactive waste and the surface environment, thus preventing human contact with the contaminated media. Depending on the environmental receptors at the site, however, capping may not adequately protect the environment. During cap installation nearby populations and site workers are at risk of exposure to contaminants from fugitive dust and gas emissions. To mitigate these risks, controlling fugitive dust and operating under favorable meteorological conditions should be practiced. Over the long term, contaminants may migrate via contact with groundwater, defeating containment objectives.

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[12] Oak Ridge National Laboratory, *Natural, Physical, and Biological Processes Compromise the Long Term Performance of Compacted Soil Caps*. Environmental Restoration Conference, 1995.

[13] U.S. Environmental Protection Agency, *Background Information Document for Radiation Site Cleanup Proposed Rule, Revised Draft*, August 1995.

Compliance with ARARs

At sites with mixed waste, the cap must comply with Resource Conservation and Recovery Act (RCRA) cap construction guidelines. At DOE facilities with low-level waste, the cap must comply with the performance criteria outlined in DOE Order 5820.2A. Compliance with other ARARs must be determined on a site-specific basis.

Long-Term Effectiveness

Capping does not remove the source of radioactivity from the area of concern. It simply impedes direct exposure to contaminants in soil and the release of contamination by isolating the contaminated media. Capping may be inadequate as a long-term solution due to the potential for weathering, cracking, subsidence or other deterioration. Monitoring radon gas emissions from the subsurface, cap integrity, and groundwater is required to ensure the long-term effectiveness of this technology. Over the long term, horizontal migration of contaminants may occur via contact with groundwater, even if the cap remains intact.

Reduction of Radiotoxicity, Mobility, or Volume

Capping does not reduce the radiotoxicity or volume of the contaminated media. While capping significantly reduces vertical mobility due to surface water leaching, it does not restrict horizontal mobility via contact with groundwater.

Short-Term Effectiveness

During cap construction, capping may pose risks to surrounding communities and site workers by exposing them to the contaminated media and fugitive dust and gas emissions. If excavation and waste consolidation from other parts of the site are required, waste transport can increase exposure risk. The cap's effectiveness in significantly reducing exposure risks occurs as soon as the cap is in place.

Implementability

Capping is a mature, well-known technology that is relatively easy to implement. Materials and equipment are usually readily available. Since the treatment is entirely *in-situ*, no offsite activity is necessary to manage, treat, or store the contaminated waste. Air temperature, precipitation, topography, other site-specific conditions, and subsurface conditions may affect implementation. If fugitive dust emissions are a problem during implementation, dust suppression measures are readily available. Installation of a gas collection and treatment system may be necessary due to radon and/or methane gas emissions.

Cost

Most costs are capital. O&M costs generally include monitoring and possible cap repairs. The cost of capping depends on the size and type of the cap required. A typical clay cap costs approximately $10 to $15 per square yard, while a typical RCRA cap (more likely to be used for radioactive waste) costs between $25 to $30 per square yard.[14] The increased cost of the RCRA cap reflects the use of multiple layers, including geomembranes. Other major cost drivers for this technology include gas collection and treatment, if necessary, and long-term monitoring and maintenance.[15]

2.1.3 Summary

Capping involves covering radioactive waste to reduce or eliminate exposure pathways. Because contaminated media are not removed or treated, there is a residual risk of exposure over the long-term due to cap disturbance and possible horizontal migration in groundwater. If the cap remains undisturbed and horizontal migration is minimal, capping protects human health by putting a barrier between the radioactively contaminated waste and the surface. During cap construction, surrounding communities and site workers may be exposed to fugitive dust and gas emissions.

The most significant advantages of capping are the ease of application, the fact that it is a well-known technology, and that it is reliable when properly maintained. The most significant disadvantages of capping are that the contaminated media is not treated or removed and that it does not limit horizontal migration of the contaminants via groundwater.

Exhibit 2-3 summarizes the data and analyses in this profile and can be used for technology comparison.

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[14] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

[15] *Ibid.*

Exhibit 2-3: NCP Criteria for Capping

NCP Criterion	Evaluation	Performance Data
Overall Effectiveness	• Highly effective and reliable when maintained properly.[16]	• Depends on cap type and degree to which it remains intact over time. • Can control direct contact with contaminated media and decay gases and prevent vertical migration of contamination to the surface.
Compliance with ARARs	• Sites with mixed waste must comply with RCRA capping requirements. • DOE sites with low-level waste must comply with DOE Order 5820.2A.	• Compliance with soil and groundwater ARARs must be determined on a site-specific basis.
Reduction of Radiotoxicity, Mobility or Volume	• Does not decrease radiotoxicity or volume of the contaminated media. • Reduces vertical but not horizontal mobility.	• Does not remove or remediate contaminated media. • Has been shown to reduce vertical contaminant migration.
Long-Term Effectiveness and Permanence	• Effective over long-term, as long as cap remains intact. • Horizontal migration of contaminants is possible over long-term.	• Dependent on proper cap maintenance and lack of disturbance. • Difficult to monitor or evaluate cap performance once installed.

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[16] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites,* EPA/540/2-88/002, August 1988.

Exhibit 2-3: NCP Criteria for Capping (Cont.)

NCP Criterion	Evaluation	Performance Data
Short-Term Effectiveness	- Effective means of containing contamination in short-term. - Requires control of potential worker and community exposure to contamination during implementation.	- Prevents contaminant exposure as soon as cap is in place. - May expose community or workers to contamination during construction.
Implementability	- Easy to implement. - Relevant site-specific factors must be considered prior to implementation.	- No offsite activity is necessary to manage, treat, or store the waste. - Site-specific conditions such as climate and topography may impact cap integrity.
Cost	- Relatively low capital cost.[17] - Maintenance over very long-term will affect overall cost.	- Costs between $10 and $30 per square yard are associated with this technology.[18] - O&M costs include monitoring and cap maintenance.

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[17] *Ibid.*

[18] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

2.2 LAND ENCAPSULATION

2.2.1 Technology Characterization

Description

Land encapsulation is a proven, well-demonstrated containment technology[19] that is generally used at the disposal stage of radioactive waste management. Other technologies are often used to reduce the volume of the radioactive waste, after which land encapsulation is used to effectively dispose of the treated waste. Land encapsulation involves excavating the disposal area and installing a liner or other impermeable material in the excavated area. Radioactive waste and/or residuals requiring disposal are then transported and backfilled into the lined, excavated area and an appropriate cap is applied (see Exhibit 2-4) (detailed description of capping technology is provided in Section 2.1).

Facility design guidelines developed by the Nuclear Regulatory Commission (NRC) and EPA for commercial, mixed low-level waste (LLW) disposal facilities include two or more composite liners (e.g., upper geomembrane and compacted soil layer) and a leachate collection system located above and between the liners. The facility design minimizes water contact with the encapsulated waste as required by the NRC.[20]

While land encapsulation can occur on site, because obtaining necessary approvals to dispose of radioactive waste is difficult, most waste is transported to off site land encapsulation facilities. The Low-Level Radioactive Waste Policy Amendments Act of 1985 (LLRWPAA) requires states and compacts to develop siting plans for LLW disposal facilities.[21] A remote area dedicated by a state or other government entity to radioactive waste containment could receive waste from other sources within and outside that jurisdiction, given the appropriate approvals. There are currently three licensed LLW disposal facilities; additional LLW facilities are expected to become operational in the near future.

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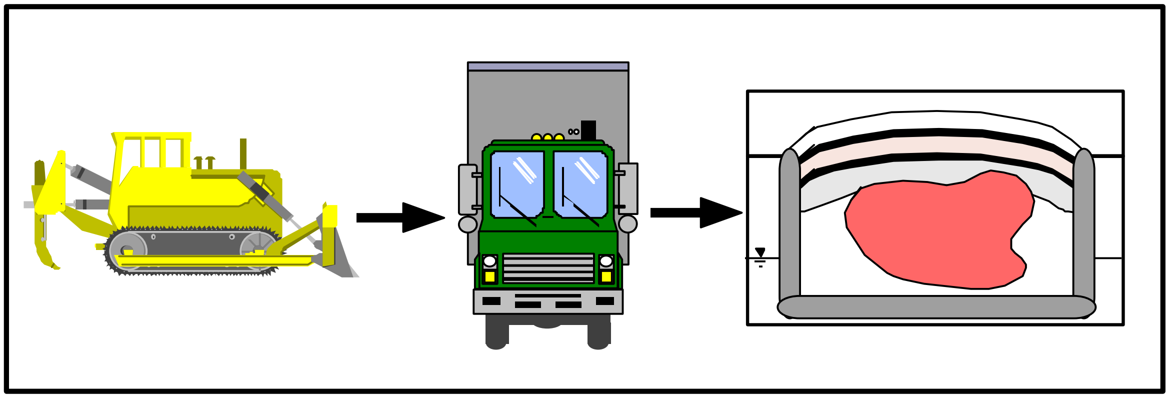
[19] *Ibid.*

[20] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[21] *Ibid.*

Given the long period of time that radioactive waste will be a hazard, the encapsulation facility must heed the degradational characteristics of construction materials more than usual for hazardous waste disposal sites.[22] Current research has focused on developing new types of materials to improve liner integrity and to reduce possible radionuclide migration. One approach involves using smectite clays, which can both bind hazardous cations and resist water. Such clays could increase resistance to leaching of the radionuclides by water.[23] Another developing technology is in-situ encapsulation of contaminant waste, in which the natural processes that convert unconsolidated soil, sand, and gravel sedimentary rock are simulated. Unlike traditional liners of silty-clay soils, this technology eliminates the potential for waste migration into groundwater.[24]

Exhibit 2-4: Land Encapsulation



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[22] *Ibid.*

[23] Argonne National Laboratory. “Encapsulation of Hazardous Ions in Smectite Clays” Project Description, 1994.

[24] Terran Environmental Inc. "In-situ Encapsulation of Buried Waste" Project Description , 1994.

Target Contaminant Groups

Land encapsulation is generally used as a final disposal method. Thus it can be applied to a wide variety of contaminants, including LLW, and mixed and commercial wastes (definitions of LLW, mixed waste and high-level waste are provided in Appendix-A). Land encapsulation may be appropriate for radionuclides, whether or not they have been extracted from a contaminated medium. Currently, no operating land encapsulation facilities accept high-level waste.

Technology Operating Characteristics

Exhibit 2-5 summarizes the operating characteristics of land encapsulation.

Exhibit 2-5: Technical Characteristics of Land Encapsulation

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	Not applicable
Emissions: Gaseous and Particulate	Gas and dust emissions from construction of the land encapsulation facility, excavation of the waste, and transportation of material are potential risks to workers, the community, and the environment.
Costs: Capital and O&M	Materials and installation costs range from $276 to 895 per cubic meter. First-year O & M costs are $0.045 per cubic meter.[25] These costs include the cost of excavation and transportation, but not acquisition of a disposal site.
Reliability	Highly certain for 100-1000 years.[26] Design and mitigation procedures can improve reliability.
Process Time	Not applicable. "Process time" may include the time devoted to either transportation of the material or construction time for a new land encapsulation facility. Once material reaches the facility, the process is complete.
Applicable Media	Soil, landfill leachates, sediments, bulk waste
Pretreatment/Site Requirements	The waste must first be excavated before being transported to the encapsulation facility. Other technologies may be applied to the waste prior to land encapsulation. In addition to licensing and/or regulatory approvals, excavation is necessary to construct a new land encapsulation facility.

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[25] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

26U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, *Assessment of Technologies for the Remediation of Radioactively Contaminated Superfund Sites*, EPA/540/2-90/001, January 1990.

Exhibit 2-5: Technical Characteristics of Land Encapsulation (Cont.)

Characteristic	Description
Type and Quantity of Residuals	Not applicable
Disposal Needs and Options	Generally, dependent on current licensed operating disposal facilities. Siting of a new disposal facility must comply with applicable regulations.
Post-treatment Conditions	Regulatory compliance procedures apply (i.e., monitoring and mitigation).
Ability to Monitor Effectiveness	Effectiveness of the encapsulation facility can be monitored by leachate collection systems and groundwater monitoring wells.

Site Considerations

Since there may be considerable public antipathy to this technology, the primary site consideration is location (e.g., proximity to residential areas). Transportation of large volumes of radioactive materials entails certain risks. Safety and licensing and/or regulatory approval considerations are more cumbersome if radionuclides have been concentrated by extraction and separation processes. Currently, there are three NRC-licensed commercial LLW disposal facilities: Hanford, Washington; Barnwell, South Carolina; and Clive, Utah. The only commercial disposal facility licensed for mixed waste is in Clive, Utah.

Site characteristics such as topography, seasonal variations in temperature and precipitation and seismic activity may impact the land encapsulation facility's integrity and must be considered. Relative to other technologies, minimal information about site soil characteristics is required prior to land encapsulation.

2.2.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

Environmental and human health risks are most prevalent when radioactive materials are being excavated and transported to an offsite land encapsulation facility. Transportation of large volumes of radioactive materials involves high costs and risks. Additional risks include excavation of radioactive material (if applicable) and handling these materials in preparation for transport to an encapsulation facility. Risks to site workers from radioactive material excavation can be reduced by using a remote excavation system for buried waste retrieval.[27]

The possibility that radioactive material in the land encapsulation facility could leach into the environment is also a risk, especially if it leaches into groundwater. Potential health impacts to site workers and residents also include exposure to fugitive dust emissions and fugitive gases, such as radon.

Compliance with ARARs

The NRC and EPA have jointly developed guidance on land encapsulation siting and designing commercial, mixed, low-level radioactive and hazardous waste land encapsulation disposal facilities.[28] The siting, construction, and operation of a land encapsulation facility at a DOE site must comply with DOE Order 5820.2A.

Long-Term Effectiveness

As a disposal facility, land encapsulation is designed to be a long-term solution to waste disposal. However, since land encapsulation does not reduce the volume or radioactivity of the contaminants, design features such as liner integrity, monitoring, and mitigation procedures are necessary to ensure effectiveness. Proximity to residential areas, site characteristics, and land management plans all play a critical role in the continued effectiveness of a land encapsulation facility.

Additionally, an appropriate site may need to be located for disposing of radionuclides that have been extracted and separated, if a land encapsulation site does not accept such materials.

Reduction of Radiotoxicity, Mobility, or Volume

Land encapsulation will not reduce the radiotoxicity or volume of the contaminated material. A sufficiently encapsulated facility will significantly reduce vertical and horizontal mobility.

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[27] Oak Ridge National Laboratory and Idaho National Engineering Laboratory, *Technology Catalog Site Remediation Profiles: Remote Excavation System* - 1993.

[28] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

Short-Term Effectiveness

If a land encapsulation facility provides sufficient capacity, a completely impermeable liner and cover can prevent risks to human health and the environment. During development of the land encapsulation facility, and excavation and transportation of waste to the facility, however, local residents and site workers may be exposed to dust and gas emissions.

Implementability

For on site encapsulation, safety and siting approval considerations may impact implementation because they can be very difficult to obtain. Generally, implementing a new land encapsulation facility is a lengthy process due to public concerns. Finding an existing, secure site outside the containment property that will accept radioactive waste may also be difficult. Safety and permitting issues also apply to transporting and handling the waste outside the boundaries of the contaminated property.

The materials and equipment necessary to construct land encapsulation facilities are generally readily available. Of the three existing NRC-licensed sites, however, restrictions apply as to the types of waste accepted (such as radium waste at Barnwell, SC) [29]. Also, the Utah facility is restricted to 11(e)(2) byproduct material, Class A low-level waste and mixed low-level waste. The Hanford facility currently accepts only waste from the Northwest and Rocky Mountain compacts.

Cost

The quantity of material for disposal most influences the cost. For large volumes of material it may be desirable to reduce the volume through other treatments prior to disposal. Costs also depend on the distance the waste must be transported to a land encapsulation site; on site land encapsulation is less expensive than off site encapsulation. The materials and installation costs range from $276 to 895 per cubic meter of soil, while first-year O&M costs are $0.045 per cubic meter.[30] Remote

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[29] *Ibid.*

[30] *Ibid.*

excavation of a contaminated site costs from $203 to 244 per cubic foot, not including transportation or disposal costs.[31]

2.2.3 Summary

Land encapsulation is a containment technology generally used at the disposal stage of radioactive waste management. Land encapsulation facilities are designed to be long-term solutions to waste disposal, although they do not reduce the radiotoxicity or volume of waste.

The following factors may limit the applicability and effectiveness of this process:

- difficulty in obtaining permits for siting and constructing a land encapsulation facility for radioactive waste;
- likelihood of liner deterioration, liner penetration, and leaching over the long-term;
- limited number of permitted facilities accepting radioactive waste;
- risks associated with the possible excavation, handling, and transportation of radioactive waste.

Exhibit 2-6 summarizes the data and analyses presented in this profile and can be used for technology comparison.

Exhibit 2-6: NCP Criteria for Land Encapsulation

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Covers and liners are designed to encapsulate waste.	• Eliminates radiation effects. Site characteristics and monitoring are crucial.
Compliance with ARARs	• Required in permit process.	• Joint NRC-EPA siting and facility design guidance or DOE Order 5820.2A applies. • For off-site, transport regulations apply.

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[31] Oak Ridge National Laboratory and Idaho National Engineering Laboratory, *Technology Catalog Site Remediation Profiles: Remote Excavation System* - 1993.

Exhibit 2-6: NCP Criteria for Land Encapsulation (Cont.)

NCP Criterion	Evaluation	Performance Data
Reduction of Radiotoxicity, Mobility, or Volume	• Does not reduce radiotoxicity or volume; reduces vertical and horizontal mobility.	• Involves immobilization but not removal or destruction.
Long-Term Effectiveness and Permanence	• Designed to be a long-term solution for disposal.	• A proven, well-demonstrated technology. • Reliable for 100-1000 years. • Site characteristics, liner integrity, and management determine effectiveness.
Short-Term Effectiveness	• No reduction of radiotoxicity or volume. Effectively contains waste in the short-term.	• Potential to expose local residents and site workers to fugitive dust and gas emissions.
Implementability	• Difficult to gain approval for building a facility. • Substantial permit requirements. • Construction processes are not difficult or time-consuming.	• Significant public antipathy. • Easy to construct under appropriate site conditions.
Cost	• Development of a new facility is expensive. Costs are reduced if facility is in place.	• Capital costs range from $276 to $895 per cubic meter of contaminated soil. First-year O&M costs are $.045 per cubic meter.

2.3 CRYOGENIC BARRIERS

2.3.1 Technology Characterization

Description

A cryogenic barrier is a containment technology that freezes soil to create an ice barrier around a contaminated zone. This barrier reduces the mobility of radionuclide contaminants by confining the materials and any contaminated groundwater that might otherwise flow through the site. To create the barrier, two rows of freeze pipes are inserted in an array outside and beneath the contaminated zone, using standard well drilling techniques. The first row of freeze pipes is installed around the circumference of the site at angles below the contaminated zone; the second set of freeze pipes is installed a set distance away from the first row. Careful installation of the piping is necessary to ensure complete barrier formation. Once installed, the array of pipes is connected via a manifold to a refrigeration plant. In a completely closed system, the pipes carry a coolant that freezes the inner volume between the two rows of freeze pipes to create the ice barrier. Coolants consist of environmentally benign brines such as salt water, propylene glycol, or calcium chloride. Soil moisture content of 14 percent to 18percent is considered optimal for implementing the cryogenic barrier. [32] Injection pipes can be placed within the barrier to optimize soil moisture and to insert monitoring devices (see Exhibit 2-7). Laboratory tests with Cesium-137 showed no detectable diffusion through the cryogenic barrier, although sorption on soil grains may have been responsible for the immobility.[33]

Cryogenic barriers are often used when the waste mass is too large for practical treatment and where soluble and mobile constituents pose an imminent threat to a drinking water source. Cryogenic barriers can be positioned to maximum depths of 1,000 feet and do not require excavation for installation.[34] Barrier thickness, ranging from 15 to 50 feet, and temperature may vary to suit site conditions. Ongoing refrigeration is required to maintain cryogenic barriers; heat generated from high-level

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[32] Cryocell, *Responses to Commonly Asked Questions About Frozen Soil Barriers Containing Hazardous Waste.*

[33] U.S. Department of Energy, *Frozen Soil Barrier Technology, Innovative Technology Summary Report*, DOE/EM-0273, April 1995.

[34] Oak Ridge National Laboratory, Oak Ridge National Laboratory Technology Logic Diagrams, Volume 3, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

radioactive waste can increase the electrical power needs.[35] With adequate refrigeration, the ice does not degrade or weaken over time and is repairable in situ. If ground movement fractures the barrier, the fissures can be repaired by injecting water into the leakage area.[36]

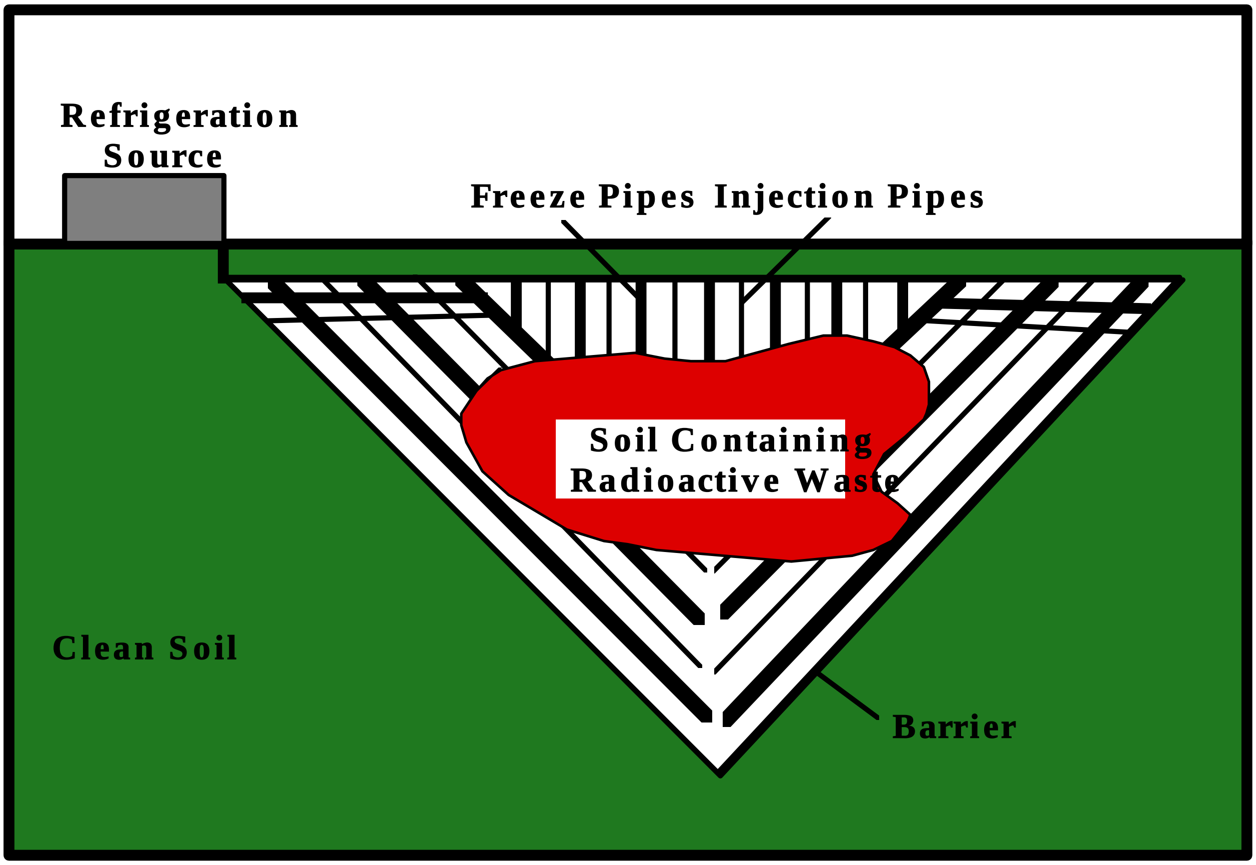

Exhibit 2-7: Cryogenic Barrier

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[35] Fremond, M., *Ground Freezing 94*, from the Proceedings of the Seventh International Symposium on Ground Freezing, Nancy, France, October 24-28, 1994.

[36] U.S. Environmental Protection Agency, Office of Research and Development, *Superfund Innovative Technology Evaluation Program: Technology Profiles*, Seventh Edition, EPA/540/R-94/526, November 1994.

Using refrigeration to freeze soils has been employed in large-scale engineering projects for a number of years. While cryogenic barriers have been field tested, they have not yet been demonstrated at an actual radionuclide-contaminated site.

Target Contaminant Groups

Cryogenic barriers provide subsurface containment for a wide variety of waste in soil and groundwater, including radionuclides, metals, and organics. While cryogenic barriers are used for radionuclides in soluble form, the solubility of the radionuclides depends on site-specific conditions such as pH and other chemicals present.

Technology Operating Characteristics

Exhibit 2-8 summarizes the operating characteristics of cryogenic barriers.

Exhibit 2-8: Technical Characteristics of Cryogenic Barriers

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	Not applicable
Emissions: Gaseous and Particulate	Not applicable
Costs: Capital and O&M	Costs are based on the volume of frozen soil required to contain the waste. Capital costs range from \$10 to \$14 per cubic foot; operation and maintenance costs are approximately \$1 per cubic foot per year.[37]
Reliability	Fully demonstrated for geotechnical applications to construction sites.[38] Field demonstrated at clean sites.[39]
Process Time	A cryogenic barrier can be established within a few months. Containment of the radioactive waste occurs as soon as the barrier is in place.[40]

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[37] U.S. Department of Energy, *Frozen Soil Barrier Technology, Innovative Technology Summary Report*, DOE/EM-0273, April 1995.

[38] Oak Ridge National Laboratory, Oak Ridge National Laboratory Technology Logic Diagrams, Volume 3, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

[39] RKK, Ltd. Vendor Information.

[40] Fremond, M., *Ground Freezing 94*, from the Proceedings of the Seventh International Symposium on Ground Freezing, Nancy, France, October 24-28, 1994.

Exhibit 2-8: Technical Characteristics of Cryogenic Barriers (Cont.)

Characteristic	Description
Applicable Media	Soil, sediment, leachates, bulk waste, and groundwater
Pretreatment/Site Requirements	Power for the refrigeration plant to freeze the soil is required.[41] Soil moisture content of 14% to 18% is considered optimal.
Type and Quantity of Residuals	Generates no waste stream or residues.[42]
Disposal Needs and Options	Not applicable. The contaminated media remain on-site.
Post-treatment Conditions	All waste remains on site. Refrigeration plant remains on-site to maintain frozen barrier.
Ability to Monitor Effectiveness	Target contaminants can be monitored using monitoring wells positioned internally and externally to the barrier. A fiber optics temperature sensor system can monitor barrier temperature.[43] Potential radioactive emissions from the contaminated area can be monitored.

Site Considerations

Design criteria for cryogenic barriers is site-specific and depends on waste type, topography, soil condition, thermal conductivity, and groundwater movement. Cryogenic barriers are adaptable to any geometry, however drilling technologies may present a constraint. Power for the refrigeration plant to freeze the soil is required; remote sites may require electrical power and utility installation.[44] Heat from high-level radioactive waste can increase electrical power needs for maintaining frozen barriers. In extremely dry soils, moisture must be supplemented with injection pipes placed within the barrier. For applications in humid and high ambient temperature

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[41] Oak Ridge National Laboratory, *Oak Ridge National Laboratory Technology Logic Diagrams, Volume 2, Part B, Remedial Action*, ORNL/M-2751/V2/Pt.B, September 1993.

[42] U.S. Environmental Protection Agency, Office of Research and Development, *Superfund Innovative Technology Evaluation Program: Technology Profiles*, Seventh Edition, EPA/540/R-94/526, November 1994.

[43] Cryocell, *Responses to Commonly Asked Questions About Frozen Soil Barriers Containing Hazardous Waste*

[44] Oak Ridge National Laboratory, *Oak Ridge National Laboratory Technology Logic Diagrams, Volume 2, Part B, Remedial Action*, ORNL/M-2751/V2/Pt.B, September 1993.

regions, proper ground insulation and near surface refrigerant piping may be required to ensure that surface to 2-foot depths are adequately frozen.[45]

2.3.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

Cryogenic barriers protect human health and the environment by reducing vertical and lateral migration of radioactive contaminants. This technology reduces risk exposure pathways as long as the pipes and refrigeration system remain intact. Because the radioactive waste remains in place, there is a potential risk to human health and the environment from radioactive emissions, particularly for waste located near the ground surface. These potential emissions should be carefully monitored.

Compliance with ARARs

At DOE sites with low-level waste, cryogenic barriers must meet the performance criteria outlined in DOE Order 5820.2A. Compliance with other ARARs must be determined on a site-specific basis.

Long-Term Effectiveness

Cryogenic barriers do not eliminate the radiotoxicity of the contaminants, they simply limit their vertical and lateral migration. Demonstration results indicate a non-detectable contaminant diffusion rate through a 15-m cryogenic barrier in thousands of years.[46] However, the frozen barrier must be maintained without any penetrations in order to be effective in the long-term. Monitoring the performance of cryogenic barriers with monitoring wells and fiber optics temperature sensory systems is necessary to ensure the long-term effectiveness of this technology. Also, because the radioactive waste remains on site, continual monitoring around the contaminated area is required to detect potential radioactive emissions.

Reduction of Radiotoxicity, Mobility, or Volume

Although cryogenic barriers do not reduce the radiotoxicity or volume of the contaminated material, they do reduce the horizontal and vertical mobility of contaminants in soil and groundwater.

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[45] U.S. Department of Energy, *Frozen Soil Barrier Technology, Innovative Technology Summary Report*, DOE/EM-0273, April 1995.

[46] Cryocell, *Responses to Commonly Asked Questions About Frozen Soil Barriers Containing Hazardous Waste*

Short-Term Effectiveness

Health and safety issues are associated with drilling, prior to installation of the refrigerant piping. If drilling occurs in contaminated areas, site workers can be exposed to radiation from the drilling equipment. The cryogenic barrier effectively contains radioactive waste upon implementation and activation. However, because the waste remains on-site, radioactive emissions may be produced from the contaminated area.

Implementability

Site conditions must be evaluated before implementing cryogenic barriers. Standard well drilling techniques are used to drill or drive the freeze pipes into place. This technology requires a power source, since a refrigeration plant is needed to maintain the refrigerant. Necessary equipment, such as mobile refrigeration units, freeze fittings, insulated piping systems, and drilling equipment, is readily available. The establishment of a complete cryogenic barrier system can be implemented, using large-scale temporary refrigeration equipment, in just a few months.

Cost

Costs are based on the volume of frozen soil required to effectively contain the radioactive waste. Total capital cost for the cryogenic barrier is estimated to range between $10 to $14 per cubic foot. Using more expensive cryogenics (e.g., liquid nitrogen) in areas with low freezing points could increase capital costs.[47] Average operation and maintenance costs are approximately $1 per cubic foot per year. Heat from high-level radioactive waste may increase electrical power needs and maintenance costs.

2.3.3 Summary

A cryogenic barrier is a containment technology that prevents vertical and horizontal migration of contaminants, including radionuclides. The technology involves installing freeze pipes outside and beneath the contaminated zone to form an ice barrier. Cryogenic barriers are effective upon implementation and provide long-term reduction in risk exposure pathways, as long as the pipes and refrigeration system

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[47] U.S. Department of Energy, *Frozen Soil Barrier Technology, Innovative Technology Summary Report*, DOE/EM-0273, April 1995.

remain intact. A monitoring system can be incorporated within and around the cryogenic barriers to ensure effectiveness.

Cryogenic barriers have been fully demonstrated for geotechnical applications to construction sites, and have been field demonstrated at clean sites. The waste type, topography, soil condition, thermal conductivity, and groundwater movement of a specific site must be assessed prior to implementation. In order for cryogenic barriers to be effective, soil moisture must be adequate and a suitable power source must be available at the site. The technology’s advantages include *in-situ* application, which reduces the potential exposure to radionuclides, and relatively easy barrier maintenance. Disadvantages of cryogenic barriers include the potential for radioactive emissions from the contaminated area and the need for ongoing refrigeration to maintain the barrier.

Exhibit 2-9 summarizes the data and analyses presented in this profile and can be used for technology comparison.

Exhibit 2-9: NCP Criteria for Cryogenic Barriers

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	`• Eliminates risks of migration by containing of waste. • Potential radioactive emissions from the contaminated area, particularly if waste is located near the ground surface.	• Useful for reducing migration of contaminants.
Compliance with ARARs	• Compliance with soil and groundwater ARARs must be determined on a site-specific basis.	• DOE sites with low-level waste must comply with DOE Order 5820.2A.
Reduction of Radiotoxicity, Mobility, or Volume	• Reduces mobility, but not radiotoxicity or volume, of contaminated media.	• Process does not remove or reduce contaminants. • Reduces vertical and lateral migration of contaminants.

Exhibit 2-9: NCP Criteria for Cryogenic Barriers (Cont.)

NCP Criterion	Evaluation	Performance Data
Long-Term Effectiveness and Permanence	• Leaves untreated contaminated media in place. • Potential radioactive emissions from the contaminated area. • Long-term barrier effectiveness depends on proper maintenance.	• Demonstration results show a nondetectable contaminant diffusion rate through a 15-m cryogenic barrier in thousands of years. • A monitoring system should be incorporated to evaluate the barrier's effectiveness and to detect radioactive emissions.
Short-Term Effectiveness	• Effective in reducing contaminant migration once the barrier is in place. Barriers can be fully implemented within 3 months. • Potential risk of exposure to site workers if drilling occurs in contaminated areas.	• Requires large-scale temporary refrigeration equipment for response in the short-term.
Implementability	• Equipment and power is needed to freeze the soil. • Site-specific characterization is needed.	• No offsite activity is necessary to treat or store the waste. • Depends on waste type, topography, soil condition, thermal conductivity, and groundwater movement.
Cost	• Costs are mainly associated with electrical power needs and are dependent on the size of the contaminated area and the heat produced by the contained waste.	• Capital costs are reported to range from $10 to $14 per cubic foot. O&M costs are approximately $1 per cubic foot per year. • Heat from high-level radioactive waste can increase O&M costs.

2.4 VERTICAL BARRIERS

2.4.1 Technology Characterization

Description

A vertical barrier is a containment technology that is installed around a contaminated zone to help confine radioactive waste and any contaminated groundwater that might otherwise flow from the site. Vertical barriers also divert uncontaminated groundwater flow away from a site. Vertical barriers must reach down to an impermeable natural horizontal barrier, such as a clay zone, in order to effectively impede groundwater flow. This technology is often used when the waste mass is too large to practically treat and where soluble and mobile constituents pose an imminent threat to a drinking water source. Vertical barriers are frequently used in conjunction with a surface cap to produce an essentially complete containment structure.[48] Two types of vertical barriers used to contain radioactive waste are slurry walls and grout curtains.

Slurry walls are subsurface barriers that consist of a vertically excavated trench filled with a slurry. The slurry both hydraulically shores the trench to prevent the collapse of the side walls during excavation and produces a barrier to groundwater flow (see Exhibit 2-10). The slurry is generally a mix of bentonite and water or cement, bentonite, and water.[49] When a strong vertical barrier is required, diaphragm walls are constructed with pre-cast or cast-in-place concrete panels. Composite slurry walls, consisting of an impervious artificial barrier in a wall excavated with self-hardening slurry, are more resistant to chemical attacks and also reduce the barrier's hydraulic conductivity.[50] Slurry walls are generally 0.6 to 1.2 meters (2 to 4 feet) thick

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[48] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[49] *Ibid*.

[50] Mauro, M. "Construction of Deep Barrier Walls for Waste Containment." Environmental Restoration Conference , 1995.

and are typically placed at depths less than 15 meters (50 ft),[51] although slurry walls up to 200 feet in depth have been successfully constructed.[52]

Grout curtains are narrow, vertical, grout walls installed in the ground. They are constructed by pressure-injecting grout directly into the soil at closely spaced intervals around the waste site. The spacing is selected so that each "pillar" of grout intersects the next, thus forming a continuous wall or curtain.[53] Grout curtains may be used up-gradient of the contaminated area, to prevent clean water from migrating through waste, or down-gradient, to limit migration of contaminants. Grout curtains are generally used at shallow depths (30 to 40 ft maximum depth).[54] Typical grouting materials include hydraulic cements, clays, bentonite and silicates. However, these materials may crack or may not be durable or chemically compatible. Polymer grouts are used for barrier applications because they are impermeable to gases and liquids and resist radiation, as well as acidic and alkaline environments. A barrier that is currently undergoing field testing consists of a conventional cement grout curtain with a thin lining of polymer grout. Close-coupled barriers such as this can be used for a wide range of waste in addition to radionuclides, and in a variety geohydrologic conditions.[55]

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[51] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

[52] Mauro, M. “Construction of Deep Barrier Walls for Waste Containment.” Environmental Restoration Conference , 1995.

[53] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[54] Oak Ridge National Laboratory, Oak Ridge National Laboratory Technology Logic Diagrams, Volume 3, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

[55] Heiser, J. “Demonstration of Close-Coupled Barriers for Sub-Surface Containment of Buried Waste” Environmental Restoration Conference, 1995.

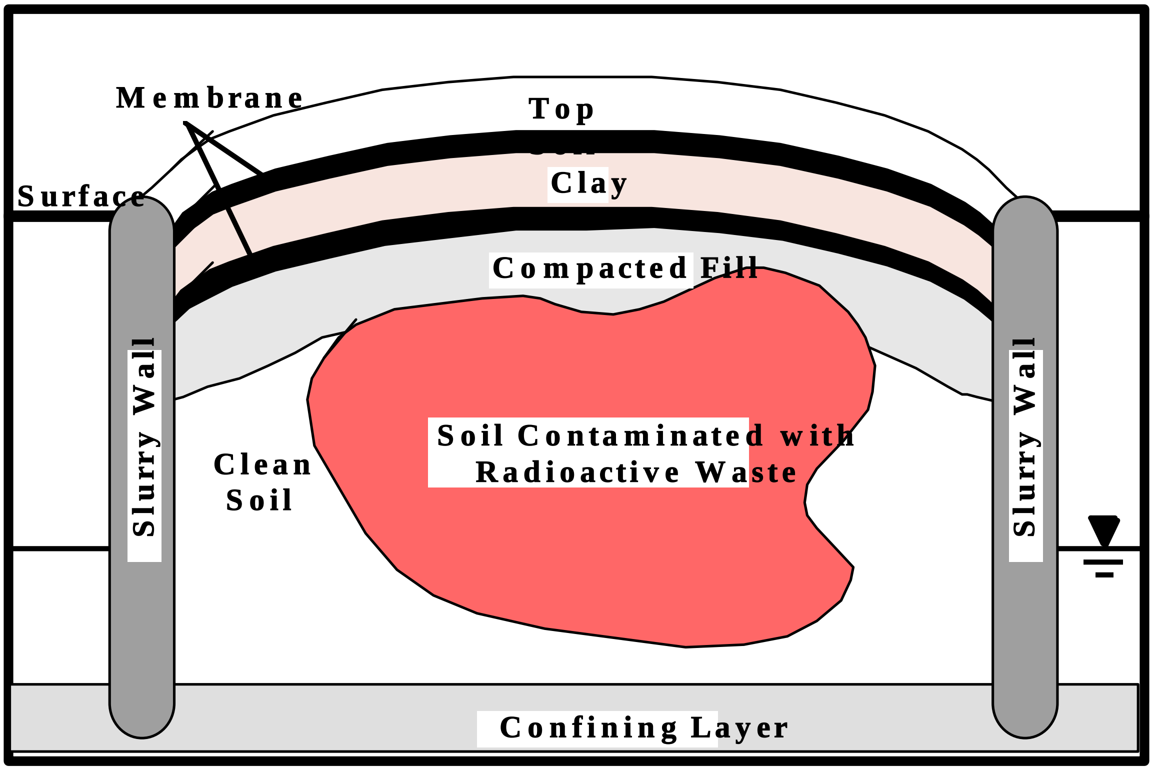

Exhibit 2-10: Vertical Barriers

Target Contaminant Groups

Vertical barriers provide subsurface containment for a wide variety of waste, including radionuclides, metals, and organics.

Technology Operating Characteristics

Exhibit 2-11 summarizes the operating characteristics of vertical barriers.

Exhibit 2-11: Technical Characteristics of Vertical Barriers

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	Not applicable

Exhibit 2-11: Technical Characteristics of Vertical Barriers (Cont.)	
Characteristic	**Description**
Emissions: Gaseous and Particulate	Not applicable
Costs: Capital and O&M	Most costs are capital; O&M costs involve monitoring and mitigation. Slurry walls range from $540 to $750 per square meter.[56] Grout curtains range from $30 to $40 per square foot.[57]
Reliability	Reliable upon implementation, however vertical barriers often deteriorate over time.
Process Time	Not applicable. The barrier is effective upon implementation.
Applicable Media	Soil, sediment, leachates, bulk waste, and groundwater
Pretreatment/Site Requirements	Detailed knowledge of soil characteristics and site geology.
Type and Quantity of Residuals	Not applicable
Disposal Needs and Options	Not applicable
Post-Treatment Conditions	Regulatory compliance procedures would apply (e.g. monitoring and mitigation). Institutional controls, such as deed, site access, and land use restrictions, are usually required.
Ability to Monitor Effectiveness	Can monitor the contamination level of nearby groundwater and the integrity of the vertical barriers.

Site Considerations

Successful installation of a vertical barrier requires detailed knowledge of the soil's physical and chemical characteristics and the subsurface geology. Many common chemical (particularly organic) contaminants that may be present at radioactive waste sites can destroy certain grout materials or prevent them from setting. Therefore, characterization of the site waste, leachate, and barrier material chemistry, as well as compatibility testing of the barrier material with the likely

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[56] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, October 1994.

[57] Oak Ridge National Laboratory, Oak Ridge National Laboratory Technology Logic Diagrams, Volume 3, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

chemical environment, is required.[58] Other site conditions that may also affect the integrity of the barrier include climate, which influences wet-dry cycling, and tectonic activity.

2.4.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

In general, vertical barriers protect human health and the environment by reducing exposure pathways due to the migration of contaminants. Their effectiveness largely depends on the presence of a confining layer of clay or rock, into which the vertical barrier is keyed. Without a confining layer, the vertical barrier will not form an effective barrier because groundwater will flow under the barrier. Possible deterioration of the barrier walls, caused by chemicals in the waste (e.g., organic compounds) and wet-dry cycling in soils, could cause leaching of contaminated groundwater into the surrounding environment.[59]

During trench excavation, if applicable, nearby populations and site workers are at risk of exposure to radioactive contaminants due to fugitive dust and gas emissions. To mitigate these hazards, fugitive dust control techniques and limiting operations to favorable meteorological conditions should be practiced.

Compliance with ARARs

Compliance with ARARs must be determined on a site-specific basis. At DOE facilities, vertical barriers must comply with performance criteria outlined in DOE Order 5820.2A.

Long-Term Effectiveness

Vertical barriers have been used for decades as long-term solutions for controlling seepage of contaminated groundwater. However, vertical barriers do nothing to eliminate the toxicity associated with radionuclides or any other contaminants — they simply confine the contaminants to the site, thereby inhibiting contaminant migration. Slurry walls and grout curtains both have the potential to degrade or deteriorate over time due to certain chemicals contained in the waste and

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[58] Siskind, B. and Heiser, J. "Regulatory Issues and Assumptions Associated with Barriers in the Vadose Zone Surrounding Buried Waste." Brookhaven National Laboratory, 1993.

[59] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

various weathering processes. In contaminated environments, their long-term effectiveness is very dependent on contaminant types and concentrations. The long-term effectiveness of vertical barriers may be improved through use of such materials as HDPE membranes and polymer grouts, which have increased chemical resistance and reduced hydraulic conductivity.

Monitoring the barrier(s) and the surrounding groundwater is necessary to ensure long-term effectiveness. Technologies that help monitor subsurface barriers include sensors placed within and adjacent to barriers to detect significant changes in moisture content, and the use of gaseous tracers to locate breaches.[60]

Reduction of Radiotoxicity, Mobility, or Volume

Vertical barriers do not reduce the radiotoxicity or volume of contaminated material, although they reduce the horizontal mobility of contaminants in soil or groundwater plumes.

Short-Term Effectiveness

As soon as they are in place, vertical barriers can significantly reduce exposure risks. However, it is difficult to obtain truly low permeabilities in grout curtains that are constructed of nonconsolidated materials. Also, many chemical contaminants can prevent certain grout materials from setting.[61] These factors may limit the effectiveness of grout curtains.

Implementability

Vertical barriers in soil and soil-like materials are relatively easy to install.[62] Because slurry walls have been used for decades, the equipment and methodology are readily available and well-known. However, the process of designing the proper mix of wall materials to contain specific contaminants is less well developed. Excavation and backfilling of the slurry trench is critical and requires experienced contractors.[63]

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[60] MWLID Sandia/Westinghouse Hanford, "Verification of Sub-Surface Barriers using Time Domain Reflectometry (TDR) with Waveguides" 1994.

[61] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[62] *Ibid.*

[63] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, October 1994.

Cost

Vertical barrier costs are mostly capital costs; operation and maintenance costs include monitoring and mitigation. Estimated costs for the design and installation of a standard slurry wall in soft to medium soil range from $540 to $750 per square meter. The use of an HDPE membrane in a slurry wall will increase the capital cost. Grout curtains with conventional materials generally cost between $30 to $40 per square foot. Use of a close-coupled barrier with a polymer grout lining increases the capital cost. These costs do not include variable costs required for chemical and radiological analyses, feasibility, or compatibility testing. Testing costs depend heavily on site-specific factors. Other site-specific factors that significantly impact the final cost of slurry wall or grout curtain installation include:

- type, activity, and distribution of contaminants;
- depth, length, and width of the wall;
- geological and hydrological characteristics;
- distance from the source of materials and equipment;
- requirements for wall protection and maintenance.[64]

2.4.3 Summary

A vertical barrier is a containment technology used to help confine radioactive waste and any contaminated groundwater that might otherwise flow from the site. Two types of vertical barriers used to contain radioactive waste are slurry walls and grout curtains. Both are often used in conjunction with capping to provide more thorough waste containment. Vertical barriers are effective upon implementation. Costs of this technology depend on the barrier materials selected and site-specific conditions. Although installing vertical barriers requires expertise, the process is not complex and materials are readily available.

The following factors may limit the applicability and effectiveness of using vertical barriers:

- vertical barriers must reach down to an impermeable horizontal barrier to effectively impede groundwater flow;
- thorough characterization of the subsurface is required because settling or unstable ground can limit effectiveness;

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[64] Oak Ridge National Laboratory, Oak Ridge National Laboratory Technology Logic Diagrams, Volume 3, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

- conventional barrier materials do not withstand attack by strong acids, bases, salt solutions, and some organic chemicals;
- vertical barriers can degrade or deteriorate over time.

Exhibit 2-12 summarizes the data and analyses presented in this profile and can be used for technology comparison.

Exhibit 2-12: NCP Criteria for Vertical Barriers

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Eliminates many risks due to migration by containing the waste.	• Successfully diverts uncontaminated groundwater flow. • Useful for reducing contaminant migration.
Compliance with ARARs	• Compliance with soil and groundwater ARARs must be determined on a site-specific basis.	• DOE sites must comply with performance criteria in Order 5820.2A.
Reduction of Radiotoxicity, Mobility, or Volume	• Reduces mobility, but not radiotoxicity or volume, of contaminated media.	• Process does not remove or reduce contaminants. • Reduces lateral migration of contaminants.
Long-Term Effectiveness and Permanence	• Leaves untreated contaminated media in place. • Potentially ineffective in the long-term due to potential barrier deterioration.	• Depends on contaminant types and concentrations. • Possibility of barrier deterioration over the long-term. Possible site conditions that could affect barrier integrity include climate and tectonic activity.
Short-Term Effectiveness	• Potential risks to site workers if extensive excavation is required.	• The effectiveness of grout curtains may be reduced if constructed of non-consolidated materials or in the presence of certain chemicals.[65]

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[65] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

Exhibit 2-12: NCP Criteria for Vertical Barriers (Cont.)

NCP Criterion	Evaluation	Performance Data
Implementability	• Relatively easy to implement. • Equipment and methodology are well-known and readily available.	• Excavation and backfilling slurry trench requires experienced contractors. • Thorough characterization of waste type, topography, soil condition, thermal conductivity, and groundwater movement is important.
Cost	• Most costs are capital; O&M costs include monitoring and mitigation. • Capital cost is dependent on the type of barriers materials selected.	• Slurry walls: $540 to $750 per square meter. • Grout curtains: $30 to $40 per square foot. • HDPE membranes or polymer grouts increases cost.

SOLIDIFICATION/STABILIZATION

Solidification/Stabilization technologies reduce the mobility of hazardous and radioactive contaminants in the environment through both physical and chemical processes. Stabilization seeks to trap contaminants within their "host" medium (i.e., the soil, sand, and/or building materials that contain them), by inducing chemical reactions between the stabilizing agent and contaminants, thus reducing their mobility. Solidification encapsulates the waste in a monolithic solid of high-structural integrity. Solidification does not involve chemical interaction between the contaminants and the solidification agents but are bonded mechanically. Solidification and stabilization techniques are often used together. The intent of solidification and/or stabilization processes would be to limit the spread of radioactive material and to trap and contain radon within the monolithic solid. While the contaminants would not be removed and would remain radioactive, the mobility of the contaminants would be eliminated or reduced.

Solidification/Stabilization has been implemented full-scale and may be employed *in-situ* or *ex-situ.* *In-situ* techniques use auger/caisson systems and injector head systems to apply agents to *in-situ* soils. *Ex-situ* techniques differ from *in-situ* techniques because *ex-situ* processes involve digging up the materials and machine-mixing them with the solidifying agent instead of injecting the agent to the materials in place. *Ex-situ* processes typically require disposal of the resultant materials. *In-situ* and *ex-situ* techniques can be used alone or combined with other treatment and disposal methods to yield a product or material suitable for land disposal or, in other cases, that can be applied to beneficial use. Both techniques have been used as final and interim remedial measures.

This profile presents:

- Cement solidification/stabilization (S/S)
- Chemical solidification/stabilization (S/S)

There may be one or more sub-options applicable to each process.

The flow diagrams in Exhibit 2-13 and Exhibit 2-14 illustrate the general process involved with *ex-situ* and *in-situ* Solidification/Stabilization technologies respectively.

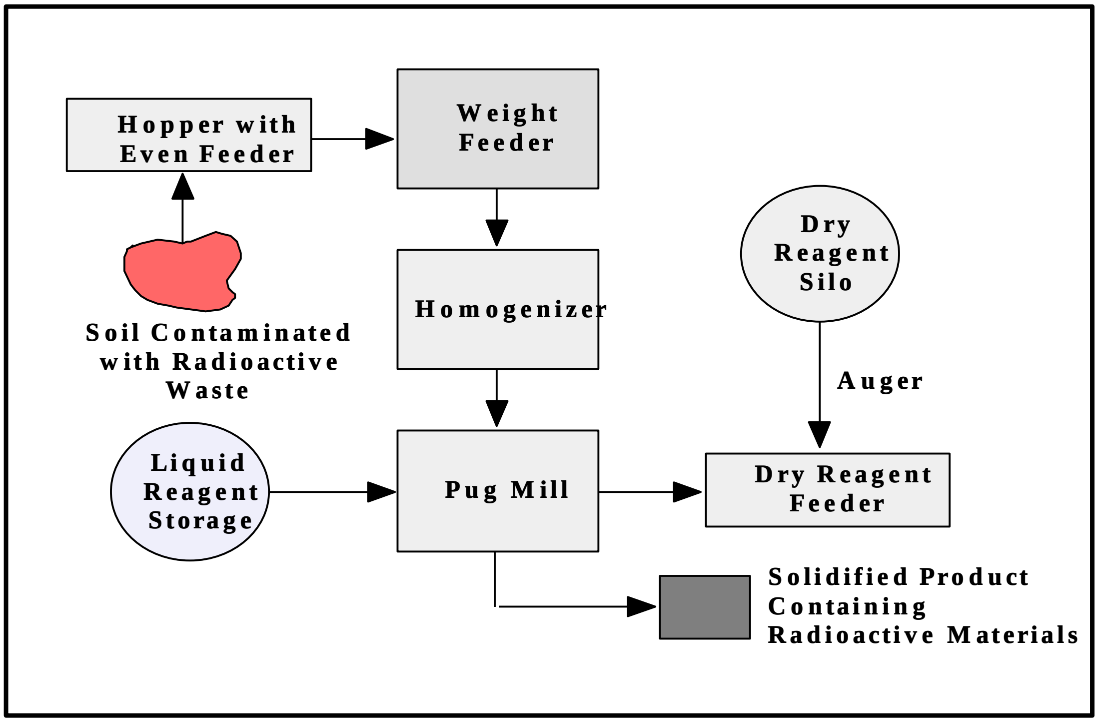

Exhibit 2-13: *Ex-Situ* Solidification/Stabilization

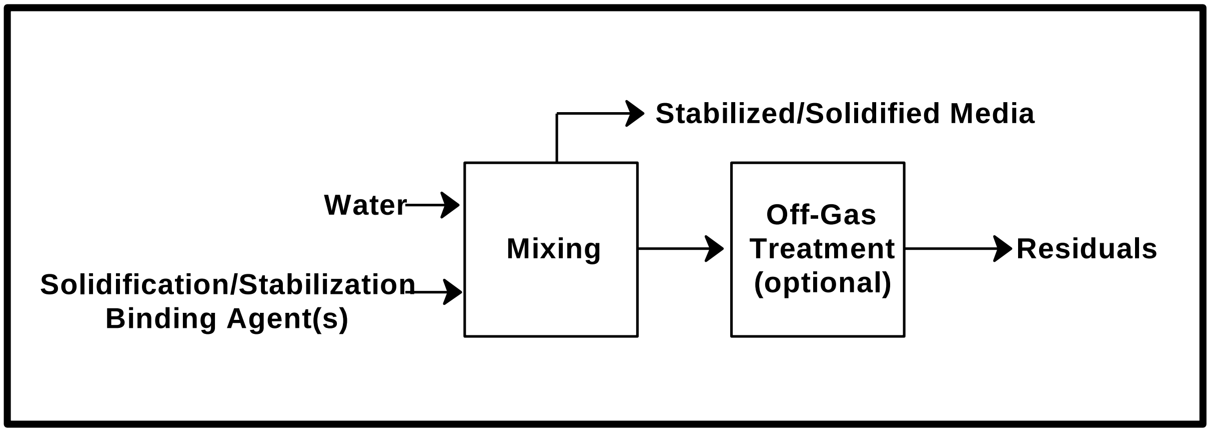

Exhibit 2-14: *In-Situ* Solidification/Stabilization

2.5 CEMENT SOLIDIFCATION/STABILIZATION

2.5.1 Technology Characterization

Description

Cement solidification/stabilization (S/S) processes involve the addition of cement or a cement-based mixture which limits the solubility or mobility of the waste constituents. These techniques are accomplished *in-situ* by either injecting a cement-based agent into the contaminated materials, or *ex-situ* by excavating the materials, machine-mixing them with a cement-based agent, and depositing the solidified mass in a designated area. The goal of the S/S process is to limit the spread of radioactive material via leaching, and to trap and contain radon within a densified soil mass. This process does not remove or inactivate contaminants, but eliminates or reduces contaminant mobility.

The end product resulting from the solidification process is a monolithic block of waste with high structural integrity. Types of solidifying/stabilizing agents include the following: Portland; gypsum; modified sulfur cement, consisting of elemental sulfur and hydrocarbon polymers; and grout, consisting of cement and other dry materials, such as acceptable fly ash or blast furnace slag. Processes utilizing modified sulfur cement are typically performed *ex-situ.*

Target Contaminant Groups

Properly implemented, cement S/S can apply to most contaminants, including all classes of radioactive waste, organics, inorganics, heavy metals, and mixed waste. This technology, however, may have limited effectiveness against SVOCs and pesticides. In general, *in-situ* cement S/S can be considered at any site from which radioactive waste cannot be removed. Type I Portland cement-based grout is commonly used to solidify most hazardous waste, while Types II and V Portland cement-based grouts are used for waste containing sulfates or sulfites.

Technology Operating Characteristics

Cement S/S could be considered for a variety of situations but is best suited to highly porous, coarse-grained, low-level radioactive waste in permeable matrices.

Exhibit 2-15 summarizes the operating characteristics of cement solidification/stabilization.

Exhibit 2-15: Technical Characteristics of Cement Solidification/Stabilization (S/S)

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	Not applicable
Emissions: Gaseous and Particulate	If necessary, a hood can be placed over the system to capture volatile contaminants released during the injection process.
Unconfined Compressive Strength	Strengths for modified sulfur cement twice those of Portland cements have been achieved. Strengths for sulfur cement are in the range of 27.6 MPA (4000 psi).[66]
Costs: Capital and O&M	For *ex-situ* solidification/stabilization processes, overall costs from more than a dozen vendors are under $100 per ton, including excavation. The *in-situ* soil mixing/auger techniques average $40 - $60 per cubic yard for shallow applications and $150 - $250 per cubic yard for deeper applications.[67]
Reliability	The long-term effects of weathering, groundwater infiltration, and physical disturbance cannot be predicted accurately.
Process Time	The shallow *in-situ* soil mixing technique for *in-situ* applications processes 40 - 80 tons per hour on average, and the deep soil mixing technique averages 20 - 50 tons per hour.[68]
Applicable Media	Soils, sediments, sludges, refuse

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[66] U.S. Environmental Protection Agency, Solid Waste and Emergency Response, Innovative Site Remediation Technology, *Solidification/Stabilization*, Volume 4, EPA 542-B-94-001, June 1994.

[67] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

[68] *Ibid.*

Exhibit 2-15: Technical Characteristics of Cement Solidification/Stabilization (S/S) (Cont.)

Characteristic	Description
Pre-Treatment/Site Requirements	Before *in-situ* cement solidification/stabilization is applied at any site, extensive laboratory studies should be conducted to incorporate performance criteria, process criteria, and site-specific criteria.[69] Laboratory studies also can address design issues such as achieving a specific permeability, minimizing volume increase, or eliminating surface berms. Prior to modified sulfur cement S/S, the waste should be dried.[70]
Type and Quantity of Residuals	Radioactive materials are left in place. No residuals are produced.
Disposal Needs and Options	The solidified/stabilized mass remains in place when utilizing the *in-situ* approach. Excavated and mixed mass can be contained or buried on or off site.
Post-Treatment Conditions	With the *in-situ* approach or on site burial, all waste will remain at the site. Institutional and engineering controls will most likely be required. *Ex-situ* solidification may facilitate the transportation of off site disposal of radioactive contaminants with the use of containers, especially where volume reduction or extraction techniques have been applied, previously.
Ability to Monitor Effectiveness	The level of performance for stabilization process is measured by the amount of constituents that can be leached from the stabilized material. Two techniques recognized by USEPA as measure of leachability are the Extraction Process (EP) Toxicity Test and the Toxicity Characteristic Leaching Procedure (TCLP).[71]

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[69] U.S. Environmental Protection Agency, Office of Research and Development, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste,* EPA/625/R-93/013, September 1993.

[70] U.S. Environmental Protection Agency, Solid Waste and Emergency Response, Innovative Site Remediation Technology, *Solidification/Stabilization*, Volume 4, EPA 542-B-94-001, June 1994.

[71] U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, *Summary of Treatment Technology Effectiveness for Contaminated Soil*, PB92-963351, June 1990.

Site Considerations

The *in-situ* method also may not be suitable if masses are thin, discontinuous, and at or near the surface. Special concerns may be posed by other types of hazardous waste (e.g., organic chemicals) that may interfere with solidifying the radioactive waste. Some factors include inorganic acids that will decrease durability for Portland Type I cement; chlorinated organics that may increase set time and decrease durability of cement if concentration is too high; and oil and grease that will decrease unconfined compressive strength.[72]

In-situ S/S may not be suitable for some sites because gamma radiation might not be reduced sufficiently, and because maintenance of utilities would be difficult. Consideration must also be given to any debris such as barrels, scrap metals, and wood pieces that may interfere with the solidification process. Environmental risks related to drilling through the buried waste exist, especially if liquid-filled drums are pierced and their contents are spilled. The fluid inside the containers may contain material detrimental to the cementation process. If whole drums can be located, removal should be considered to eliminate risk of puncture.

Several soil characteristics influence whether the technology will contain the waste effectively. These characteristics include void volume, which determines how much grout can be injected into the site; soil pore size, determines the size of the cement particles that can be injected; and permeability of the surrounding, which determines whether water will flow preferentially around the solidified mass.

2.5.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

Although this technology does not reduce the toxicity or volume of contaminants, if successful, it has been proven to greatly reduce the mobility, thus protecting human health and the environment by reducing risk of exposure. However, process control is relatively poor and it is difficult to verify that the monolith actually contains the waste. Since cement solidification may not shield or eliminate radiation effects, some form of capping or shielding may be appropriate.

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[72] U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, *Solification/Stabilization of Organics and Inorganics*, EPA/540/S-92/015, May 1993.

Compliance with ARARs

The treatment must result in residual soil levels that comply with NRC requirements and RCRA LDRs. Since no material is actually removed from the site during *in-situ* solidification, the site must be appropriate for leaving the material on site in a less mobile form. Compliance with other ARARs need to be determined on a site-specific basis.

Long-Term Effectiveness

Leach resistance of some solidified/stabilized waste is relatively high.[73] However, the long-term effects of weathering, groundwater infiltration, and physical disturbance associated with uncontrolled future land use can significantly affect the integrity of the stabilized mass and contaminant mobility in ways that cannot be predicted.[74]

Reduction of Radiotoxicity, Mobility, or Volume

While solidification and stabilization reduce the mobility of a contaminant, the volume of the waste increases, and there is only an incidental effect on toxicity. *In-situ* processes have demonstrated the capability to reduce the mobility of contaminated waste by greater than 95 percent.[75]

Short-Term Effectiveness

In-situ processes result in risk of exposure since injection is performed vertically over the waste. During *ex-situ* processes there are potential risks of exposure to workers during the excavation, mixing, and handling of waste. Also, fugitive dust emissions resulting from excavation could potentially expose workers and the surrounding community.

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[73] PNL-SA-21482 October 1992.

[74] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

[75] *Ibid.*

Implementability

Cement S/S is well demonstrated and easy to implement. Most reagents and additives are generally widely available and relatively inexpensive industrial commodities. However, detailed characterization of the site and the waste matrix is required to determine the suitability of *in-situ* processes.

Cost

Costs can vary based on specific soil conditions, contaminants, and availability of solidification agents. Also, *ex-situ* costs for transportation and offsite disposal of the solidified material play a role in the overall cost. Low costs may reflect *in-situ* mixing techniques and high costs may reflect in-drum mixing techniques.

2.5.3 Summary

The following factors may limit the applicability and effectiveness of cement S/S:

In-situ Techniques

- Depth of contaminants may limit some types of application processes.
- Future usage of the site may "weather" the materials and affect ability to maintain immobilization of contaminants.
- Some processes result in significant increase in volume (up to double the original volume).
- Certain waste are incompatible with variations of this process. Treatability studies are generally required. Reagent delivery and effective mixing are more difficult than for *ex-situ* applications.
- Like all *in-situ* treatments, confirmatory sampling can be more difficult than for *ex-situ* treatments.[76]

Ex-situ Techniques

- Environmental conditions may affect the long-term immobilization of contaminants.
- Some processes result in a significant increase in volume (up to double the original volume).

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[76] *Ibid.*

- Certain waste are incompatible with different processes. Treatability studies are generally required.
- VOCs are generally not immobilized.
- Long-term effectiveness has not been demonstrated for many contaminant/process combinations.[77]

Solidification/stabilization technologies are well demonstrated, can be applied to the most common site and waste types, require conventional materials handling equipment, and are available competitively from a number of vendors.

Exhibit 2-16 summarizes the data and analyses presented in this profile and can be used for technology comparison.

Exhibit 2-16: NCP Criteria for Cement Solidification/Stabilization (S/S)

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Limited overall protectiveness at site; however, does prevent migration of contaminants to exposure pathways.	• May not shield or eliminate radiation effects.
Compliance with ARARs	• Determined on a site-specific basis.	• Determined on a site-specific basis.
Reduction of Radiotoxicity, Mobility, or Volume	• Does not reduce toxicity or volume; does reduce mobility.	• *In-situ* processes do not involve removal or destruction of contaminants, however, solidification may be able to reduce the release of radon and associated radioactivity to acceptable levels at the waste site without removal of materials for off site containment.
Long-Term Effectiveness and Permanence	• Technology is not proven in the long-term.	• Cement S/S is acceptable for reducing the leachability of radionuclides or heavy metals. However, the long-term effects of weathering, groundwater infiltration, and physical disturbance cannot be predicted.

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[77] *Ibid.*

Exhibit 2-16: NCP Criteria for Cement Solidification/Stabilization (S/S) (Cont.)

NCP Criterion	Evaluation	Performance Data
Short-Term Effectiveness	• Risk exists to both workers and/or the nearby community during solidification processes.	• Fugitive dust generation from excavation and handling of waste during *ex-situ* processes poses a health and safety risk to workers and nearby communities. Risk to workers also results from drilling during *in-situ* techniques.
Implementability	• Easy to implement.	• Based onsite circumstances, technology may have to be combined with other treatment methods (e.g., use of soil cover or cap). Sufficient mixing must occur between soil and grouting materials to be effective.
Cost	• Relatively low cost technology.	• Documented costs range from \$40 - \$250 per cubic yard. Availability of solidification agent selected and, for *ex-situ* processes, transportation and disposal costs will affect the overall cost.

2.6 CHEMICAL SOLIDIFCATION/STABILIZATION

2.6.1 Technology Characterization

Description

Chemical Solidification/Stabilization (S/S) involves adding chemical reagents to waste in order to limit the waste solubility and mobility. It is accomplished either *in-situ*, by injecting a solidifying/stabilizing agent into contaminated materials, or *ex-situ*, by excavating and machine-mixing the materials with the solidifying/stabilizing agent and then placing the solidified soil in containers or burying it on site. Onsite burial of the solidified soil requires a soil cover sufficiently thick to absorb gamma radiation. Chemical S/S agents include thermoplastic polymers (asphalt bitumen, paraffin, polyethylene), thermosetting polymers (vinyl ester monomers, urea formaldehyde, epoxy polymers), and other proprietary additives. Chemical grouts can also be used as S/S agents, however little information is available on this process.

The chemical S/S process limits the spread of radioactive material via leaching, and traps and contains radon within a dense soil mass. Rather than inactivate contaminants, this process eliminates or reduces the contaminants' mobility.

Target Contaminant Groups

Properly implemented, chemical S/S can apply to many contaminants, including all classes of radioactive waste, organics, inorganics, heavy metals, and mixed waste. This process may not be effective on other organics (e.g., SVOCs and pesticides) that can inhibit the chemical bonding of stabilizers or the mechanical bonding of solidifying agents.

Technology Operating Characteristics

Exhibit 2-17 summarizes the operating characteristics of chemical solidification/stabilization.

Exhibit 2-17: Technical Characteristics of Chemical Solidification/Stabilization

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	Not applicable
TCLP Results	Poor for organic waste constituents. Excellent for metals.
Unconfined Compressive Strength	220 to 1570 psi[78] 390 to 860 psi[79]
Emissions: Gaseous and Particulate	Volatile compounds can be released if mechanical mixing is involved.[80]
Costs: Capital and O&M	For *ex-situ* processes, overall costs are under \$100 per ton, including excavation. The *in-situ* soil mixing/auger techniques average \$40 - \$60 per cubic yard for shallow applications and \$150 - \$250 per cubic yard for deeper applications. Most reagents and additives are also widely available, relatively inexpensive industrial commodities.[81]
Reliability	The reliability of most chemical stabilizing agents has yet to be fully determined. Some testing has been performed on polyethylene waste.

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[78] U.S. Environmental Protection Agency, EPA/540/M5/89/001, 1989.

[79] *Ibid.*

[80] *Ibid.*

[81] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

Exhibit 2-17: Technical Characteristics of Chemical Solidification/Stabilization (Cont.)

Characteristic	Description
Process Time	A typical full-scale polyethylene extruder can process 900 kilograms of mixed material per hour consisting of 30% binder and 70% waste. The extruded material takes only a few hours to cool and to set.[82] The shallow soil mixing technique for *in-situ* applications processes 40 to 80 tons per hour on average; the deep soil mixing technique averages 20 to 50 tons per hour.[83]
Applicable Media	Soils, sediments, sludges, refuse
Pretreatment/Site Requirements	No pretreatment is required. However, testing must be performed to assess the effectiveness of the chemical mix with the contaminant.
Disposal Needs and Options	Solidified/stabilized mass remains in place with *in-situ* approach. Excavated and mixed mass must be contained or buried on- or off-site.
Post-Treatment Conditions	With the *in-situ* approach or on-site burial, all waste will remain at the site. Institutional controls will probably be required.
Ability to Monitor Effectiveness	Rigorous verification involves digging up the perimeter of the stabilized/solidified area. Additionally, S/S does not lend itself to waste retrieval.

Site Considerations

While chemical S/S can be used in a variety of situations, it is better suited to fine-grained soil with small pores. The *in-situ* method may not be suitable for residential sites because gamma radiation may not be sufficiently reduced, and because maintenance of utilities would be difficult. The *in-situ* method also may not be suitable if masses are thin, discontinuous, and at or near the surface. Special concerns can be encountered by the presence of other types of hazardous waste that

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[82] U. S. Environmental Protection Agency, Office of Research and Development, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, EPA/625/R-93/013, September 1993.

[83] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

may interfere with the solidification process -- organic chemicals could be particularly troublesome.

2.6.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

This technology provides protectiveness by greatly reducing the mobility of radioactive materials. The solidified mass, under proper conditions, will remain intact for long periods of time, although it may not shield or eliminate radiation effects. Some form of capping or shielding may therefore be appropriate.

Compliance with ARARs

During *in-situ* chemical S/S, no material is actually removed from the site. The site must be appropriate for leaving the material on site in a less mobile form. This technology generally meets RCRA LDR requirements for metals, however organics in the waste may inhibit cementation and chemical bonding processes and result in non-compliance.

Long-Term Effectiveness

Radioactive materials will remain onsite or wherever the solidified mass is disposed of. The S/S process itself may not provide adequate shielding from all types of radiation; covering or capping may be required. S/S should greatly reduce or eliminate the threat of groundwater contamination or other migration, although long-term site maintenance and institutional controls would be required. The long-term effects of weathering, groundwater infiltration, and physical disturbance associated with uncontrolled future land use can significantly and unpredictably affect the integrity of the stabilized mass.[84]

Research is underway on the viability and reliability of most chemical stabilizing agents. Water immersion and temperature fluctuation tests on polyethylene waste forms showed no significant changes in compressive strength. In addition, exposure tests of radiation up to 10^8 rad increased cross-linking in the waste forms,

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[84] *Ibid.*

thus were stronger, more stable under thermal cycling, more resistant to solvents, and more resistant to leaching.[85]

Reduction of Radiotoxicity, Mobility, or Volume

While S/S reduces contaminant mobility, the volume of the waste increases; there is only an incidental effect on toxicity.

Short-Term Effectiveness

Potential risks of exposure to workers exist during waste handling. Also, fugitive dust emissions resulting from excavation could expose workers and the surrounding community to contaminants. Transportation of waste to offsite disposal facility for *ex-situ* treatment also increases exposure risks to workers and community.

Implementability

This process is generally easy to implement (e.g., uses conventional materials and widely available equipment).

Cost

Costs vary. *In-situ* chemical processes usually cost less than *ex-situ* processes. Nonetheless, the range of costs is relatively low compared to other technologies.

2.6.3 Summary

Although chemical S/S may effectively reduce the mobility of radioactive contaminants, it may not affect volume or toxicity. It is applicable to the most common site and waste types, uses conventional materials handling equipment, and is widely available. This technology usually requires capping or covering, engineering controls, and/or institutional controls.

Factors that may limit the applicability and effectiveness of *in-situ* and *ex-situ* S/S include:

In-situ techniques

- depth of contaminants may limit some types of application;

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[85] U.S. Environmental Protection Agency, Office of Research and Development, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Wastes*, EPA/625/R-93/013, September 1993.

- future site use may "weather" the materials and affect their ability to immobilize contaminants;
- some processes result in a significant volume increase (up to double the original);
- certain waste are incompatible with process variations — treatability studies are generally required; reagent delivery and effective mixing are more difficult than for *ex-situ* applications;
- confirmatory sampling can be more difficult than for *ex-situ* treatments.[86]

Ex-situ techniques

- environmental conditions may affect long-term contaminant immobility;
- some processes result in a significant volume increase (up to double the original);
- certain waste are incompatible with different processes treatability studies are generally required;
- VOCs are generally not immobilized;
- long-term effectiveness has not been demonstrated for many contaminant/process reagent combinations.[87]

Additionally, a major factor driving the selection process beyond basic waste compatibility is the availability of suitable reagents. Chemical S/S processes require that potentially large volumes of bulk reagents and additives be transported to project sites. Transportation costs may therefore dominate project budgets and may quickly become uneconomical in cases where materials are not locally available.[88]

Exhibit 2-18 summarizes the data and analyses presented in this profile and can be used for technology comparison.

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[86] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

[87] *Ibid.*

[88] *Ibid.*

Exhibit 2-18: NCP Criteria for Chemical Solidification/Stabilization

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Limited overall protectiveness at site; however, does prevent migration of contaminants to exposure pathways.	• May not shield or eliminate radiation effects. • Effective in reducing leachability of radioactive material. Some organic constituents of mixed waste can reduce effectiveness.

Exhibit 2-18: NCP Criteria for Chemical Solidification/Stabilization (Cont.)

NCP Criterion	Evaluation	Performance Data
Compliance with ARARs	• Determined on a site-specific basis.	• Determined on a site-specific basis.
Reduction of Radiotoxicity, Mobility, or Volume	• Does not reduce toxicity or volume of contaminants; reduces mobility. • Process can increase volume of media after solidification.	• Does not remove or destroy contaminants.
Long-Term Effectiveness and Permanence	• Radioactive materials remain on site or wherever the solidified mass is disposed of. • Process itself does not provide adequate shielding from all types of radiation. • Process leads to effective long-term reduction in exposure risks via groundwater.	• Long-term site maintenance of the site and institutional controls may be required. • Process can greatly reduce the threat of groundwater contaminants. • TCLP results are excellent for metal and radionuclides; poor for organics.

Exhibit 2-18: NCP Criteria for Chemical Solidification/Stabilization (Cont.)

NCP Criterion	Evaluation	Performance Data
Short-Term Effectiveness	• Excavation of waste can expose site personnel. • Process can be completed within short timeframe. • Transportation for off-site disposal can increase risk to community.	• Volatile contaminants can be released during mixing. • 1800 pounds per hour for polyethylene process; only a few hours for cooling and setting of mass. • *Ex-situ* process may require offsite disposal of solidified mass.
Implementability	• Easy to implement. • Many chemical stabilizing agents need further testing and development.	• Requires soil cover or cap of sufficient thickness. • Optimal conditions for many chemical agents not determined.
Cost	• Costs depend on the availability and/or transportation of the solidifying agents.	• Costs range from $40 to $250 per ton.

CHEMICAL SEPARATION TECHNOLOGIES

Chemical separation involving the use of solvent/chemical extraction separates and concentrates radioactive contaminants from soil. The process residuals require further treatment, storage, or disposal. Radionuclide contaminants can be extracted by using inorganic salts, mineral acids, complexing agents, or organic solvents. There are notable differences in the extractability rates of each agent due to the types and concentrations of contaminants as well as varying conditions within the method. The implementability of this technology is controlled by site-specific factors and their applicability must be determined on a site by site basis.

2.7 SOLVENT/CHEMICAL EXTRACTION

2.7.1 Technology Characterization

Description

Solvent/chemical extraction is an *ex-situ* chemical separation technology that separates hazardous contaminants from soils, sludges, and sediments to reduce the volume of hazardous waste that must be treated. Solvent/chemical extraction involves excavating and transferring soil to equipment that mixes the soil with a solvent. This equipment may handle contaminated soil either in batches, for dry soil, or as a continuous flow, for pumpable waste. When the hazardous contaminants have been sufficiently extracted, the solvent is separated from the soil and distilled in an evaporator or column. Distilled vapor consists of relatively pure solvent that is recycled into the extraction process; the liquid residue, which contains concentrated contaminants, undergoes further treatment or disposal (see Exhibit 2-19). While not all radionuclides and solvent will be removed from the contaminated soil, if it is sufficiently clean it can be returned to its original location. Otherwise, it may require separate storage or disposal.

Solvent/chemical extraction has been used extensively to extract uranium from mineral ores. However, using this technology to treat soils contaminated with radionuclides or mixed waste requires further development.[89] Solvents that could be used to remove radioactive waste include: complexing agents, such as EDTA (ethylenediamine-tetraacetic acid); inorganic salts; organic solvents; and mineral acids, such as sulfuric, hydrochloric, or nitric acid. Each solvent's effectiveness in removing different contaminants depends on concentrations, pH, and solubility.[90,91]

While it can sometimes be used as a stand-alone technology, solvent/chemical extraction is commonly used with other technologies, such as

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[89] *Ibid.*

[90] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[91] U.S. Department of Energy, Office of Technology Development, *Effective Separation and Processing Integrated Program (ESP-IP),* DOE, EM-0126P, 1994.

solidification/stabilization, incineration, or soil washing, depending on site-specific conditions.

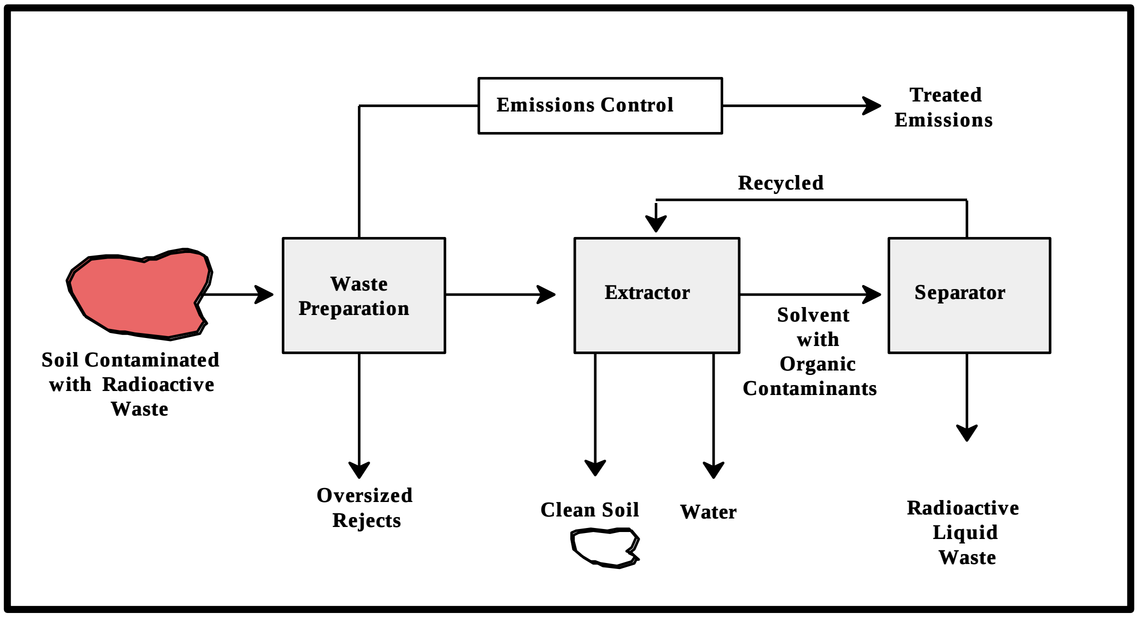

Exhibit 2-19: Solvent Extraction

Target Contaminant Groups

Depending on the solvents used, solvent/chemical extraction may potentially extract various radionuclides or mixed waste from contaminated media, using either a batch or continuous flow system.[92] Laboratory experiments with uranium mill tailings indicate that inorganic salt extraction of radium and thorium is feasible, while mineral acids have been used to extract radium, thorium, and uranium from mineral ores. Complexing agents have also successfully removed radioisotopes of cobalt, iron, chromium, uranium, and plutonium from nuclear process equipment. Laboratory experiments suggest EDTA may be useful in extracting radium from soils and tailings.[93]

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[92] Oak Ridge National Laboratory, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

[93] U.S. Environmental Protection Agency, *Background Information Document for Radiation Site Cleanup Proposed Rule, Revised Draft*, August 1995.

Solvent/chemical extraction effectively treated sediments, soils, and sludges containing such organic contaminants as PCBs, VOCs, halogenated solvents, and petroleum waste, as well as organically bound metals. This technology has also been effective commercially in treating media containing heavy metals.

Technology Operating Characteristics

Exhibit 2-20 summarizes the operating characteristics of solvent/chemical extraction.

Exhibit 2-20: Technical Characteristics of Solvent/Chemical Extraction

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	Results from 22 studies indicate that contaminant removal ranges from 13% to 100% for soils contaminated with radioactive waste and heavy metals. These results vary significantly depending on the contaminant, the solvent type used, and demonstration conditions.[94,95] Contaminant removal is approximately 50% to 95% for petroleum and other hydrocarbons.[96]
Emissions: Gaseous and Particulate	Excavation may cause fugitive dust emissions.[97]
Costs: Capital and O&M	Cost estimates range from $100 to $400 per ton.[98] Costs are lower if physical separation is used to remove "clean" soil fractions prior to solvent extraction.

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[94] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[95] U.S. Environmental Protection Agency, *Emerging Technology Summary: Acid Extraction Treatment System for Treatment of Metal Contaminated Soils*, EPA/540/SR-94/513, August 1994.

[96] Oak Ridge National Laboratory, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

[97] U.S. Environmental Protection Agency and U.S. Department of Defense, *Remediation Technology Screening Matrix and Reference Guide*/Version 1, 1993.

[98] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

Exhibit 2-20: Technical Characteristics of Solvent/Chemical Extraction (Cont.)

Characteristic	Description
Reliability	A fully developed technology. Bench-scale, laboratory-scale, and pilot-scale tests have been performed for soils contaminated with radionuclides.[99,100] Several pilot-scale and full-scale tests have been completed for application to soils contaminated with petroleum hydrocarbons, PCBs, and other organics.[101,102] Pilot-scale and full-scale tests on a commercial level have been performed for soils contaminated with heavy metals.[103,104]
Process Time	Throughput rate may range from 2 to 5 tons per hour.[105]
Applicable Media	Soil, sludges, and sediments
Pretreatment/Site Requirements	Soil excavation, soil characterization (i.e., particle size, partition coefficient, action exchange capacity, organic content, moisture content, and the presence of metals volatiles, clays, and complex waste), and treatability studies are required.[106]
Type and Quantity of Residuals	Process liquid residue consisting of contaminant-rich solvent.[107]
Disposal Needs and Options	The process liquid residue concentrated with contaminants must undergo further treatment, storage, or disposal. Soils that do not meet cleanup requirements must be treated further, stored, or disposed of.[108]

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[99] U.S. Environmental Protection Agency, Office of Research and Development, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[100] U.S. Department of Energy, Office of Technology Development, *Effective Separation and Processing Integrated Program (ESP-IP)*, DOE, EM-0126P, 1994.

[101] Oak Ridge National Laboratory, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

[102] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

[103] *Ibid*, pg. 3-39.

[104] U.S. Environmental Protection Agency, *Emerging Technology Summary: Acid Extraction Treatment System for Treatment of Metal Contaminated Soils*, EPA/540/SR-94/513, August 1994.

[105] Oak Ridge National Laboratory, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

[106] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

[107] *Ibid.*

[108] *Ibid.*

Exhibit 2-20: Technical Characteristics of Solvent/Chemical Extraction (Cont.)

Characteristic	Description
Post-treatment Conditions	The distilled vapor consisting of relatively pure solvent is recycled into the extraction process. The process liquid residue may be treated (preferably by ion exchange or precipitation), stored, or disposed of. If sufficiently clean, the soil may be returned to the excavation site. Otherwise it is treated further, stored, or disposed of.[109]
Ability to Monitor Effectiveness	Data not available

Site Considerations

Soil properties such as particle size, pH, partition coefficient, cation exchange capacity, organic content, moisture content, and contaminant concentrations and solubilities are factors that could affect the efficiency and the operability of solvent/chemical extraction. Careful treatability studies are encouraged. Soils with high clay, silt, or organic content may cause dewatering problems in the contaminated waste stream; chemical extraction is not practical for soil with more than 6.7 percent organic material (humus).[110]

Equipment and facilities are needed to perform the solvent/chemical extraction process and to store waste residuals. Whether the soil can be returned to the site with no further treatment will depend on cleanup requirements. Facility and process costs vary significantly depending on the pretreatment, extraction, and post-treatment required.

2.7.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

As an *ex-situ* technology, soil is removed and treated and returned as fill that may contain some residuals from the chemical extraction process. Risks from external

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[109] Oak Ridge National Laboratory, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

[110] U.S. Environmental Protection Agenct, *Background Information Document for Radiation Site Cleanup Proposed Rule, Revised Draft*, August 1995.

exposure or long-term direct contact are thus reduced or eliminated. Liquid process waste remains contaminated and must be treated further, stored, or disposed of.

Compliance with ARARs

Treatment must result in soil levels that comply with NRC and RCRA LDR requirements. The requirements of RCRA LDRs may also apply to the residual waste produced from this technology. Any aqueous discharges must comply with MCLs, NPDES discharge limits, or total activity annual release limits. Compliance with other ARARs must be determined on a site-specific basis.

Long-Term Effectiveness

Since contaminants are removed from soil, this technology is very effective in the long-term. Treated media can only be returned to the site if they meet site-specific requirements. Additional studies are necessary to document the effectiveness of removing radioactive and mixed waste from the soil.

Reduction of Radiotoxicity, Mobility, or Volume

By removing contaminants, this technology reduces the overall toxicity of the contaminated media. It also concentrates the contaminants into a smaller volume, allowing more efficient final disposal. The process liquid residue containing concentrated waste must be treated further, stored, or disposed of. The treated soil may also require separate storage or disposal, depending on cleanup standards.

Short-Term Effectiveness

Excavation associated with solvent/chemical extraction poses a potential health and safety risk to site workers due to fugitive dust emissions and direct contact with contaminated soil. Personal protective equipment, at a level commensurate with the contaminants involved, may be required during excavation. With enclosed systems and use of dust control measures during soil preparation, this technology poses little threat to the surrounding community.

Implementability

This technology may be used to remove radionuclides and mixed waste, although this application requires further development. In addition to excavation, soil pretreatment and post-treatment processing may be required. Field trials and careful treatability studies are necessary to determine any limiting constraints.

Cost

Medium to high capital and operating and maintenance costs are associated with this technology. Costs range from $100 to $400 per ton. Facility and process costs vary depending on the pretreatment, extraction, and post-treatment required. A multiple-stage extraction process would add to the capital and operating costs. Operating and maintenance costs are also associated with storing of the treatment process waste.

2.7.3 Summary

Solvent/chemical extraction has effectively treated media contaminated with radionuclides. Its efficiency depends on many site-specific conditions, and further development and site-specific characterization is needed to ensure effectiveness for all types of radioactive materials.

Factors that may limit this technology's applicability and effectiveness include:

- traces of solvents may remain in treated soils — toxicity of the solvent is an important consideration;
- some soil types and moisture content levels will adversely impact process performance;
- multiple solvents may be needed for mixed waste and mixed radionuclides;
- chemical extractants tend to dissolve a large portion of the soil matrix — if more than 2 to 3 percent of the matrix is dissolved, this technology may not be feasible;
- interference from thorium may limit the application of EDTA in removing radium when both radionuclides are present.[111]

Exhibit 2-21 summarizes the data and analyses presented in this profile and can be used for technology comparison.

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[111] *Ibid.*

Exhibit 2-21: NCP Criteria for Solvent/Chemical Extraction

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• As an *ex-situ* treatment technology, reduces risk due to long-term exposure. • Excavation process poses a potential risk to site workers.	• Fully demonstrated for non-radioactive waste. • Further studies are needed to determine effectiveness in treating radioactive and mixed waste.
Compliance with ARARs	• The requirements of RCRA LDRs , CWA, and NRC may apply to the effluent and residual waste produced from this technology.	• Performance data must be assessed in relation to preremediation concentrations and cleanup standards to determine compliance with ARARs.
Reduction of Radiotoxicity, Mobility, or Volume	• Removes radionuclides; does not affect toxicity, mobility, or volume.	• Process removes most types of radionuclides from contaminated media to varying degrees. • Process liquid residuals contain concentrated contaminants.
Long-Term Effectiveness and Performance	• Removes contaminants from soils, permanently addressing principal threats. • Process liquid residuals contain concentrated contaminants.	• Needs further development to ensure effectiveness in treating radioactive waste.
Short-Term Effectiveness	• Potential health and safety risk to workers from excavation.	• Requires personal protective equipment during excavation at a level commensurate with the contaminants involved. • With enclosed systems and dust control measures during soil preparation, appears to pose little threat to the community.
Implementability	• Applies to soils, sediments, and sludges. • Disposal or storage facilities need to be available for process liquid residuals.	• Processing pretreatment and post-treatment of the soil may be required. • Treatability studies and field trials are necessary to identify the technology's limitations.
Cost	• Medium to high capital and O&M costs due to off-site storage or disposal of residuals.	• $100 to $400 per ton.

PHYSICAL SEPARATION TECHNOLOGIES

Physical separation technologies are a class of treatment in which radionuclide-contaminated media are separated into clean and contaminated fractions by taking advantage of the contaminants' physical properties. These technologies work on the principle that radionuclides are associated with particular fractions of the media, which can be separated based on their size and other physical attributes. In solid media (i.e. soil, sediment) most radioactive contaminants are associated with smaller particles, known as soil fines (clays and silts). Radionuclides in liquid media are either solvated by the liquid media (i.e., one molecule of the radionuclide surrounded by many molecules of the liquid) or are present as microscopic particles suspended in the solution. Physical separation of the contaminated media into clean and contaminated fractions reduces the volume of contaminated media requiring further treatment and/or disposal.

Physical separation technologies can be applied to a variety of solid and liquid media including soil, sediment, sludge, groundwater, surface water, and debris. In addition to treating radionuclides, physical separation technologies can be used to treat semivolatile organic compounds, oils, PCBs, and heavy metals.

The profiles in this Section address the following physical separation technologies: dry soil separation, soil washing, and column and centrifugal flotation.

2.8 DRY SOIL SEPARATION

2.8.1 Technology Characteristics

Description

Dry soil separation separates radioactive particles from clean soil particles. In this process, radionuclide-contaminated soil is excavated and screened to remove large rocks. Large rocks are crushed and placed with soil on a conveyor belt, which carries the soil under radiation detectors that measure and record the level of radiation in the material. Radioactive particles are tracked and mechanically diverted through automated gates, which separate the soil into contaminated and clean segments. Volumes of radioactive materials can be further processed and/or disposed of (see Exhibit 2-22).[112] Dry soil separation can substantially reduce the volume of radioactive waste (>90%) and has been used on a commercial scale at Johnston Atoll in the South Pacific and the Savannah River site in South Carolina.[113]

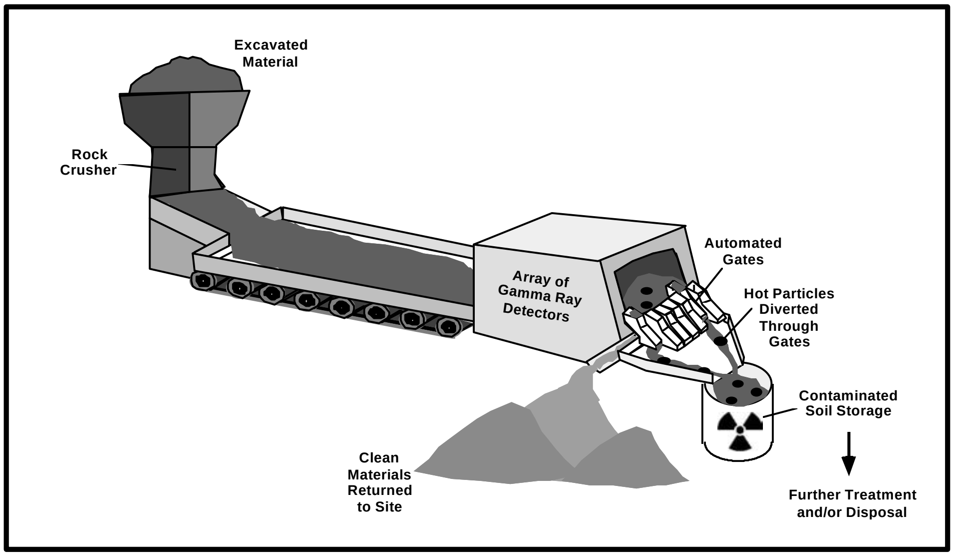

Exhibit 2-22: Dry Soil Separation

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[112] U.S. Environmental Protection Agency, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, EPA/625/R-93/013, September 1993.

[113] Thermo Nutech, Environmental Field Services Group, *Statement of Qualifications and Description of Thermo Nutech's Segmented Gate System*, Oakridge, TN, 1996.

Target Contaminant Groups

Dry soil separation has been used to sort radioactive particles from contaminated soils at Johnston Atoll and the Savannah River site. This technique effectively treats soils contaminated with gamma emitting radionuclides, including Th, U, Cs-137, Co-60, Pu-239, Am-241 and Ra-222. Dry soil separation can effectively treat large volumes of contaminated soil and can treat radioactively contaminated asphalt, concrete, or any solid host matrix transportable by conveyor belts.[114]

Technology Operating Characteristics

Exhibit 2-23 summarizes the operating characteristics of dry soil separation.

Exhibit 2-23: Technical Characteristics of Dry Soil Separation

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	Volumes of soils contaminated with Pu-239 and Am-241 on Johnston Atoll were reduced by >90%. Am-241 and Ra-222 concentrations in clean soil fractions were reduced below their respective limits of detection at 2pCi/g and 5pCi/g.[115,116] A 99% volume reduction of radioactively contaminated material was demonstrated at the Savannah River Site. Cs-137 levels in clean soil fractions were reduced by 99% to less than the level of detection at 4pCi/g.[117,118]
Emissions: Gaseous and Particulate	Excavation and processing may cause fugitive gas and dust emissions.

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[114] *Ibid.*

[115] *Ibid.*

[116] U.S. Environmental Protection Agency, *Superfund Innovative Technology Evaluation Program, Technology Profiles Seventh Edition*, EPA/540/R-94/526, November 1994.

[117] Thermo Nutech, Environmental Field Services Group, *Statement of Qualifications and Description of Thermo Nutech's Segmented Gate System*, Oakridge, TN, 1996.

[118] U.S. Environmental Protection Agency, *Superfund Innovative Technology Evaluation Program, Technology Profiles Seventh Edition*, EPA/540/R-94/526, November 1994.

Exhibit 2-23: Technical Characteristics of Dry Soil Separation (Cont.)

Characteristic	Description
Costs: Capital and O&M	The total cost to treat over 100,000 cubic yards of radioactively contaminated soil on Johnston Atoll was $15 million. Capital costs of $2.4 million were needed to construct the treatment facility.[119]
Reliability	The system consistently and successfully segregates contaminated soil into radioactive and clean segments. Dry soil separation accounts for every kilogram of excavated soil and produces a very clean soil fraction, which can be safely returned to the site or potentially sold as a commodity, due to its uniform size.[120]
Process Time	The entire cleanup process (excavating and processing over 100,000 cubic yards of radionuclide-contaminated soil) on Johnston Atoll is expected to take 140 weeks.[121] Tons/hour information not available.
Applicable Media	Soil, sand, dry sludge, crushed asphalt or concrete, or any dry host matrix that can be transported by conveyor belts.[122]
Pretreatment/Site Requirements	Soil excavation is required. Large rocks, concrete, or asphalt must be crushed before being placed on the conveyor belt. Soil must be contaminated with gamma emitting radionuclides.
Type and Quantity of Residuals	Large quantities of clean soils can be returned to the site or sold for fill. Small quantities of radioactive materials require further treatment and/or disposal.
Disposal Needs and Options	Large volumes of clean soil can be returned to the site or sold as clean fill. Radioactively contaminated materials may require further treatment and/or disposal. Contaminated materials may be classified as high level or TRU waste, depending on the types of waste present, and could therefore require special handling and disposal.
Post-Treatment Conditions	Clean soil fractions can be returned to the site. Radionuclide-contaminated segments require further treatment and/or disposal.

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[119] U.S. Environmental Protection Agency, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, EPA/625/R-93/013, September 1993.

[120] *Ibid.*

[121] *Ibid.*

[122] U.S. Environmental Protection Agency, *Superfund Innovative Technology Evaluation Program, Technology Profiles Seventh Edition*, EPA/540/R-94/526, November 1994.

Exhibit 2-23: Technical Characteristics of Dry Soil Separation (Cont.)	
Characteristic	**Description**
Ability to Monitor Effectiveness	Because all excavated soil is screened for radioactivity, non-radioactive materials can be returned to the site with no further monitoring.[123] Radioactive components require proper treatment and/or disposal and monitoring.

Site Considerations

Dry soil separation can be used when gamma emitting radionuclides are present at a site and radioactivity is distributed in a nonuniform fashion. It can treat any dry material that can be crushed to a uniform size, and can be used at any site where contaminated materials can be removed or excavated. A commercially available portable treatment system could be moved to a wide variety of sites.[124]

2.8.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

Dry soil separation can substantially reduce the volume of radionuclide-contaminated materials at a site. However, radionuclide-contaminated materials may require special handling, or treatment and/or disposal. Fugitive gas and dust emissions during excavation and processing could pose risks to site workers and local communities.

Compliance with ARARs

The treatment must result in residual soil levels that comply with NRC, RCRA, and any applicable local regulatory requirements. Particulate emissions would be regulated by the Clean Air Act. Contaminated fractions would have to be treated and/or disposed of according to NRC and/or DOE orders.

Long-Term Effectiveness

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[123] U.S. Environmental Protection Agency, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, EPA/625/R-93/013, September 1993.

[124] Thermo Nutech, Environmental Field Services Group, *Statement of Qualifications and Description of Thermo Nutech's Segmented Gate System*, Oakridge, TN, 1996.

Because all excavated soils are screened and segregated by their radioactivity, clean soils can be returned to the site or commercially sold, in some cases.[125] Volume reductions of radionuclide-contaminated soils >90 percent ensure that most of the soil can be safely reused.[126] However, highly radioactive residual materials require further treatment and/or disposal.

Reduction of Radiotoxicity, Mobility, or Volume

This technology effectively separates radioactive soil particles from clean soil particles, thus reducing the volume of soil requiring further treatment or disposal. Large percentages of the soil can be safely reused. However, excavation and processing increase fugitive gas and dust emissions of radionuclide contaminants; remaining radioactive materials require further treatment and/or disposal. Therefore, while dry soil separation reduces the volume of the contaminated soil, the toxicity and mobility of the original contaminants are not addressed by this technology.

Short-Term Effectiveness

This process works best for soils contaminated with gamma emitting radionuclides, and may not adequately separate radioactive materials that are weak gamma emitters. Additionally, fugitive gas and dust generated during excavation and processing may pose health and safety risks for workers and the local community.

Implementability

The technology can be implemented without significant difficulties, however the soil must first be excavated. Contaminated soil residuals require further treatment and/or disposal. Portable treatment plants are commercially available.

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[125] U.S. Environmental Protection Agency, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, EPA/625/R-93/013, September 1993.

[126] Thermo Nutech, Environmental Field Services Group, *Statement of Qualifications and Description of Thermo Nutech's Segmented Gate System*, Oakridge, TN, 1996.

Cost

Costs of using this technology can be attributed to leasing capital equipment; operating large capacity systems, or operating the systems for long periods of time; excavation; and disposal of residual radioactive waste.

2.8.3 Summary

Dry soil separation has been applied to radionuclide-contaminated soils at Johnston Atoll and the Savannah River site in South Carolina. In both cases, this technology has proven very effective at substantially reducing the volumes of radionuclide contaminated soils achieving reductions of >90 percent at each site.[127] Further, dry soil separation is economical because it allows large volumes of clean material to be returned to a site without further processing or monitoring.[128] This technology works best, however, with gamma emitting radionuclides. Radioactive fractions require additional treatment and/or disposal. Fugitive gas and dust emissions also need to be controlled to minimize health risks to workers and local communities. The following factors may limit the applicability and effectiveness of this process:

- ability to excavate or remove contaminated materials;
- ability to control fugitive gas and dust emissions during excavation and processing;
- radionuclide types and distribution in the soil;
- ability to crush dry substrates;
- additional management of residuals.

Exhibit 2-24 summarizes the data and analyses presented in this profile and can be used for technology comparison.

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[127] *Ibid.*

[128] U.S. Environmental Protection Agency, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, EPA/625/R-93/013, September 1993.

Exhibit 2-24: NCP Criteria for Dry Soil Separation

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Substantial volume reductions of radioactive material possible. • Radioactive residuals need additional treatment and/or disposal. • Fugitive gas and dust emissions could pose health risks to workers and local communities.	• Volumes of soils contaminated with Pu-239 and Am-241 on Johnston Atoll were reduced by >90%. Am-241 and Ra-222 concentrations were reduced below their respective limits of detection at 2pCi/g and 5pCi/g.[129,130] • A 99% volume reduction of radioactively contaminated material was demonstrated at the Savannah River site. Cs-137 levels were reduced by 99% to less than the level of detection at 4pCi/g.[131,132]
Compliance with ARARs	• The requirements of RCRA LDR, CAA, NRC, and DOE orders may apply to the residual waste produced from this technology.	• Performance data, such as removal efficiencies, must be assessed in relation to preremediation concentrations and cleanup standards to determine compliance with ARARs.
Long-Term Effectiveness and Permanence	• Reduces the volume of radioactively contaminated soils. • Waste produced in this process requires further treatment and/or disposal.	• Technology achieves consistent and successful segregation of contaminants from soil, resulting in significant volume reduction of contaminated soils. • Waste produced in this process requires further treatment and/or disposal.
Reduction of Radiotoxicity, Mobility, or Volume	• Does not reduce toxicity or mobility of contaminants in separated waste. • Reduces the volume of radioactively contaminated soils.	• Process separates clean and contaminated soil fractions, thereby reducing the volume of soil and addressing principal threats. • Contaminated materials will require further treatment and/or disposal.

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[129] *Ibid.*

[130] U.S. Environmental Protection Agency, *Superfund Innovative Technology Evaluation Program, Technology Profiles Seventh Edition*, EPA/540/R-94/526, November 1994.

[131] Thermo Nutech, Environmental Field Services Group, *Statement of Qualifications and Description of Thermo Nutech's Segmented Gate System*, Oakridge, TN, 1996.

[132] U.S. Environmental Protection Agency, *Superfund Innovative Technology Evaluation Program, Technology Profiles Seventh Edition*, EPA/540/R-94/526, November 1994.

Exhibit 2-24: NCP Criteria for Dry Soil Separation (Cont.)

NCP Criterion	Evaluation	Performance Data
Short-Term Effectiveness	• Fugitive gas and dust emissions could pose health threats to workers and local communities.	• Fugitive gas and dust emissions could pose health threats to workers and local communities.
Implementability	• This technology is commercially available and has successfully treated radionuclide-contaminated soils.	• Requires soil excavation. • A mobile commercial treatment system is available.
Cost	• Varying costs are associated with this technology, depending on site-specific conditions and requirements. • Costs for treating and/or disposing of separated radioactive waste could be high. • Costs of this treatment are considered low compared to some alternatives.	• Treatment costs at Johnston Atoll were $2.4 million to build the plant and a total of $15 million to clean the entire site (at least 100,000 cubic yards of contaminated soil were treated).[133]

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[133] U.S. Environmental Protection Agency, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, EPA/625/R-93/013, September 1993.

2.9 SOIL WASHING

2.9.1 Technology Characteristics

Description

Soil washing is a process in which water, with or without surfactants, mixes with contaminated soil and debris to produce a slurry feed. This feed enters through a scrubbing machine to remove contaminated fine soil particles (silts and clay) from granular soil particles. Contaminants are generally bound more tightly to the fine soil particles and not to larger grained sand and gravel. Separation processes include screening to divide soils into different particle sizes, and chemical extraction of radionuclides. The output streams of these processes consist of clean granular soil particles, contaminated soil fines, and process/wash water, all of which are tested for contamination. Soil washing is effective only if the process transfers the radionuclides to the wash fluids or concentrates them in a fraction of the original soil volume. In either case, soil washing must be used with other treatment technologies, such as filtration or ion exchange. Clean soil (sand and gravel) can be returned to the excavation area, while remaining contaminated soil fines and process waste are further treated and/or disposed of.

Soil washing is most effective when the contaminated soil consists of less than 25 percent silt and clay and at least 50 percent sand and gravel; soil particles should be between 0.25 mm and 2 mm in diameter for optimum performance. When soil particles are too large (greater than 2 mm in diameter), removal of oversized particles may be required; when particles are smaller than 0.063 mm in diameter soil washing performance is poor because these particles are very difficult to separate into contaminated and uncontaminated components.

Other factors impacting the effectiveness of soil washing include the cation exchange capacity of the soil and the use of extractants. If the soil's cation exchange capacity is too high, separating pollutants from the soil particles is difficult. Alternatively, heating the wash water and using surfactants may make metal removal more efficient.[134]

One type of soil washing system developed specifically by EPA for treating radioactively contaminated soils is the VOlume Reduction/Chemical Extraction (VORCE) plant. VORCE pilot plants have been tested at Department of Energy sites in New Jersey and

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[134] U.S. Environmental Protection Agency, *Innovative Site Remediation Technology, Soil Washing/Soil Flushing* Volume 3, EPA 542-B-93-012, November 1993.

Tennessee. Initial studies have shown that systems similar to VORCE plants effectively reduce the mass of radioactively contaminated soils. EPA believes the pilot operations could be expanded to treat larger quantities of soil and to become more cost-effective.[135]

Exhibit 2-25 illustrates the general process involved with soil washing.

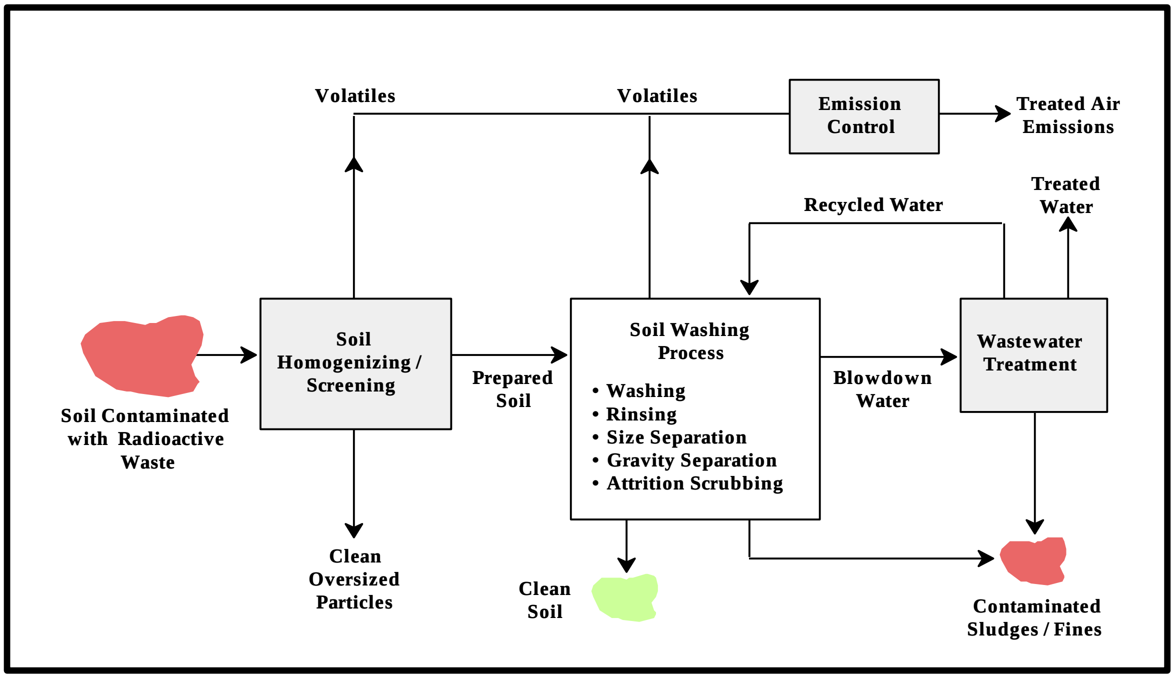

Exhibit 2-25: Soil Washing

Target Contaminant Groups

Soil washing has been used in two pilot plant tests, to decontaminate plutonium-contaminated soil at a site in Rocky Flats Colorado and to extract radium from uranium mill tailings at a site in Canada.[136] The VORCE plant has been used at sites in Tennessee and New Jersey to treat thorium- and cesium-contaminated soils.[137] Soil washing has also been

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[135] U.S. Department of Energy, *Results of a Soil Washing Demonstration Project for Low-Level Radioactively Contaminated Soil*, DOE/OR/21949-404, June 1996.

[136] U.S. Environmental Protection Agency, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[137] U.S. Department of Energy, *Results of a Soil Washing Demonstration Project for Low-Level Radioactively Contaminated Soil*, DOE/OR/21949-404, June 1996.

used to treat other radionuclides, including uranium, thorium, and cesium; organics, including polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pentachlorophenol (penta), creosote, heavy petroleum, cyanides; and heavy metals, including cadmium, chromium, copper, lead, mercury, nickel, and zinc.

Technology Operating Characteristics

Exhibit 2-26 summarizes the operating characteristics of dry soil washing.

Exhibit 2-26: Technical Characteristics of Soil Washing

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	In pilot-plant test runs, plutonium-contaminated soils to 45, 284, 7515, 1305, and 675 pCi/g were cleaned to contamination levels of 1, 12, 86, 340, and 89 pCi/g respectively, using different processes.[138] At a site in Texas, soil washing combined with ion exchange reduced uranium concentrations from an average of 70 ppm to 20.7 ppm. This process cleaned the soil sufficiently well that virtually all the soil could be returned to the site.[139] In an experiment with Pu-contaminated soil, contaminated soil mass was reduced by 65% and soil exhibiting activity levels in the range of 900 to 140,000 pCi/g of Pu was reduced to <6 pCi/g Pu.[140] Treating soils at sites in New Jersey and Tennessee with the VORCE plant reduced the mass of contaminated soils by 63.8% and 70% respectively. The VORCE plant reduced Th-232 concentrations from 18.1 pCi/g to <5 pCi/g at the New Jersey site, and reduced Cs-137 levels from 160 pCi/g to <50 pCi/g at the Tennessee site.[141]
Emissions: Gaseous and Particulate	Some gaseous emissions may result if VOCs are in waste. Excavation may lead to fugitive gas and dust emissions.

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[138] U.S. Environmental Protection Agency, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[139] U.S. Environmental Protection Agency, Federal Remediation Technologies Roundtable, *Synopses of Federal Demonstrations of Innovative Site Remediation Technologies*, EPA, 542/B-92/003, August 1992.

[140] Argonne National Laboratory, *Soil Washing as a Potential Remediation Technology for Contaminated DOE Sites*, DE93-009205, March 1993.

[141] U.S. Department of Energy, *Results of a Soil Washing Demonstration Project for Low-Level Radioactively Contaminated Soil,* DOE/OR/21949-404, June 1996.

Exhibit 2-26: Technical Characteristics of Soil Washing (Cont.)

Characteristic	Description
Costs: Capital and O&M	Disposal and transportation costs for radioactive soils are about $900 per ton. Based on pilot testing results, volume reduction at a rate of 1.5 tones per hour costs approximately $300 per hour.[142] Treatment costs for the VORCE plant ranged from $111 to $134 per ton for processing between 20 to 100 tons per hour. Total costs could be as high as $280 per ton when waste is transported off site.[143]
Reliability	The process consistently and successfully segregates contaminated soil into two unique streams: washed soil and fines slurry. The washed soil was safely returned to the site with no further treatment.[144]
Process Time	A soil washing plant in Bruni, Texas, achieved a cleanup rate of 20 tons of radionuclide-contaminated soil per hour.[145] An expanded VORCE type plant could process 20 to 100 tons of radionuclide contaminated soil per hour.[146]
Applicable Media	Soil, sediment, sludge
Pretreatment/Site Requirements	Soil excavation is required, as is mechanical screening, to remove various oversized materials and separation to generate coarse- and fine-grained fractions. Site soils should have the proper grain size distribution, clay content, and cation exchange capacity. Radionuclides at the site largely determine the proper soil washing mixture or feasibility of the process.
Type and Quantity of Residuals	Process wash waters, silt, and clay. Contaminated silt, clay, and wash waters may require further treatment or disposal.

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[142] U.S. Environmental Protection Agency, Federal Remediation Technologies Roundtable, *Synopses of Federal Demonstrations of Innovative Site Remediation Technologies*, EPA, 542/B-92/003, August 1992.

[143] U.S. Department of Energy, *Results of a Soil Washing Demonstration Project for Low-Level Radioactively Contaminated Soil*, DOE/OR/21949-404, June 1996.

[144] U.S. Environmental Protection Agency, *Innovative Site Remediation Technology, Soil Washing/Soil Flushing* Volume 3, EPA 542-B-93-012, November 1993.

[145] *Ibid.*

[146] U.S. Department of Energy, *Results of a Soil Washing Demonstration Project for Low-Level Radioactively Contaminated Soil*, DOE/OR/21949-404, June 1996.

Exhibit 2-26: Technical Characteristics of Soil Washing (Cont.)

Characteristic	Description
Disposal Needs and Options	Process water is potentially suitable for recycling as wash water, but would likely require further treatment (e.g., ion-exchange) before being recycled. If treated water cannot be reused as wash water it must be discarded in accordance with applicable discharge requirements.[147] Contaminated silt, clay, and wash waters may require further treatment or disposal. Contaminated soil fines could be incinerated or disposed of as radioactive waste; wash water can be treated by ion exchange.[148]
Post-Treatment Conditions	Process wash water may become radioactively contaminated. Treating this water through ion exchange will allow water to be reused in some cases.[149] Contaminated silt, clay, and wash waters may require further treatment or disposal.
Ability to Monitor Effectiveness	Partitioned soil and wash water must be tested for radioactive contamination; monitoring is not difficult.

Site Considerations

Soil washing is useful in situations where radioactive contaminants are closely associated with fine soil particles and soils have the proper particle size distribution. Better success can be obtained with sandy soils and soils with low cation exchange capacities; humus soils (i.e. soils with high, naturally occurring, organic content or high cation exchange capacities) may be difficult to clean.[150]

Whether the segregated uncontaminated washed soil can be returned to the site with no further treatment, thus increasing cost-effectiveness, depends on cleanup and land disposal requirements. Soil character, moisture content, particle size distribution, and contaminant concentrations and solubilities are factors that impact the efficiency and operation of soil washing.[151]

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[147] U.S. Environmental Protection Agency,*Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[148] U.S. Environmental Protection Agency,*Innovative Site Remediation Technology, Soil Washing/Soil Flushing* Volume 3, EPA 542-B-93-012, November 1993.

[149] U.S. Environmental Protection Agency,*Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[150] *Ibid.*

[151] U.S. Environmental Protection Agency,*Innovative Site Remediation Technology, Soil Washing/Soil Flushing* Volume 3, EPA 542-B-93-012, November 1993.

2.9.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

Although this technology is not yet fully demonstrated, protectiveness has been achieved in preliminary studies. In some cases the volume of radionuclide-contaminated soil was reduced 30 to almost 100 percent.[152] However, soil fines generally remain contaminated and require further treatment and/or disposal; process wash water may also be contaminated and may require further treatment and/or disposal.

Compliance with ARARs

The treatment must result in residual soil levels that comply with NRC, RCRA, and any applicable local regulatory requirements.

Long-Term Effectiveness

Although studies indicate that contaminants are consistently and successfully segregated from soil, more studies are needed to document the effectiveness of segregating radioactive materials from soil.

Reduction of Radiotoxicity, Mobility, or Volume

This technology effectively separates contaminated soil fines from clean, larger soil particles, thereby reducing the volume of soil requiring further treatment or disposal. However, the process wash water may contain elevated levels of radionuclide contaminants and may also require treatment and/or disposal. While soil washing reduces the volume of the contaminated soil, it does not reduce the toxicity or mobility of the original contaminants, and, therefore, additional management of residuals is required.

Short-Term Effectiveness

Fugitive gas and dust generated during excavation may lead to health and safety risks for workers.

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[152] *Ibid.*

Implementability

This process may not work for humus soil, nor for other than low levels of radionuclide contamination in soils. Process wash water must be stripped of radioactive contaminants.[153] Demonstrations indicate the technology can be implemented without significant difficulties. However, the soil must first be excavated, residual soil fines require further treatment and/or disposal, and the process wash water may also require treatment and/or disposal. If onsite plants are not constructed, transportation costs could increase the treatment costs significantly.

Cost

Costs of using this technology are attributed to leasing capital equipment; operating large capacity systems, or operating the systems for long periods of time; transportation; and disposal of residual radioactive waste.

2.9.3 Summary

Soil washing has been applied to organic- and heavy metal-contaminated soil, and has been pilot tested with radionuclide-contaminated soil. While this technology is generally effective in treating these contaminants in soil, further development is needed to ensure effectiveness with radionuclide contamination in soil. Soil washing appears to work best for soils contaminated with low-level radioactivity. The following factors may limit the applicability and effectiveness of this process: organic content of soil or high soil cation exchange capacities; additional management of residuals; radionuclide concentrations and types in the soil; and soil particle size.

Soil washing costs may be reduced by leasing equipment and processing the soils in large quantities or over long periods of time.

Exhibit 2-27 summarizes the data and analyses presented in this profile and can be used for technology comparison.

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[153] U.S. Environmental Protection Agency, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

Exhibit 2-27: NCP Criteria for Soil Washing

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Preliminary studies indicate that protectiveness is achieved.	• The VORCE plant reduced the mass of contaminated soils by 63.8 % to 70% and reduced Th-232 concentrations from 18.1 pCi/g to <5 pCi/g and Cs-137 levels from 160 pCi/g to <50 pCi/g.[154]
Compliance with ARARs	• RCRA LDR, CWA, and NRC requirements may apply to the effluent and residual waste produced from this technology.	• Performance data, such as removal efficiencies, must be assessed in relation to preremediation concentrations and cleanup standards to determine compliance with ARARs.
Long-Term Effectiveness and Permanence	• This technology needs further development to ensure effectiveness with radioactive materials. • Residual waste is present in soil fines and may be present in process/wash waters.	• Demonstrations and studies indicate a consistent and successful segregation of contaminants from soil. • Residual contamination is present in soil fines and may be present in process/wash waters.
Reduction of Radiotoxicity, Mobility, or Volume	• Does not reduce toxicity or mobility of contaminants in residuals.	• Process separates clean (granular soil and gravel) and contaminated (clay and silt) soil fractions, thereby reducing the volume of soil and addressing principal threats. • Process/wash waters may be contaminated and may require further treatment or disposal.
Short-Term Effectiveness	• Technology does not pose an immediate threat.	• Potential risk to workers or nearby community due to excavation and processing.

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[154] U.S. Department of Energy, *Results of a Soil Washing Demonstration Project for Low-Level Radioactively Contaminated Soil,* DOE/OR/21949-404, June 1996.

Exhibit 2-27: NCP Criteria for Soil Washing (Cont.)

NCP Criterion	Evaluation	Performance Data
Implementability	• Variations of this technology are widely available and have been used successfully to treat radionuclide-contaminated soils.	• Requires excavation and an adequate water supply. • Numerous commercial soil washing systems are available.
Cost	• Costs of this technology vary depending on site-specific conditions and requirements.	• Costs can be reduced by leasing capital equipment. • Costs are reduced with larger systems and systems that operate on-line for extended periods of time

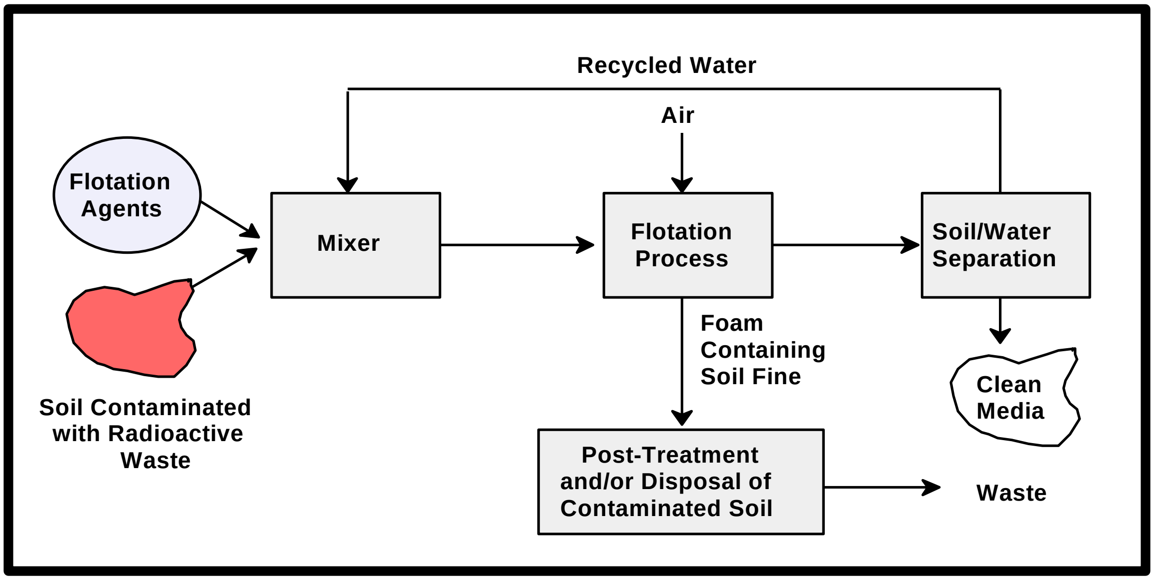
2.10 FLOTATION

2.10.1 Technology Characterization

Description

Flotation separates radionuclide-contaminated soil fractions (usually the fine soil particles such as silts and clays) from the clean soil fractions (large granular soil particles and gravel) in order to reduce the volume of soil requiring treatment or disposal. During flotation, radionuclide-contaminated soil is pretreated to remove coarse material and then mixed with water to form a slurry. A flotation agent (a chemical that binds to the surface of the contaminated soil particles to form a water repellent surface) is then added to the solution to make contaminated soil particles float. Small air bubbles are then formed in the solution through either air injection or chemical processes. These air bubbles adhere to the floating particles, transport them to the surface, and produce a foam containing the radionuclide-contaminated soil particles. The foam is mechanically skimmed from the surface or allowed to overflow into another vessel, where it is collected for treatment and/or disposal. After dewatering and drying and if the soil meets ARARs, the clean soil can then be returned to the excavation area. Flotation can be performed in a stationary column or rotating vessel, using centrifugal force to enhance the process (see Exhibit 2-28).

Exhibit 2-28: Flotation



Target Contaminant Groups

Contaminants that can be treated using flotation include heavy metals, such as lead and mercury, and radionuclides, such as uranium and plutonium. Flotation is used extensively in the mining industry to concentrate constituents such as uranium from ores. It has also been tested, with various mechanical designs for effectiveness in reducing the volume of soil contaminated with plutonium, uranium, or heavy metals.

Technology Operating Characteristics

Exhibit 2-29 summarizes the operating characteristics of flotation.

Exhibit 2-29: Technical Characteristics of Flotation

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	In tests conducted by the U.S. Bureau of Mines, flotation was 95% effective in separating uranium from sandstone ores containing 0.25% uranium oxide.[155] Radium was reduced in uranium mill tailings from 290-230 pCi/g to 50-60 pCi/g by flotation.[156] In bench scale tests with bismuth as a surrogate for plutonium oxide, the separation effectiveness ranged from 70 to 90%.[157]
Emissions: Gaseous and Particulate	If VOCs or radon are present in soil, gaseous emissions may be generated during treatment. In addition, excavation of contaminated soil may generate fugitive gas and dust.
Costs: Capital and O&M	Capital costs for a flotation unit vary from $25,000 to $160,000, depending on the size of the unit. O&M costs vary from $3 to $15 per 1,000 gallons of treated slurry. The larger the unit, the lower the O&M cost per 1,000 gallons. However, capital costs are lower for the smaller flotation units.[158]

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[155] Organization for Economic Cooperation and Development, *Uranium Extraction Technology*, OECD, Paris 1983.

[156] Raicevic, D., *Decontamination of Elliot Lake Uranium Tailing*, CIM Bulletin, 1970.

[157] U.S. Department of Energy, *Heavy Metals Contaminated Soil Project, Resource Recovery Project, and Dynamic Underground Stripping Project: Technology Summary*, DOE/EM-0129P, February 1994.

[158] U.S. Environmental Protection Agency, *Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

Exhibit 2-29: Technical Characteristics of Flotation (Cont.)

Characteristic	Description
Reliability	Bench scale tests have shown consistent and successful segregation of radionuclide-contaminated fines from clean, larger, soil-particle fractions.[159] Clean soil may be returned to the excavated site, although the fines and wash solution may require further treatment and/or disposal.
Process Time	Not documented in the literature reviewed.
Applicable Media	Soil, sediment
Pretreatment/Site Requirements	Soil excavation; potential grinding of soil to reduce particle size for treatment.[160]
Type and Quantity of Residuals	Foam containing contaminated soil fines.
Disposal Needs and Options	Excavated soil requires backfilling. Returned cleaned material may contain some residual contamination. Radionuclide-contaminated foam requires further treatment and/or disposal.
Post-Treatment Conditions	Residual foam containing radionuclide-contaminated soil fines requires further treatment and/or disposal.
Ability to Monitor Effectiveness	Clean soil fractions can easily be sampled and analyzed for radionuclide contamination levels.

Site Considerations

Soil-specific site considerations, such as particle size and distribution, radionuclide distribution, soil characteristics (clay, sand, humus, silt), specific gravity and chemical composition, and mineralogical composition, may impact the effectiveness of flotation. Larger soil particles may have to be ground or removed from the soil prior to flotation. In addition, soils with high organic content (i.e., humus soils) may be difficult to treat with this technology. Flotation is most effective at separating soil particles in the size range of 0.1 - 0.01 mm. The availability of appropriate flotation agents to bind to the contaminant(s) of concern is also important to consider. If a flotation agent is not available for a particular contaminant, unless one is developed the flotation process will be ineffective.[161] To effectively remove radionuclide-contaminated soil particles the solution used in the flotation process must

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[159] U.S. Department of Energy,*Heavy Metals Contaminated Soil Project, Resource Recovery Project, and Dynamic Underground Stripping Project: Technology Summary*, DOE/EM-0129P, February 1994.

[160] U.S. Environmental Protection Agency,*Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites*, EPA/540/2-88/002, August 1988.

[161] *Ibid.*

be treated. For example, treatment of uranium mine tailings in Canada failed to remove significant levels of radium from the tailings because high levels of dissolved radium had built up in the recycled wash water, reducing the removal efficiency of the process.[162]

2.10.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

This technology has not been fully demonstrated for reducing the volume of radionuclide-contaminated soil. However, in tests conducted by the U.S. Bureau of Mines flotation removed 95 percent of the uranium from sandstone ores containing 0.25 percent uranium oxide. Additional studies with uranium mill tailings showed effective removal of radium.[163] Given the demonstrated efficiency of this technology, it is expected to effectively reduce the volume of contaminated soil, thus reducing the potential threat to human health.

Compliance with ARARs

The treatment must result in residual soil levels that comply with NRC, RCRA, and any local regulatory requirements.

Long-Term Effectiveness

Although mining industry operations have consistently and successfully segregated contaminated fines from clean soil (i.e., uranium removal from sandstone ore), additional studies are needed to document the effectiveness of separating radionuclide-contaminated fines from soil. Additionally, the residual foam generated by the flotation process requires further treatment and/or disposal.

Reduction of Radiotoxicity, Mobility, and Volume

This technology effectively separates contaminated soil fines from the clean, larger soil particles, thus reducing the volume of material requiring further treatment and/or disposal. However, the foam generated during this process contains elevated levels of contaminants and requires treatment and/or disposal. While flotation reduces the volume of the contaminated soil, the residual is highly concentrated and requires

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[162] *Ibid.*

[163] *Ibid.*

additional management, since the toxicity and mobility of the original contaminants are not addressed by this technology.

Short-Term Effectiveness

The organic content of the soil may reduce this treatment's effectiveness. In addition, clay and silt increase the volume of contaminated material removed in the generated foam, thus increasing the volume of material requiring additional treatment.[164] Fugitive gas and dust generated during the excavation and grinding of contaminated soil may pose a threat to workers' health and safety.

Implementability

Although many flotation systems are being developed to address radionuclide-contaminated soils, none have been tested beyond the bench scale.[165] Implementation of this technology requires intensive knowledge of the soil characteristics, including particle size and shape distribution; association of radionuclides with particle size; clay, humus, sand and silt content; and specific gravity, chemical composition, and mineralogical composition. In addition, suitable flotation agents must be available.[166] The residual generated by this technology requires additional treatment and/or disposal.

Costs

Capital costs for this technology are driven by leasing large capacity flotation equipment; O&M costs are associated with operating the system for extended periods of time. Treating and disposing of highly concentrated residuals also add to costs.

2.10.3 Summary

Flotation has been used by the mining industry to separate heavy metals and radionuclides from ores, and has been tested at the bench scale for reducing the volume of radionuclide-contaminated soil. Further development is needed to ensure this technology's effectiveness for radionuclide-contaminated soil. In addition, the following factors may limit flotation's applicability.

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[164] *Ibid.*

[165] *Ibid.*

[166] *Ibid.*

- no reduction in the toxicity or mobility of the radioactive contaminants, may produce residuals with higher toxicity and mobility;
- management of residual may be required;
- availability of a suitable flotation agent;
- limited demonstration of technology;
- organic content and particle size of soil.

Exhibit 2-30 summarizes the data and analyses presented in this profile and can be used for technology comparison.

Exhibit 2-30: NCP Criteria for Flotation

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Preliminary studies indicate that protectiveness is achieved.	• Not yet fully demonstrated. • Preliminary studies indicate that the volume of contaminated soil can be reduced by 70 to 90 percent.
Compliance with ARARs	• The requirements of RCRA LDR and NRC may apply to the residual waste produced by this technology.	• Performance data such as removal efficiencies must be assessed in relation to preremediation concentrations and cleanup standards to determine compliance with ARARs.
Long-Term Effectiveness and Permanence	• This technology needs further development to ensure effectiveness with radionuclide-contaminated soils. • Residual waste is present in soil fines.	• Bench scale tests and studies indicate a consistent and successful segregation of contaminants from soil. • Residual contamination present in soil fines requires further treatment and/or disposal.
Reduction of Radiotoxicity, Mobility, or Volume	• Does not reduce toxicity or mobility of contaminants in residuals. • Separates contaminated soil fractions (soil fines) from clean soil fractions (granular soil and gravel).	• Process separates clean and contaminated soil fractions, thus reducing the volume of soil requiring treatment.
Short-Term Effectiveness	• Technology does not pose an immediate threat. • Potential risk to workers from fugitive gas and dust during soil excavation.	• Potential risk to workers and/or nearby community. • Residual waste requires further treatment and/or disposal.

Exhibit 2-30: NCP Criteria for Flotation (Cont.)		
NCP Criterion	**Evaluation**	**Performance Data**
Implementability	• Several variations of this technology have been successfully tested at the bench scale. • Availability of flotation agents limits the applicability of this technology.	• Requires excavation of soil and may require grinding. • Numerous flotation systems are being tested for radionuclide-contaminated soil.
Cost	• Varying capital and O&M costs may be associated with this technology and generally depend on the size of the flotation unit.	• O&M costs are lower with larger systems, however larger systems increase capital costs.

VITRIFICATION

Vitrification involves heating contaminated media to extremely high temperatures, then cooling them to form a solid mass. Upon cooling, a dense glassified mass remains, trapping radioactive contaminants. The process can be applied to contaminated soil, sludge, sediment, mine tailings, buried waste, and metal combustibles. Different devices may be used, such as plasma torches or electric arc furnaces. Vitrification technologies may be particularly useful for treating radioactive or mixed waste. An off-gas system may be required for emissions during vitrification because some organic contaminants will likely be destroyed and some inorganics, including low melting point radionuclides, will volatilize due to the high temperatures involved.

Vitrification processes can be performed both *in-situ* and *ex-situ.* This section discusses both processes in detail. *Ex-situ* processes addressed include: plasma centrifugal furnace, arc melter vitrification, graphite DC plasma arc melter, plasma fixed hearth, and thermal plasma processes.

2.11 *IN-SITU* VITRIFICATION

2.11.1 Technology Characterization

Description

In-situ vitrification (ISV) uses an electric current to melt soil or other media at extremely high temperatures (1,600 to 2,000 °C or 2,900 to 3,650 °F).[167] Radionuclides and other pollutants are immobilized within the vitrified glass, a chemically stable, leach-resistant material similar to obsidian or basalt rock. ISV destroys or volatilizes most organic pollutants by pyrolysis. A vacuum hood is often placed over the treated area to collect off-gases, which are treated before release. ISV is currently available on a commercial scale. Exhibit 2-31 illustrates the general process involved with *In-situ* Vitrification.

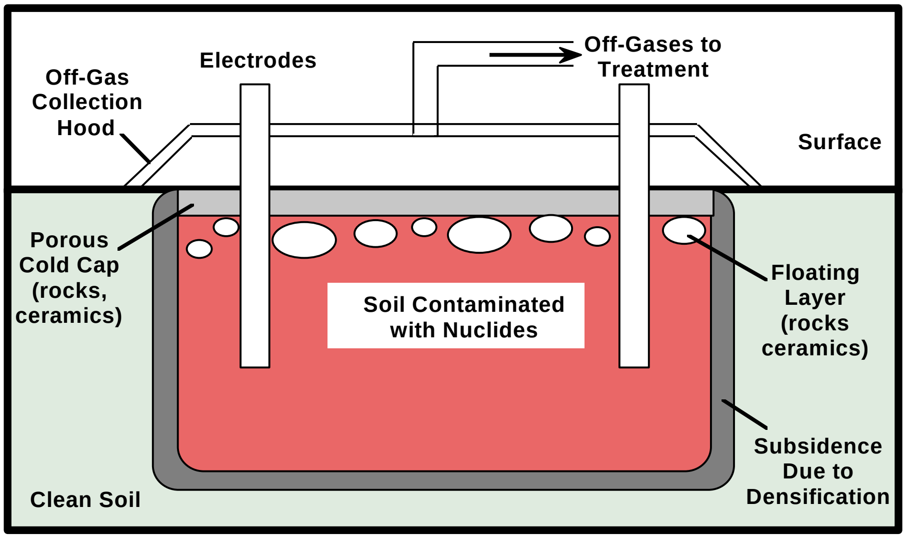

Exhibit 2-31: *In-situ* Vitrification

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[167] U.S. Environmental Protection Agency, *Vitrification Technologies for Treatment of Hazardous and Radioactive Waste*, EPA/625/R-92/002, May 1992.

Target Contaminant Groups

ISV may be applicable to a wide range of organics and inorganics, including radioactive contaminants (i.e., uranium, radium) and asbestos.[168] Testing indicates that the process may be used to treat other buried waste, including containers.[169] Vitrification reduces the volume and mobility of the contaminated materials, but does not affect their radioactivity. Additional protective measures such as shielding may therefore be required to protect public health and the environment.

Technology Operating Characteristics

Exhibit 2-32 summarizes the operating characteristics of *in-situ* vitrification.

Exhibit 2-32: Technical Characteristics of *In-situ* Vitrification

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	Process reduces the volume and mobility of contaminants but does not affect their radioactivity. Volatile radionuclides requiring further treatment and/or disposal may be released during the process. TCLP test results show that vitrification reduces leaching significantly.[170]
Emissions: Gaseous and Particulate	Process requires air emissions collection system due to volatilized contaminants. Cesium-137, Sr-90, and tritium may volatilize under certain conditions.[171] Combustible gases may also be produced in some cases; ignition of these gases could release radionuclides into the atmosphere.[172]

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[168] *Ibid.*

[169] Shade, J.W., Thompson, L.E., and Kindle, C.H., In-Situ Vitrification of Buried Waste Sites.

[170] Shade, J.W., Thompson, L.E., and Kindle, C.H., In-Situ Vitrification of Buried Waste Sites.

[171] Oak Ridge National Laboratory, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt.B, September 1993.

[172] Thompson, L.E., J.S. Tixier, and J.K. Luey, *In-Situ Vitrification: Planned Applications for the Office of Environmental Restoration, Proceedings of ER Ô93 Environmental Remediation Conference*, Augusta, Georgia (1993).

Exhibit 2-32: Technical Characteristics of *In-situ* Vitrification

Characteristic	Description
Costs: Capital and O&M	Treatability tests are \$25,000 to \$30,000, plus analytical fees. Equipment mobilization/demobilization is \$200,00 to \$300,000. ISV costs from \$300 to \$450 per ton.[173]

Exhibit 2-32: Technical Characteristics of *In-situ* Vitrification (Cont.)

Characteristic	Description
Reliability	ISV is commercially available and operating at several DOE sites, including Hanford, WA and Oak Ridge, TN.
Process Time	Melt rate of 3 - 5 tons per hour.
Applicable Media	Soil, sludge, sediment, mine tailings, some buried waste, incinerator ash[174]
Pretreatment/Site Requirements	ISV requires an on-site electrical distribution system. No excavation is required, but soil parameters must be evaluated. ISV can only treat near-surface contamination (within 5-7 meters of the surface). Construction of an off-gas collection and treatment system is also required.
Type and Quantity of Residuals	Volume reduction of 20% to 50%; air filter scrubber water may contain partially oxidized organics and volatilized radionuclides (e.g., cesium-137).
Disposal Needs and Options	Vitrified mass remains in place but may require additional radiation barriers to protect the public and the environment. Trapped volatile radionuclides require treatment and/or disposal.
Post-Treatment Conditions	Subsidence occurs due to volume reduction.
Ability to Monitor Effectiveness	The vitrified mass can be tested for TCLP leaching requirements; radionuclide mobility can be assessed by sampling groundwater around the perimeter of the vitrified mass; concentrations of volatile radionuclides can be monitored during the vitrification process; radiation levels can be monitored at the site after vitrification.

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[173] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide, Second Edition*, NTIS PB95-104782, October 1994.

[174] U.S. Environmental Protection Agency, *Vitrification Technologies for Treatment of Hazardous and Radioactive Waste*, EPA/625/R-92/002, May 1992.

Site Considerations

High soil moisture and salt content can increase electrical needs and cost. Void volumes and percentages of metals, rubble, and combustible organics must be considered. ISV is most effective for near-surface contamination although new approaches may increase treatment depths to 10 meters.[175]

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[175] Thompson, L.E., J.S. Tixier, and J.K. Luey, *In Situ Vitrification: Planned Applications for the Office of Environmental Restoration, Proceedings of ER Ô93 Environmental Remediation Conference*, Augusta, Georgia (1993).

2.11.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

Aside from the high levels of electricity used in the process, ISV is relatively safe for workers and the public — no material is extracted, thus exposure is minimal. Vitrification does not necessarily provide any additional shielding from radiation, so some form of backfill or cap over the vitrified mass may be necessary to reduce surface doses in the long-term. An off-gas treatment system may be necessary to prevent vitrification emissions from escaping into the air; special care may be required to prevent combustible gas buildup during vitrification.

Compliance with ARARs

If the waste left in place is characterized as a RCRA hazardous waste, then RCRA requirements (e.g., surface impoundment regulations) are applicable or relevant and appropriate. Compliance with other ARARs must be determined on a site-specific basis.

Long-Term Effectiveness

The vitrified mass is very resilient to weathering, which makes it effective for long-term containment of waste. Since the material remains on-site, however, monitoring is required to determine its effectiveness. Because vitrification affects only the volume and mobility of the waste, additional shielding may be required to protect against radiation exposure.

Reduction of Radiotoxicity, Mobility, or Volume

Radioactive materials remain immobilized in the vitrified/contaminated materials mass, preventing migration of these contaminants. Volume reductions may range from 20 to 50 percent for ISV, and vary widely depending on waste type.[176] The toxicity and volume of the radionuclides are not addressed by this technology.

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[176] U.S. Environmental Protection Agency, *Vitrification Technologies for Treatment of Hazardous and Radioactive Waste*, EPA/625/R-92/002, May 1992..

Short-Term Effectiveness

Volatile radionuclides (Cs-137, Sr-90, tritium, and others) may be released during vitrification; these substances should be captured by an off-gas system. If precautions are not taken, however, ignition of built-up combustible gases could release radionuclides and other substances into the environment. The radioactivity of the contaminated materials is not reduced by vitrification.

Implementability

ISV is a proven, commercially available technology. An electrical distribution system, off-gas treatment system, and process control system are required for implementation. Since the treatment is entirely *in-situ*, no offsite activity is necessary to manage, treat or store waste. ISV can process 3 to 5 tons of waste per hour; waste can be treated to depths of 5 to 7 meters. Equipment trailers can be moved within 24 hours to a new spot. Depending on the radioactivity of the vitrified mass, protective barriers surrounding the mass may be required.

Cost

Initial setup may require an electrical distribution system, off-gas treatment system, and process control system. At present, these are typically located in mobile trailers that can be moved from site to site. Electrical demands can be substantial for each application. The high capital and electric costs may be offset over the site's life because the long-term stability of the vitrified mass may result in lower monitoring costs compared to other *in-situ* stabilization techniques. Also, the vitrified material is less likely to require future retreatment. Since the technology treats the material *in-situ*, no offsite transportation, treatment, storage, or disposal costs are added, unless the vitrified mass requires removal at a later date. Costs rise if radiation barriers must be built. Cost estimates for *in-situ* vitrification range from $300 - $450 per ton.[177]

2.11.3 Summary

ISV volatilizes or destroys some organics and immobilizes nonvolatile radionuclides. The high temperatures rapidly volatilize some organic compounds and volatile radionuclides, including Cs-137, Sr-90, and 3 tritium. Control of these off-gases, as well as the high voltage used, present potential health and safety risks.

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[177] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide, Second Edition*, NTIS PB95-104782, October 1994.

In general, the process is highly complex and implementation is difficult. The process works best on homogeneous soils since different strata may interfere with the extent (i.e., depth in soil) to which the process is effective. ISV reduces the volume and mobility of radionuclides but does not reduce their radioactivity. Therefore, protective barriers that limit exposure to radioactive emissions may still be required at some sites. The following factors may impact the applicability and effectiveness of this process:

- soil moisture and content;
- contamination depth;
- volatilization of some radionuclides;
- radiation emissions require additional management.

Exhibit 2-33 summarizes the data and analyses presented in this profile and can be used for technology comparison.

Exhibit 2-33: NCP Criteria for *In-situ* Vitrification

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Limited overall protectiveness at site; however prevents migration of contaminants.	• Demonstrated • Vitrified mass is stable for geologic time periods. • Does not shield or eliminate radiation effects.
Compliance with ARARs	• RCRA requirements may be applicable. • Compliance with other ARARs determined on site-specific basis.	• Waste remains in place.

Exhibit 2-33: NCP Criteria for *In-situ* Vitrification (Cont.)

NCP Criterion	Evaluation	Performance Data
Reduction of Radiotoxicity, Mobility, or Volume	• Does not reduce the radioactivity of contaminants. • Reduces toxicity and volume of organic contaminants. • Reduces mobility of inorganic contaminants (e.g., radionuclides, heavy metals).	• May result in the removal and / or destruction of organic contaminants. • Effectively immobilizes inorganics (e.g., radionuclides, heavy metals).
Long-Term Effectiveness and Permanence	• Needs further development to ensure effectiveness.	• Models predict that vitrified waste could immobilize contaminants for 1000 to 1 million years.[178]
Short-Term Effectiveness	• Requires an off-gas collection system to prevent release of volatile radionuclides and build-up of combustible gases. • Relatively short process time.	• Volatile substances (Pb, Cd, possibly Cs) could contaminate other components of the treatment system.[179]
Implementability	• Difficult to implement and control. • May interfere with current site activities.	• Electrical distribution and off-gas control system needed. • Treatment of 3 to 5 tons / hour to a depth of 5 to 7 meters. • Subsidence occurs due to volume reduction. • Radiation barriers may need to be constructed.

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[178] U.S. Environmental Protection Agency, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, EPA/625/R-93/013, September 1993.

[179] *Ibid.*

Exhibit 2-33: NCP Criteria for *In-situ* Vitrification (Cont.)

NCP Criterion	Evaluation	Performance Data
Cost	- High	- High capital costs.

2.12 *EX-SITU* VITRIFICATION

2.12.1 Technology Characterization

Description

Ex-situ vitrification technologies generally involve applying existing technologies (e.g., metals processing) to new purposes. *Ex-situ* vitrification applies heat to destroy some contaminants (e.g., organics) and immobilize others (e.g., radioactive waste) into a dense, glassified mass. Heating devices used include plasma torches and electric arc furnaces. *Ex-situ* vitrification is useful for treating radioactive and mixed wastes. While the final nonleaching glassy solid product can be stored without further treatment, vitrification does not reduce the waste's radioactivity. Vitrified waste must therefore be stored in facilities that protect the public from radiation exposure.[178]

E*x-situ* vitrification technologies vary in design and application. For example, some processes use a plasma torch technology similar to that used to refine titanium. In this process, waste is fed into a rotating hearth; the waste and molten material are held against the side by centrifugal force. During the rotation, the waste moves through plasma generated by a stationary torch. To remove the molten material from the furnace, the hearth's rotation slows and the slag flows through a bottom opening.[179] Effluent gases are generally kept in a separate container where high temperatures combust/oxidize the contents.[180]

Other *ex-situ* vitrification processes use electricity, such as an arc furnace that contain carbon electrodes, cooled side walls, a continuous feed system, off-gas treatment system, and slag and metals tapping capability.[181] In this process, waste is fed into the top of a refractory chamber where it is heated to temperatures greater

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[178] Hoffeiner, W., Chrubasik, A., Eschenbach, R.C.,*Volume Reduction and Vitrification of Nuclear Waste with Thermal Plasma*, Proceeds of the 1993 International Conference on Nuclear Waste Management and Environmental Remediation, Volume 3, 1993.

[179] U.S. Department of Energy, Office of Environmental Management Office of Technology Development,*Buried Waste Integrated Demonstration*, DOE/EM-0149P, March 1994

[180] Hoffeiner, W., Chrubasik, A., Eschenbach, R.C.,*Volume Reduction and Vitrification of Nuclear Waste with Thermal Plasma*, Proceeds of the 1993 International Conference on Nuclear Waste Management and Environmental Remediation, Volume 3, 1993.

[181] U.S. Department of Energy, Office of Environmental Management, Office of Technology Development,*Buried Waste Integrated Demonstration*, DOE/EM-0149P, March 1994

than 1500°C by carbon electrodes. The weight of the waste pushes the molten slag through a bottom opening into a cooling chamber, where slag and molten metals can be separated. Volatile substances, including some radionuclides, emitted during the process are treated in an off-gas collection and treatment system.[182] Exhibit 2-34 illustrates the general process associated with *Ex-situ* Vitrification.

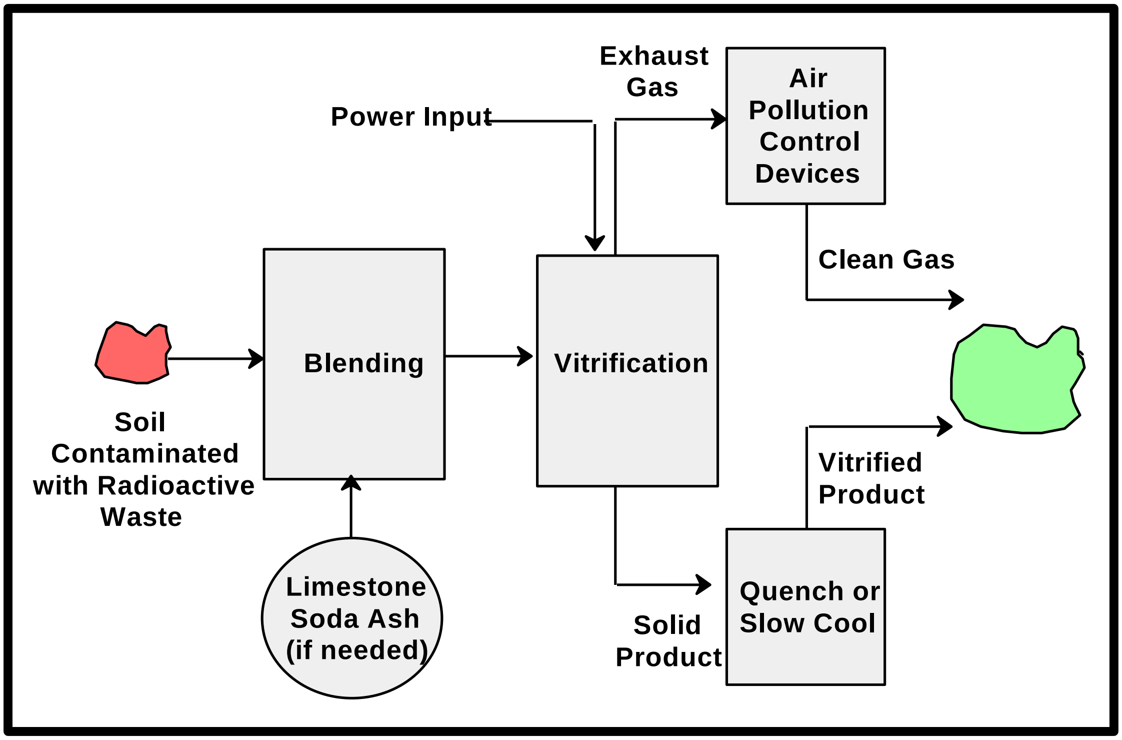

Exhibit 2-34: *Ex-situ* Vitrification

Target Contaminant Groups

These processes can treat and vitrify hazardous, radioactive (both low-level and transuranic wastes - elements heavier than uranium), and mixed waste.[183] *Ex-situ* vitrification has been used with radionuclides, combustibles, inorganic materials, and metals.

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[182] U.S. Environmental Protection Agency,*Superfund Innovative Technology Evaluation Program: Technology Profiles, Seventh Edition* EPA/540/R-94/526, November 1994.

[183] U.S. Department of Energy, Office of Environmental Management Office of Technology Development,*Buried Waste Integrated Demonstration*, DOE/EM-0149P, March 1994

Technology Operating Characteristics

One electric arc vitrification unit currently in use can process a nominal 1.5 tons per hour of buried waste-type feeds and soil. This technology has been used in the steel industry to process excess of 105 tons per day.[184] Some ex-situ vitrification plants are very compact, are flexible in process control, and are highly automated.[185] Additionally, material of different forms can be fed into furnaces. For example, liquids may be pumped; shredded waste can be screw fed; and steel drums can be directly inserted by robotics, opened, and completely melted inside the furnace.[186]

Technology Operating Characteristics

Exhibit 2-35 summarizes the operating characteristics of *ex-situ* vitrification.

Exhibit 2-35: Technical Characteristics of *Ex-situ* Vitrification

Characteristic	Description
Destruction and Removal Efficiencies (DREs)	*Ex-situ* vitrification significantly reduces the mobility and volume of radionuclide-contaminated waste (volume reductions up to 65% with some waste), but does not reduce their radioactivity; volatile radionuclides trapped during the process require further treatment and/or disposal.[187]
Emissions: Gaseous and Particulate	Since vitrification processes may cause polluted flue gases (i.e., containing radionuclides),[188] appropriate gas collection systems must be used to minimize emissions. Some processes use a wet gas cleaning system, producing extremely clean off-gas.[189] Excavation of contaminated materials could cause fugitive gas and dust emissions of radionuclides.

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[184] *Ibid.*

[185] Hoffeiner, W., Chrubasik, A., Eschenbach, R.C., *Volume Reduction and Vitrification of Nuclear Waste with Thermal Plasma*, Proceeds of the 1993 International Conference on Nuclear Waste Management and Environmental Remediation, Volume 3, 1993.

[186] *Ibid.*

[187] U.S. Department of Energy, Office of Environmental Management Office of Technology Development, *Technology Catalogue, First Edition*, DOE/EM-0138P, February 1994.

[188] Hoffeiner, W., Chrubasik, A., Eschenbach, R.C., *Volume Reduction and Vitrification of Nuclear Waste with Thermal Plasma*, Proceeds of the 1993 International Conference on Nuclear Waste Management and Environmental Remediation, Volume 3, 1993.

[189] *Ibid.*

Exhibit 2-35: Technical Characteristics of *Ex-situ* Vitrification (Cont.)

Characteristic	Description
Costs: Capital and O&M	The cost to develop and build an *ex-situ* system (electric arc furnace) that can process 5 tons per hour could cost from $50 to $100 million.[190] Operating costs could range from $400 to 500 per ton, to $1,900 per ton.[191,192]
Reliability	These processes are proven industrial technologies. Testing is required to determine thermal properties of waste constituents. TCLP requirements are generally met.[193] Vitrified mass has high strength properties; actual values will vary with cooling method (e.g., quench or air cooled), use of fluxing agents, and composition of soil or other media.
Process Time	Some *ex-situ* vitrification processes can process 3 to 5 tons per day.[194]
Applicable Media	Buried waste, debris, soils, metals (including radionuclides), combustibles, and sludges
Pretreatment/Site Requirements	Requires excavation. High energy use requires sufficient electric or fuel sources. May require addition of suitable glass-making substrates.
Type and Quantity of Residuals	Some volatile heavy metal and radioactive contaminants may volatilize and require treatment in an off-gas system.[195] Vitrified mass contains radioactive material that requires final handling and disposal.

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[190] U.S. Environmental Protection Agency, *Superfund Innovative Technology Evaluation Program: Technology Profiles, Seventh Edition* , EPA/540/R-94/526, November 1994.

[191] Oak Ridge National Laboratory, *Oak Ridge National Laboratory Technology Logic Diagrams, Volume 2, Part B, Remedial Action,* ORNL/M-2751/V2/Pt.B, September 1993.

[192] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide, Second Edition*, NTIS PB95-104782, October 1994.

[193] *Ibid.*

[194] U.S. Department of Energy, Office of Environmental Management Office of Technology Development, *Buried Waste Integrated Demonstration*, DOE/EM-0149P, March, 1994.

[195] U.S. Department of Defense, Environmental Technology Transfer Committee, Remediation *Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

Exhibit 2-35: Technical Characteristics of *Ex-situ* Vitrification (Cont.)

Characteristic	Description
Disposal Needs and Options	*Ex-situ* vitrification products are disposable without further stabilization treatment, but must be safely stored to prevent radiation exposure.
Post-Treatment Conditions	Excavation requires backfilling with suitable materials. Vitirified waste requires proper storage.
Ability to Monitor Effectiveness	Vitrified waste can be tested for TCLP leaching. Radiation can be monitored during *ex-situ* vitrification and at the disposal site. Groundwater monitoring is required at the disposal site.

Site Considerations

Ex-situ vitrification applies to a broad range of solid media (e.g., debris, soil, etc.). The composition of the radionuclide-contaminated media may affect the strength properties of the vitrified material. In some cases glass-making materials (e.g., sands high in boro-silicates) may have to be added to the waste. *Ex-situ* vitrification has been used to treat many different types of radioactive waste, including transuranic (TRU) waste.[196]

2.12.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

Although these technologies have not been fully demonstrated, protectiveness has been achieved in preliminary studies. *Ex-situ* vitrification immobilizes radioactive waste and volatilizes and/or destroys the organics in mixed waste. Because radioactivity is still present, shielding from vitrified masses is necessary to reduce or eliminate possible exposure. Additionally, some processes may produce polluted flue gases which require further treatment.

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[196] U.S. Department of Energy, Office of Environmental Management, Office of Technology Development, *Technology Catalogue, First Edition*, DOE/EM-0138P, February 1994.

Excavation of contaminated soils could cause radiation exposure to workers from fugitive gas and dust emissions.[197]

Compliance with ARARs

Ex-situ vitrification treatments must result in residual soil levels that comply with NRC and RCRA requirements. *Ex-situ* vitrification has been found, in some cases, to fulfill stringent environmental requirements.[198] Compliance with other ARARs needs to be determined on a site-specific basis.

Long-Term Effectiveness

Past demonstrations and studies indicate contaminants are consistently and successfully destroyed and/or immobilized in applicable media. Vitrified masses have high strength and generally meet EPA TCLP testing requirements. Long-term monitoring is required after disposal of vitrified masses.

Reduction of Radiotoxicity, Mobility, or Volume

Many *ex-situ* vitrification technologies have reduced off-gas flows, high organic destruction efficiency, high waste volume reduction, and the ability to treat almost any type of waste.[199] Mobility is greatly reduced for contaminants trapped within the vitrified mass, however the radioactivity of radionuclide contaminants is not reduced. Volume reductions may range as high as 65 percent for *ex-situ* vitrification, varying widely depending on waste type.[200]

Short-Term Effectiveness

Excavation and/or handling of contaminated media may increase the risk to workers and surrounding populations. The high automation typical of *ex-situ* vitrification processes significantly reduces risk to workers and negative

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[197] Hoffeiner, W., Chrubasik, A., Eschenbach, R.C., *Volume Reduction and Vitrification of Nuclear Waste with Thermal Plasma*, Proceeds of the 1993 International Conference on Nuclear Waste Management and Environmental Remediation, Volume 3, 1993.

[198] *Ibid.*

[199] U.S. Department of Energy, Office of Environmental Management, Office of Technology Development, *Buried Waste Integrated Demonstration*, DOE/EM-0149P, March 1994.

[200] U.S. Department of Energy, Office of Environmental Management, Office of Technology Development, *Technology Catalogue, First Edition*, DOE/EM-0138P, February 1994.

environmental impacts.[201] In some cases, however, polluted flue gases may need further treatment.

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[201] Hoffeiner, W., Chrubasik, A., Eschenbach, R.C., *Volume Reduction and Vitrification of Nuclear Waste with Thermal Plasma*, Proceeds of the 1993 International Conference on Nuclear Waste Management and Environmental Remediation, Volume 3, 1993.

Implementability

Demonstrations and studies at several sites (Oakridge, TN, Washington, DC)[202] indicate that *ex-situ* vitrification technologies can be implemented without significant difficulties. Contaminated materials (e.g., debris, soils) must first be excavated, however. Also, a high degree of specialized skill and training is required.

Cost

Capital costs for *ex-situ* vitrification is high due to its heavy use of energy and the need to transport radioactive waste. Due to the stability of the vitrified product, however, long-term maintenance costs are reduced, even if additional containment shielding is required. Approximate overall costs range from $400 to 500 per ton, to $1,900 per ton.[203,204]

2.12.3 Summary

Ex-situ vitrification technologies have been demonstrated at several federal facilities contaminated with radioactive waste. *Ex-situ* vitrification can treat many different forms of radioactive waste and forms a strong, stable, leach-resistant product that is more easily handled. However, vitrification does not affect the radioactivity of the final product; disposal at a site with suitable radiation barriers is thus necessary. The process may also expose workers or local populations to radioactive contaminants during excavation of contaminated sites. Further, volatile radionuclides must be collected and treated during vitrification. *Ex-situ* vitrification technologies are still largely in the developmental stages, thus more research on the treatment of radioactive waste needs to be conducted. Factors that may impact the applicability and effectiveness of the process include the following:

- radioactive constituents of waste;
- properties of contaminated media;
- risks posed to workers and local communities from excavation and transport of radioactive waste;

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[202] U.S. Department of Energy, Office of Environmental Management, Office of Technology Development, *Minimum Additive Waste Stabilization, Technology Summary*, DOE/EM-0124P, February 1994.

[203] Oak Ridge National Laboratory, *Oak Ridge National Laboratory Technology Logic Diagrams, Volume 2, Part B, Remedial Action*, ORNL/M-2751/V2/Pt.B, September 1993.

[204] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide, Second Edition*, NTIS PB95-104782, October 1994.

- disposal options for radioactive vitrified masses.

Exhibit 2-36 summarizes the data and analyses presented in this profile. It can be used for technology comparison.

Exhibit 2-36: NCP Criteria for *Ex-situ* Vitrification

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Reduces volume and mobility of radioactive waste but proper disposal requires adequate radiation shielding. Risks posed to workers and communities must be considered.	• Technologies are in various stages of demonstration.
Compliance with ARARs	• Vitrified mass would have to comply with LNRC and RCRA LDR requirements. • Compliance with other ARARs must be determined on a site-specific basis.	• Performance data, such as removal efficiencies, must be assessed in relation to preremediation concentrations and cleanup standards to determine compliance with ARARs.
Long-Term Effectiveness and Permanence	• Past demonstrations and studies indicate that long-term effectiveness and permanence are achieved with these technologies. • Additional shielding to prevent exposure to radiation is required during handling/disposal. • Polluted flue gases may need further treatment.	• Demonstrations and studies indicate radioactive contaminants are consistently and successfully immobilized in a vitrified mass. Radioactivity is affected.
Reduction of Radiotoxicity, Mobility, or Volume	• Reduces toxicity of certain contaminants (e.g., organics) and successfully immobilizes those that cannot be destroyed (e.g., radionuclides). • Does not reduce toxicity of radionuclides.	• Demonstrations and studies indicate radioactive contaminants are consistently and successfully immobilized in a vitrified mass.

Exhibit 2-36: NCP Criteria for *Ex-situ* Vitrification (Cont.)		
NCP Criterion	**Evaluation**	**Performance Data**
Short-Term Effectiveness	• Excavation and transportation of contaminants pose an immediate threat. • Fugitive gas and dust generated during excavation may expose workers and the surrounding community to health and safety risks. • Radioactivity is not shielded in final product.	• Potential risk to workers or nearby community. • Additional containment and disposal is required.
Implementability	• Technologies can be implemented without difficulty.	• Demonstrations and studies indicate that implementation is not significantly difficult.
Cost	• The costs of treating radioactively contaminated waste using *ex-situ* vitrification depend on excavation costs, transportation costs, electricity requirements, the types of contaminants to be treated, and disposal fees.	• Costs are considered high.[205]

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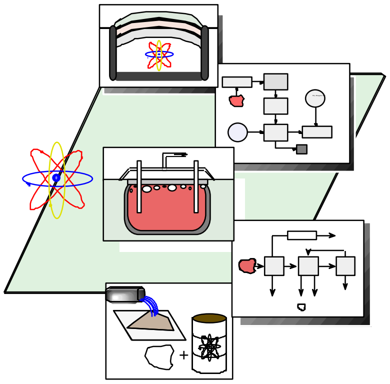
[205] *Ibid.*



SECTION III

LIQUID MEDIA TECHNOLOGY PROFILES

CHEMICAL SEPARATION

Chemical separation technologies for liquid media involve processes that separate and concentrate radioactive contaminants from groundwater, surface, or waste water. Process residuals such as filters, filter cakes, carbon units, and ion exchange resins require further treatment, storage, or disposal. Extractability rates of the different chemical separation technologies vary considerably based on the types and concentrations of contaminants, as well as differences in methodology. Whether these technologies can be implemented is determined by site-specific factors and their applicability must be determined on a site-by-site basis.

Technologies in this category include: ion exchange and chemical precipitation using carbonates, sulfates, sulfides, or lime and other hydroxides.

3.1 ION EXCHANGE & CHEMICAL PRECIPITATION

3.1.1 Technology Characterization

Chemical separation technologies for groundwater include ion exchange and chemical precipitation. Chemical separation technologies are generally ex-situ and require the construction and operation of a groundwater extraction and delivery system; they generate a treated effluent and a contaminated residual that requires further treatment or disposal.

Because there are many similarities between the two technologies, discussion about them has been combined for the target contaminant groups, site considerations, and NCP criteria evaluation.

Description

Ion exchange, a fully developed chemical separation process, is highly efficient in reducing radionuclide and inorganic metal levels in liquid waste streams to levels suitable for effluent discharge. Ion exchange has been identified as the Best Available Technology (BAT) for the removal of radium-226, radium-228, and uranium. This technology separates and replaces radionuclides in a waste stream with relatively harmless ions from a synthetic resin or natural zeolite (for strontium and cesium). Resins consist of an insoluble structure with many ion transfer sites and an affinity for particular kinds of ions. Resins are either acid-cationic (for removing positively charged ions) or base-anionic (for removing negatively charged ions); resins used for radioactive liquid waste are often either hydrogen (H+) or hydroxyl (OH-). Resins must be regenerated by exposing them to a concentrated solution of the original exchange ion, while zeolites are stored as solid waste.

A typical ion exchange unit is in a fixed bed with a vertical cylindrical pressure vessel. It contains one or more meters of exchange resin (either cationic or anionic) which is in contact with water in both a downflow and backwash upflow. Alternatively, some ion exchange units send water through a mixed-bed, which contains both cationic and anionic resins in the same bed.

Ion exchange significantly reduces contaminant mobility by immobilizing it in the exchange media, but does not affect the radiotoxicity of the contaminant itself. It is most effective when the waste stream is in the ionic form; nonionic waste streams or waste streams with suspended solids must be pretreated. Both concentrated waste removed from the resin and spent resin itself must be treated, stored, or disposed of. Also, this technology's effectiveness depends on the pH, temperature, and flow rate of the waste material, and the resin's selectivity and exchange capacity. If more than one radioactive contaminant is present, more than one treatment process may be required.

Exhibit 3-1 illustrates the general process involved with ion exchange.

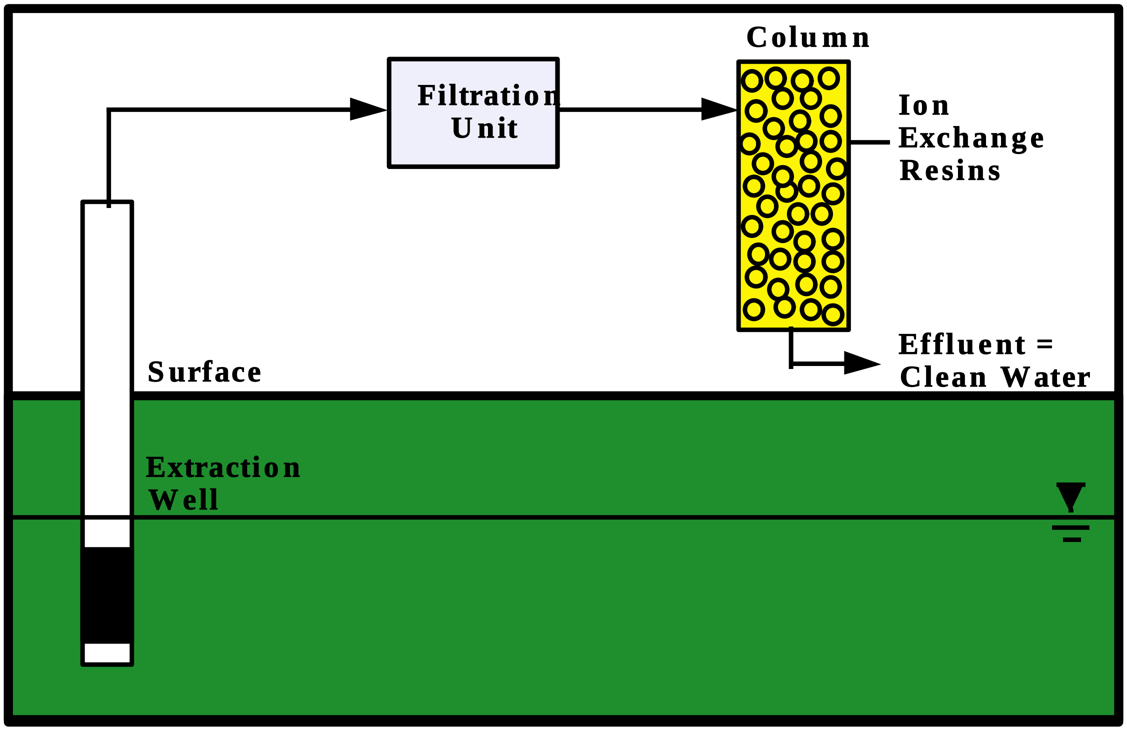


Exhibit 3-1: Ion Exchange Diagram

Chemical precipitation converts soluble radionuclides to an insoluble form through a chemical reaction or through changing the solvent's composition to diminish solubility. Precipitation adds a chemical precipitant to the radionuclide-containing aqueous waste in a stirred reaction vessel. Solids are separated by settling in a clarifier; flocculation, with or without a chemical coagulant or settling aid, may be used to enhance their removal. Commonly used precipitants include carbonates, sulfates, sulfides, lime and other hydroxides. The amounts of radionuclides that can be removed from a solution depends on the precipitant and dosage used, the concentration of radionuclides present in the aqueous waste, and the pH of the solution. Maintaining optimum pH levels within a relatively narrow range is usually necessary to achieve adequate radionuclide precipitation.

Either batch reactors or continuous flow designs can be used. Batch reactors are generally favored for flows up to 50,000 gallons per day and usually operate with two parallel tanks. Each tank acts as a flow equalizer, reactor, and settler, thus eliminating the need for separate equipment for each step. Continuous systems have a chemical feeder, flash mixer, flocculator, settling unit, filtration unit (if used), and control system for feed regulation.

Exhibit 3-2 illustrates the general process involved with chemical precipitation.

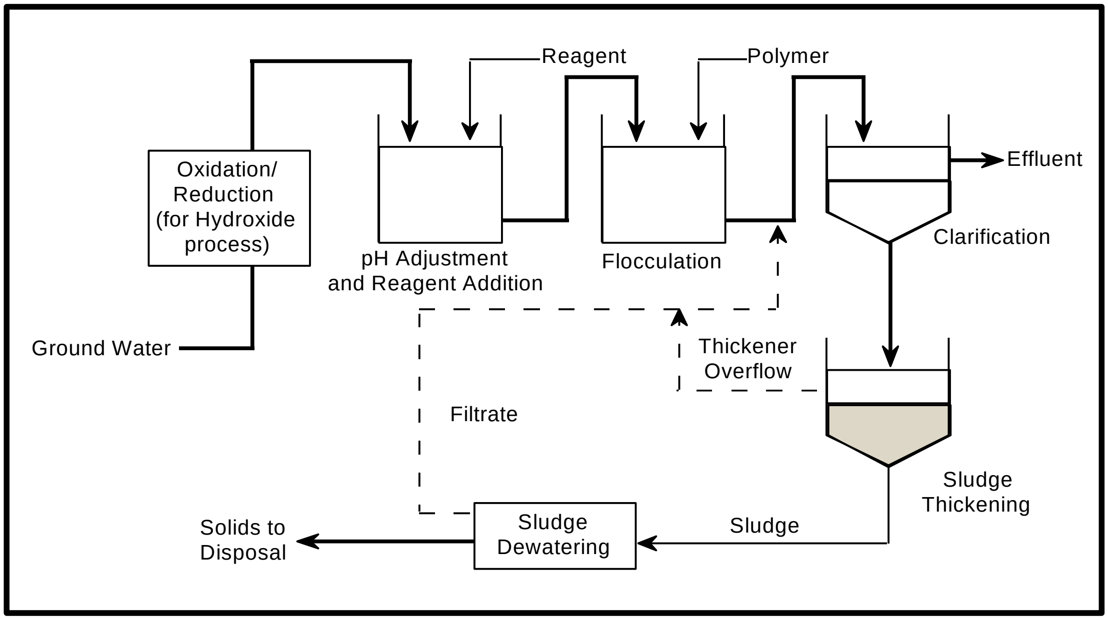


Exhibit 3-2: Chemical Precipitation Diagram

Source: Balaso, C.A., et al., 1986. *Soluble Sulfide Precipitation Study*, Arthur D. Little, Inc., Final Report to USATHAMA, Report No. AMXTH-TE-CR-87106.

Operating Characteristics

The expected ion exchange removal rates for radium and uranium are 65 percent to 97 percent and 65 percent to 99 percent, respectively. The range of removal of beta emitters such as cesium-137 and strontium-89 are 95 percent to 99 percent.[206] When ion exchange was implemented on a waste water stream at Hanford, an initial uranium concentration of 0.1 kg/m^3 was reduced by 94 percent after eight exchange cycles (5-7 days per cycle) with an approximate uranium loading of 0.035 kg/kg commercial resin.[207,208]

Resins are relatively more expensive than other adsorption reagents such as carbon, but can achieve higher degrees of selectivity than activated carbon. Cost (capital plus operating) for ion exchange is estimated to be $5 to $10 per 1,000 gallons of liquid waste.[209] Operating and maintenance costs are also associated with storing the treatment process waste.

Chemical precipitation was jar-tested on uranium-contaminated pond water, with the following results: 80 percent removal with a dose of 10 mg/L or more of ferric sulfate at pH 10, and with 20 mg/L or more at pH 6; 92 percent to 93 percent removal with a dose of 20-25 mg/L of ferrous sulfate at pH 10; and 95 percent removal with a dose of 10 mg/L of alum at pH 10.[210]

There are no available cost data on chemical precipitation for radionuclides.

Target Contaminant Groups

Chemical separation effectively reduces high levels of radionuclides, especially radium, and uranium, and dissolved metals from groundwater, surface water, and other aqueous waste streams, including extractants resulting from other chemical separation processes. Reagents, filters, and resins must be selected on a site-specific basis for the particular radionuclides present.

Site Considerations

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[206] U.S. Environmental Protection Agency, EPA625/R-93/013, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, 1993.

[207] U.S. Department of Energy, Office of Environmental Restoration, *Decommissioning Handbook*, DOE, EM-0142P, March 1994.

[208] Balaso, C.A., et al., 1986. *Soluble Sulfide Precipitation Study*, Arthur D. Little, Inc., Final Report to USATHAMA, Report No. AMXTH-TE-CR-87106.

[209] Oak Ridge National Laboratory, *Technology Evaluation Data Sheets, Part B, Dismantlement - Remedial Action*, ORNL/M-2751/V3/Pt. B, September 1993.

[210] Sorg, Thomas J., "Methods for Removing Uranium From Drinking Water," July 1988.

Characteristics such as contaminant type and concentration should be well defined to accurately predict the performance of the chemical separation technology. The presence of multiple radionuclides could impact the technology's effectiveness.

Ion exchange treatment is effective only for liquid waste streams that are in ionic form. Nonionic forms (insoluble particles, colloids, and neutral molecules and complexes) require pretreatment. Pretreatment may also be required to remove solids, modify the pH of the influent stream for optimum removal efficiencies, or remove competing ions.

3.1.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

These technologies significantly reduce the volume of contaminants in the liquid medium, the toxicity of the liquid medium, but not the mobility of the contaminants remaining in the liquid medium. The processes yeild purified liquid medium and the contaminated process residuals which can be stored, further processed, or disposed of.

Compliance with ARARs

The requirements of RCRA LDRs may apply to the residual waste produced. Aqueous discharges must comply with MCLs or NPDES discharge limits.

Long-Term Effectiveness

Both technologies reduce contamination in liquid waste streams. Continued testing will improve efficiency.

Potential risks are reduced by removing the contaminants of concern and by placing the treated residuals in a controlled environment. However, the concentrated stream of waste removed from the ion exchange resin and precipitated solids requires treatment, storage, or disposal. Spent ion exchange resin can be rigorously eluted to lower its radionuclide content before disposal and can be incorporated into cement for storage or disposal.

Reduction of Radiotoxicity, Mobility, or Volume

These technologies significantly reduce contaminant mobility and the volume it occupies, but not its radiotoxicity. The processes yield a large volume of purified solution and concentrated residuals that can be stored or disposed of. Residuals from ion exchange include brine waste, caustic or acid solution (depending on type of regeneration used), and resins containing radionuclides.

Short-Term Effectiveness

A safety consideration for workers during ion exchange is radiolytic byproducts, including benzene derivatives produced when the resin is placed in a radioactive environment. A small amount of hydrogen gas formed in the presence of organic materials can be captured by an off-gas treatment system. Toxic hydrogen sulfide gas may be generated during sulfide precipitation. This gas can be minimized by maintaining the proper pH and an off-gas treatment system.

Implementability

These technologies are fully developed and have been applied to waste streams contaminated with radionuclides and metals. Laboratory-scale tests should be conducted to select the best ion exchange materials and systems for each specific cleanup. A monitoring system can record activity, pH, conductivity, and total suspended solids for the liquid being processed. Residuals and spent resins require disposal or storage. Chemical precipitation treatability testing should be conducted to determine the appropriate selection of reagents and dosages.

Cost

Ion exchange cost (capital plus operating) is estimated to be $5 to $10 per 1,000 gallons of liquid waste. Operating and maintenance costs are also associated with storing the treatment process waste.[211]

There are no available cost data on radionuclide precipitation. However, capital cost estimates for 75- and 250-liters-per-minute packaged metals precipitation systems are approximately $85,000 and $115,000, respectively. Operating costs are typically in a range from $0.08 to $0.18 per 1000 liters of groundwater containing up to 100 mg/L of metals.[212]

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[211] Oak Ridge National Laboratory, *Technology Evaluation Data Sheets, Part B, Dismantlement-Remedial Action*, ORNL/M-27511 V3/Part B, September 1993.

[212] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, October 1994.

3.1.3 Chemical Separation Summary

Chemical separation is useful for reducing high levels of inorganic metal and radionuclide contaminants from aqueous waste streams. However, these technologies generate either a concentrated stream of waste removed from the ion exchange resin or precipitated solids, which require treatment, storage, or disposal. In addition, the ion exchange process works only on liquid waste streams in ionic form; nonionic waste streams require pretreatment.

The applicability and effectiveness of chemical separation may be affected by the following factors:

- the physical and chemical properties (e.g. temperature, pH, flow rate) of the waste material;
- a combination of elements in the waste stream; a media with more than one radioactive contaminant may require more than one treatment process;
- for ion exchange, the physical and chemical properties (e.g. exchange capacity, ionic selectivity, ionic exchange kinetics) of the exchange resin;
- efficiency of chemical precipitation depends on adequate solids separation;
- precipitation reagent addition must be carefully controlled to prevent unacceptable concentrations in treatment effluent.

Treatability studies should be conducted to select the best ion exchange materials and to determine the best operating parameters for chemical precipitation.

Exhibit 3-3 summarizes the data and analyses presented in this profile and can be used to compare these and any other technologies.

Exhibit 3-3: NCP Criteria for Chemical Separation

NCP Criterion	Evaluation	Performance Data
Overall Protectiveness	• Protects human health and the environment by reducing contaminant levels in liquid waste streams and thus potential risks due to external exposure and direct contact.	• Fully developed • Useful for reducing inorganic metal and radionuclide levels of liquid waste streams to effluent levels suitable for discharge.

Exhibit 3-3: NCP Criteria for Chemical Separation (Cont.)

NCP Criterion	Evaluation	Performance Data
Compliance with ARARs	• Requirements of RCRA LDRs, CWA, and NRC may apply to the effluent and residual waste.	• Performance data, such as removal efficiencies, must be assessed in relation to pre-remediation concentrations and cleanup standards to determine compliance with ARARs.
Reduction of Radiotoxicity, Mobility, or Volume	• Does not reduce radioactivity or toxicity. • Reduces mobility of contamination through storage or disposal of residuals • Volume occupied by the hazardous or radioactive component is reduced	• MCLs, CWA, and NRC requirements will also apply to treated water. • Ion exchange is expected to remove 65-97% radium and 65-99% uranium.[213] • Chemical precipitation proved 80% uranium removal using ferric sulfate, 92-93% uranium removal using ferrous sulfate; and 95% uranium removal using alum.[214]
Long-Term Effectiveness and Performance	• Demonstrated to reduce contamination of liquid waste-streams, including removal of radionuclides and metals. • Potential threat due to long-term storage of waste. • Continued testing will improve efficiency.	• A monitoring system can be used to record activity, pH, conductivity, and total suspended solids for the processed liquid.

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[213] U.S. Environmental Protection Agency, Office of Research and Development, *Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Waste*, EPA/625/R-93/613, September 1993.

[214] Sorg, Thomas J. "Method for Removing Uranium From Drinking Water," July 1988.

Exhibit 3-3: NCP Criteria for Chemical Separation (Cont.)		
NCP Criterion	**Evaluation**	**Performance Data**
Short-Term Effectiveness	• Potential health and safety risk to workers from off-gases and handling of treatment residuals.	• Ion exchange requires an off-gas treatment system for hydrogen gas. • Ion exchange resin placed in a highly radioactive environment produces radiolytic byproducts.
Implementability	• Applies to liquid waste only. • To operate efficiently, specific conditions for physical and chemical properties of the waste material must be met. • Disposal or storage facilities are needed for resins or residuals.	• Pretreatment required for nonionic forms of waste and to remove solids or competing ions from waste. • Laboratory-scale tests should be conducted to select the best materials and systems specific to each cleanup. • Treatability testing for chemical precipitation should be conducted to determine the proper reagents and dosages for radionuclides.
Cost	• Capital and O&M costs are encumbered with specific treatment conditions and handling of residuals.	• Capital and operating costs for ion exchange range from $5 to $10 per 1000 gallons. • Chemical precipitation capital and operating cost estimates are highly site specific.

PHYSICAL SEPARATION

Physical separation technologies for liquid media separate contaminated media into clean and contaminated fractions by taking advantage of the contaminants' physical properties.

Contaminants are either solvated by the liquid media (i.e., one molecule of the contaminant surrounded by many molecules of the liquid) or are present as microscopic particles suspended in the solution. The physical separation of the radionuclides from the liquid media results in "clean" liquid and a contaminated residue that requires further handling, treatment, and/or disposal. These residuals may take the form of a sludge, filter cake, or carbon adsorption unit. Physical separation technologies can be applied to a variety of liquid media, including groundwater, surface water, and slurried sludge or sediment.

This profile addresses the following technologies: membrane filtration (reverse osmosis and microfiltration), carbon adsorption, and aeration.

3.2 MEMBRANE PROCESSES, CARBON ADSORPTION, AND AERATION

3.2.1 Technology Characterization

Physical separation technologies for liquid media treatment include membrane processes, liquid phase carbon adsorption and aeration. The technologies are ex-situ processes and require the construction and operation of a ground-water extraction and delivery system. They generate a treated effluent waste stream of which the volume and type depend on the technology.

Because there are many similarities among these technologies, discussion about them has been combined for the target contaminant groups, site considerations, and NCP criteria evaluation.

Description

Membrane filtration uses a semipermeable membrane to separate dissolved radionuclides or solid radionuclide particles in liquid media (e.g., groundwater, surface water) from the liquid media itself. Generally, some form of pretreatment (such as filtration of suspended solids) is required in order to protect the membrane's integrity. Water flow rate and pH should be controlled to ensure optimum conditions. The effectiveness can easily be monitored by sampling the effluent and residuals. Two types of membrane processes are reverse osmosis and microfiltration.

Reverse osmosis uses a selectively permeable membrane that allows water to pass through it, but which traps radionuclide ions on the other side of the membrane. Normally, osmotic pressures would draw water to the dissolved ions. But high pressure applied to the solution forces water with lower ion concentrations through the membrane. Reverse osmosis is affected by the size and charge of the ion being treated. Because radium and uranium ions are large and highly charged, reverse osmosis is particularly effective at removing these dissolved radionuclides from contaminated solutions.

Micro and ultra filtration rely on the pore size of the membrane, which can be varied to remove particles and molecules of various sizes. Micro and ultra filtration processes generally work best for separating very fine particles (0.1-0.001 microns) from the liquid. This process is illustrated in Exhibit 3-4.

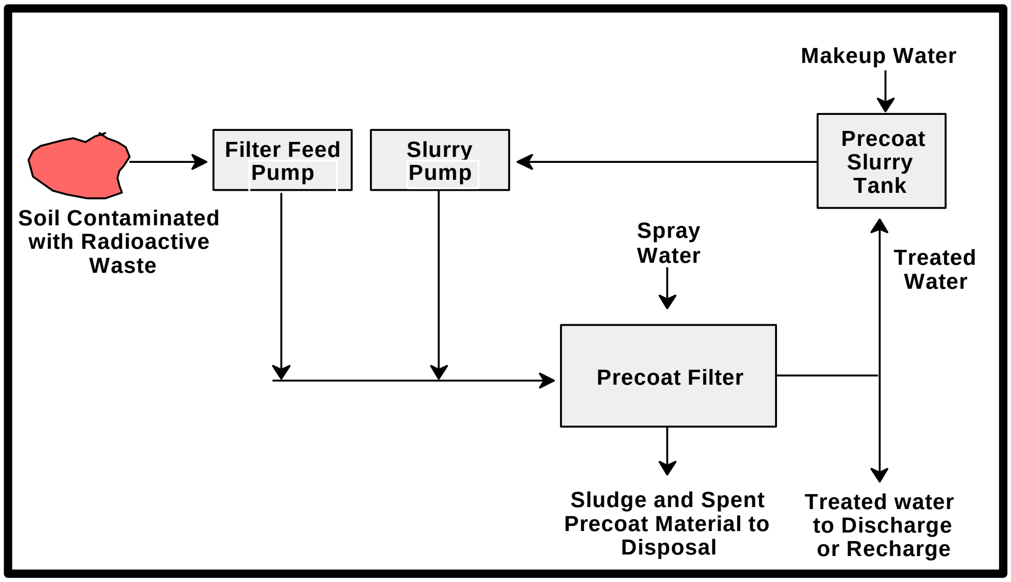

Exhibit 3-4: Microfiltration Diagram

Liquid phase **carbon adsorption** pumps groundwater through a series of vessels containing activated carbon, to which dissolved contaminants adsorb[215] (see Exhibit 3-5). Activated carbon is an effective adsorbent because of its large surface to volume ratio. When the concentration of contaminants in the effluent exceeds a certain level, the carbon can be regenerated in place; removed and regenerated at an off-site facility; or removed and disposed of. Carbon used for metals-contaminated groundwater probably cannot be regenerated, and should be removed and properly disposed of. The two most common reactor configurations for carbon adsorption systems are the pulsed or moving bed and the fixed bed. The fixed bed configuration is the most widely used for adsorption from liquids.[216]

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[215] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, *October 1994*.

[216] *Ibid.*

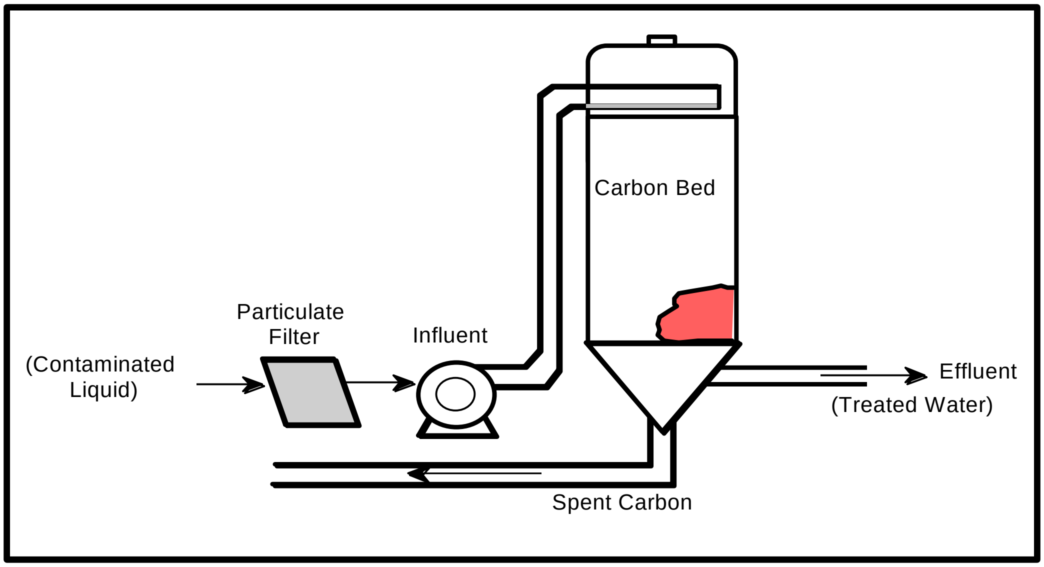

Exhibit 3-5: Carbon Adsorption Diagram

Source: U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide,* Second Edition, *October 1994.*

Aeration injects air into the groundwater, forming bubbles that rise and carry trapped and dissolved contaminants to the water surface.[217] A diffused bubble aeration system has successfully removed radon from drinking water. In this system, an air blower forces air into several treatment tanks. The radon is then stripped from the water and vented outside the treatment area.

Operating Characteristics

Through membrane processes, uranium concentrations of 300 ug/L were reduced by 99 percent in Florida ground-water[218] and initial radium concentrations of 11.6, 13.9 and 13 pCi/L were reduced to <0.1, <0.1 and 1.2 pCi/L, respectively at a site in Illinois.[219] Average flow rates during a pilot test ranged between 15-25L/min. Costs for radium removal were estimated at $1.50 to $3.00 per gallon, but did not include spent-media disposal costs.[220] Reverse osmosis generates a concentrated waste stream containing radionuclides that must be treated further or disposed of.

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[217] U.S. Environmental Protection Agency, *A Citizen's Guide to Air Sparging*, EPA/542/F-92/010, March 1992

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[218] Sorg, T., "Methods for Removing Uranium from Drinking Water", *J. Am. Water Works Assoc.* 80(7):105-11, July 1988.

[219] Clifford, D., Vijjeswarapu W., and Subramoniuan, S., "Evaluating Various Adsorbents and Membranes for Removing Radium from Groundwater", *J. Am. Water Works Assoc*. 80(7):94-104 July 1988.

[220] *Ibid.*

Removal efficiencies for microfiltration have been shown to be greater than 99 percent for uranium, plutonium, and americium with initial concentrations of 35, 30 and 30 pCi/L, respectively. Removal efficiency for gross alpha emitters was 86 percent and 43 percent for radium that had an initial concentration of 30 pCi/L.[221] Treatment costs range from $.50 to $15 per 1000 gallons and depend on the volume to be treated, treatment duration, and contaminant concentrations.[222] Depending on what is fed into the system, the micro/ultra filtration process generates three waste streams: a filter cake of solid material, a filtrate of treated effluent, and a liquid concentrate which contains the dissolved contaminants. The filter cake and/or liquid concentrate require further treatment or disposal. The process time depends on the volume of material to be treated, the contaminants present, and the concentrations of the contaminants.

Carbon adsorption effectively removes contaminants at low concentrations (less than 10 mg/L) from water at nearly any flow rate, and removes higher concentrations of contaminants from water at low flow rates (2-4L/min.). Pretreatment for the removal of solids may be required to prevent the accumulation of suspended solids in the column. Activated carbon has been used to adsorb radon and neutral forms of cobalt-60 and ruthenium-106. Activated carbon has also effectively reduced groundwater uranium concentrations from 26-100 ug/L to < 1 ug/L, the carbon capacity appeared to be limited after several months of operation.[223] Treatment costs range from $0.32 to $1.70 per 1000 liters treated, and depend on the type and concentration of contaminants present and flow rates.[224] Although activated carbon is a well-established technology for removing organic compounds, its use in the removal of inorganic contaminants has not been as widespread due to the low capacity and the difficulty in regenerating spent carbon which subsequently require treatment and disposal. Also, the presence of iron may promote fouling of the carbon.

Aeration’s overall radon removal efficiency ranged from 90 percent to 99.6 percent, with initial radon concentrations in the water ranging from 1,767 pCi/L-86,355 pCi/L.[225] This suggests that radon removal efficiency improves with increased air flow rate and/or contact time. Analysis of stack emissions during the aeration process indicated that the off-gas would need to be diluted 10^4 to 10^5 times to be similar to radon activities found in ambient air. If precipitation of iron and manganese

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[221] U.S. Environmental Protection Agency, *The Superfund Innovative technology Evaluation Capsule*, Filter Flow Technology, Inc., Colloid Polishing Filter Method, EPA/540/R-94/501-a, July 1994.

[222] *Ibid.*

[223] Sorg, T. Methods for Removing Uranium from Drinking Water, J. Am. Water Works Assoc. 80(7):105-11, July 1988.

[224] U.S. Department of Defense, Environmental Technology Transfer Committee, *Remediation Technologies Screening Matrix and Reference Guide*, Second Edition, *October 1994.*

[225] Kinner, N., Malley, J., Clement, J., Quern P. and Schell, G. *Radon Removal Techniques for Small Community Public Water Supplies.* EPA/600/S-2-90/036, November 1990.

occurs during aeration operational problems may result. Raw water quality should therefore be monitored to determine whether pretreatment is required. Treatment cost for this technology was estimated to be $2.14 per 1000 gallon, not including treatment of gas emissions.[226]

Target Contaminant Groups

Membrane processes can treat a variety of waste, including metals and organics, and effectively removes most radionuclides from water. However, tritium cannot be removed easily because of its chemical characteristics.[227] GAC can be used to treat organics, certain inorganics, and radionuclides such as uranium, cobalt-60, and ruthenium-106. Aeration effectively removes volatile organics and radon.

Site Considerations

Groundwater characteristics such as contaminant type and concentration should be well-defined in order to accurately predict system performance and costs. The physical separation technologies can be considered where radionuclide and heavy metal contaminants are associated with suspended solids in a liquid media, or where precipitating agents are available for pretreating the liquid media. Extensive pretreatment may be required to remove contaminants that will damage the membrane or activated carbon, or will precipitate in the aeration system. All technologies require a groundwater extraction and delivery system and adequate power to maintain the treatment system. Also, adequate venting and/or an air treatment system are required for aeration.

3.2.2 NCP Criteria Evaluation

Protection of Human Health and the Environment

Since these technologies remove the contaminants from the liquid media, it eliminates the migration and exposure pathways to human and environmental receptors, thereby protecting human and environmental health. However, site workers may be exposed to health risks due to the potential exposure to both untreated groundwater and the residual waste stream (e.g., filter cake, liquid concentrate or spent carbon). If waste materials are treated off site, health risks may be associated with in the transport and subsequent treatment and/or disposal. In addition, there is a potential risk of exposure to radon gas emissions from the aeration process and/or disposal.

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[226] *Ibid.*

[227] U.S. Environmental Protection Agency, *The Superfund Innovative technology Evaluation Capsule*, Filter Flow Technology, Inc., Colloid Polishing Filter Method, EPA/540/R-94/501-a, July 1994.

Compliance with ARARs

The treated effluent must comply with Clean Water Act (CWA) requirements and any local NPDES requirements prior to discharge to the environment. Air emissions from the aeration process must comply with Clean Air Act (CAA) requirements. Compliance with other ARARs must be determined on a site specific basis.

Long-Term Effectiveness

Although past applications and pilot scale tests indicate consistent and successful removal of radionuclide, heavy metal, and organic contaminants from water, more studies are needed to assess how effectively radionuclides can be removed from liquid media. However, since these technologies remove contaminants from liquid media, they eliminate migration and exposure pathways. Also, the volume of material requiring additional management (filter cake and liquid concentrate) is usually much lower than the volume of treated media. This volume reduction also reduces the potential for exposure to these contaminants. Ongoing monitoring and maintenance of the treatment system is required to ensure long-term effectiveness.

Reduction of Radiotoxicity, Mobility, or Volume

These technologies effectively remove contaminants from liquid media and concentrate them in residual filter cakes, liquid concentrates, or spent carbon; they also reduce the mobility of these contaminants. However, the contaminants' toxicity is not reduced by these technologies and residuals require further treatment and/or disposal. In the aeration process, mobility of radon is greatly reduced when radon gas emissions are captured through off-gas filtration.

Short-Term Effectiveness

For groundwater treatment, closed systems can be used to prevent any gaseous emissions (with the exception of the aeration process). Depending on the contaminated volume and how the groundwater is used, prevention measures such as institutional controls may be necessary for the duration of the treatment process. Radioactive materials in the waste stream pose a risk to onsite workers or other receptors if the materials are transported off site for further treatment and/or disposal. In addition, some contaminants may not be effectively removed by this process and may remain in the treated effluent.

Implementability

Previous applications and pilot tests indicate that these technologies can be readily implemented, with limited site preparation. However, extraction and delivery systems must be in place and adequate power must be available to maintain the treatment system. Chemical characteristics of the contaminants must be known prior to implementation. In many cases pretreatment may be required to ensure the treatment's effectiveness. In addition, residual waste may require further treatment and/or disposal. Air treatment may be required with aeration to address radon emissions.

Cost

Costs of using these technologies are driven by the capital cost of the equipment and the cost of utilities during operation. O&M costs decrease as the duration of treatment increases, indicating minimal maintenance costs.[228] Complications such as contaminant fouling of the membrane or the activated carbon result in higher costs. Pretreatment, if necessary, also will affect cost. In addition, further treatment and disposal of the waste (e.g. filter cake, liquid concentrate, spent carbon, or gas emissions) will raise costs.

3.2.3 Physical Separation Summary

Membrane processes, activated carbon and aeration have been applied to ground-water contaminated with heavy metals and organic contaminants and have been tested at the pilot scale for radionuclide-contaminated media. In general, these technologies have effectively removed these contaminants in ground-water; however further development is needed to assess their effectiveness with radionuclide-contaminated liquid media. The following factors may limit the applicability of this separation technology:

- technologies do not reduce radiotoxicity;
- residuals are contaminated and require further treatment and/or disposal;
- pretreatment may be required;
- an air treatment system may be required with aeration to address radon gas emissions.

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[228] *Ibid.*

Exhibit 3-6 summarizes the data and analyses presented in this profile, and can be used to compare these and any other technologies.

Exhibit 3-6: NCP Criteria for Physical Separation

NCP Criteria	Evaluation	Performance Data
Overall Protectiveness	• Not yet fully demonstrated for radioactive contamination • Site workers are at potential risk from residual waste. Other receptors are at risk if the waste materials are transported off site for treatment and/or disposal.	• Peliminary studies indicate protectiveness is achieved.
Compliance with ARARs	• CWA and CAA requirements may apply to the residual waste	• Performance data, such as removal efficiencies, must be assessed in relation to preremediation concentrations and cleanup standards to determine compliance with ARARs.
Long-Term Effectiveness and Permanence	• Further development is required to ensure effectiveness with radionuclide-contaminated water. • Residual waste requires further treatment and/or disposal.	• Pilot scale tests and studies indicate consistent and successful separation of contaminants from water. • Residual waste is present in filter cakes, liquid concentrates, spent carbon or gas emissions.
Reduction of Radiotoxicity, Mobility, or Volume	.• Does not reduce radioactivity or toxicity. • Reduces mobility of contamination through storage or disposal of residuals • Volume occupied by the hazardous or radioactive component is reduced	• Contaminants are concentrated in residual filter cakes and/or liquid concentrates or spent carbon, reducing the volume and mobility of the contaminants. In the case of aeration, the mobility of the contaminants is reduced when captured in off-gas filtration system.

Exhibit 3-6: NCP Criteria for Physical Separation (Cont.)

NCP Criteria	Evaluation	Performance Data
Short-Term Effectiveness	• Potential risk to onsite workers from residual waste.	• Residual waste requires further treatment and/or disposal.
Implementability	• Variations of these technologies have been successfully tested at the pilot scale. • A groundwater extraction and delivery system and adequate power are needed to maintain the treatment system.	• Numerous treatment systems are being tested for addressing radionuclide-contaminated liquid media.
Cost	• Capital and O&M costs vary for these technologies and depend on the type of treatment system and volume of groundwater to be treated.	• O&M costs decrease as the duration of treatment increases. • Waste disposal and pretreatment increase costs.

Appendix A

RADIOACTIVE CONTAMINATION: BASIC CONCEPTS & TERMS

RADIOACTIVE CONTAMINATION:
BASIC CONCEPTS & TERMS

Types of Radioactive Waste

Although there are hundreds of known radioactive isotopes, only a small fraction of these are likely to be seen at contaminated sites. This effect is due to the fact that many isotopes are nearly impossible to create without exotic scientific equipment and many others have extremely short half-lives and therefore do not exist long enough to make it outside the facility where they were created. Among the radioactive isotopes likely to be encountered in disposal and remediation sites are naturally occurring radioactive material (NORM) such as uranium-238, thorium-232, thorium-230, radium-226, and radon -222; radioactive fission products such as cesium-137 and strontium-90; and products of neutron bombardment such as cobalt-60. The radioactive isotopes in place at one particular site will depend on the source of the material spilled or disposed there.

Radioactive isotopes originate from both manufactured and natural sources. Nuclear reactors and particle accelerators, for example, can generate radioactive isotopes by forcefully de-stabilizing their nuclei in a process known as fissioning (splitting of the atom). Fissioning can split larger atoms, such as uranium or plutonium, into multiple, smaller, radioactive elements. Reactors also can create radioactive isotopes from stable elements by causing additional neutrons to be absorbed into their nuclei, which may result in an unstable (energy-emitting) configuration. This is called neutron activation. Additionally, particle accelerators, cyclotrons, and similar machines can create radioactive isotopes from stable elements by bombarding their nucleus with a variety of particles. This process is often used to create medical isotopes.

The development and use of radioactive materials inevitably results in the production of radioactive waste. The treatment and disposal of the potentially harmful waste is a matter of much concern and controversy. Again, the management of this waste had led to the development of definitions and authorities to assign responsibility for their handling. Exhibit A-1 is a summary of categories and definitions, and the authority from which it is cited. The technologies presented in this Guide are most likely to be applicable to low-level, NARM/NORM, and mixed wastes.

Exhibit A-1: Statutory and Regulatory Categories of Radioactive Waste

Category of Radioactive Waste	Definition	Citation
High-Level Waste (HLW)	Irradiated reactor fuel; liquid waste resulting from the operation of the first-cycle solvent extraction system, or equivalent, and the concentrated waste from subsequent extraction cycles, or equivalent, in a facility reprocessing irradiated reactor fuel; and solids into which such liquid waste has been converted.	Nuclear Waste Policy Act [10 CFR 60]
Low-Level Waste (LLW)	Radioactive waste not classified as high-level waste, transuranic waste, spent fuel, or byproduct materials such as uranium and thorium mill tailings.	Low-Level Radioactive Waste Policy Act [10 CFR 61]
Class A, B, C, and Greater-Than-Class-C (GTCC) Wastes	LLW categorized according to its radionuclide concentration and half-life. In general, Class A waste has the lowest concentrations of particular radionuclides. Class B and C wastes contain radionuclides in higher concentrations. GCC waste exceeds the concentration limits established for Class C waste.	10 CFR 61
Transuranic Waste (TRU Waste)	Waste containing elements with atomic numbers greater than 92 and half-lives greater than 20 years, in concentrations greater than 100 nCi/g of alpha-emitting isotopes.	40 CFR 191
AEA Waste	Waste containing or contaminated with source, byproduct, or special nuclear material.	Atomic Energy Act
NARM/NORM Wastes	Waste containing or contaminated with any radioactive material produced as a result of nuclear transformations in an accelerator, and any nuclide that is radioactive in its natural physical state (i.e., not anthropogenic), excluding source and special nuclear material.	State authority
Mixed Waste	Hazardous waste as defined by RCRA containing or contaminated with source, byproduct, or special nuclear material.	Federal Facilities Compliance Act of 1992

Nature of Radioactivity

Nearly all elements (e.g., oxygen, carbon) in nature can be found in a variety of nuclear compositions. Isotopes, which are different forms of an element, have the same atomic number, but different atomic mass. That is, their nuclei have the same number of protons but different numbers of neutrons. Carbon, for example, contains six protons in its nucleus but may have either six (carbon-12), seven (carbon-13), or eight (carbon-14) neutrons.

Isotopes that are unstable will undergo radioactive decay in order to reach a more stable nuclear configuration. These unstable isotopes are called radioactive isotopes. Radioactive isotopes spontaneously emit energy and particles in the form of alpha (positively charged) or beta (negatively charged) particles, and/or gamma rays (which are similar to X rays in behavior) as part of the radioactive decay process. This emitted or expended energy—radiation—and its spontaneous activity (radioactivity) form its potentially creative or destructive power. Carbon-14, for example, is a radioactive isotope that will decay by emitting a beta particle and form nitrogen-14.

An <u>alpha particle</u> is a positively charged particle, emitted from the nucleus of a decaying radioactive atom (alpha emitters), containing two neutrons and two protons identical to the nucleus of a helium atom. Because alpha particles are “massive” on an atomic scale, they can be easily shielded and are stopped by a sheet of paper. Thus, they do not penetrate human skin, but they can be dangerous when the alpha emitting atom is inhaled, or if the atom enters the body through a cut, food, or water, and permitted to decay inside the body. The exposure to alpha particles usually occurs through internal pathways (ingestion and inhalation).

A <u>beta particle</u> is essentially an electron emitted from the nucleus of a decaying atom. Beta particles are less massive than alpha particles but are also relatively easy to shield. Some beta particles can penetrate skin. As with alpha emitters, beta emitters cause the most damage when the atom is ingested and allowed to decay inside the body. The exposure to beta particles usually occurs mainly through internal pathways and some may occur through external pathways.

<u>Gamma rays</u> are similar to x rays (although they are produced differently); however, gamma rays are of higher energy and thus have stronger penetrating power. Gamma rays can penetrate and damage critical organs in the body and are the most difficult of the radiation types to shield. The exposure to gamma rays is usually of concern through external pathways but it can also occur through internal pathways.

Included among the naturally occurring radioactive elements are uranium-238, carbon-14, hydrogen-3 (tritium), thorium-230, radium-226, radon-222, and potassium-40. In addition, radioactive elements can be created as products of the decay of other radioactive isotopes. When the nucleus of uranium-238 decays, for example, it produces thorium-234 (radioactive) which, in turn, decays to become protactinium-234. This process of decay continues until a stable element is reached. Sequences such as these are called <u>decay chains</u>. The radioactive decay is usually a first order reaction where disintegration of radionuclide is proportional to the activity present. Exhibit A-2 presents the radioactive decay process for the uranium (U) series. Uranium-238 decays to a final stable atom of lead (Pb^{206}). The half-life and decay energy for each of the newly formed decay products is shown in Exhibit A-3.

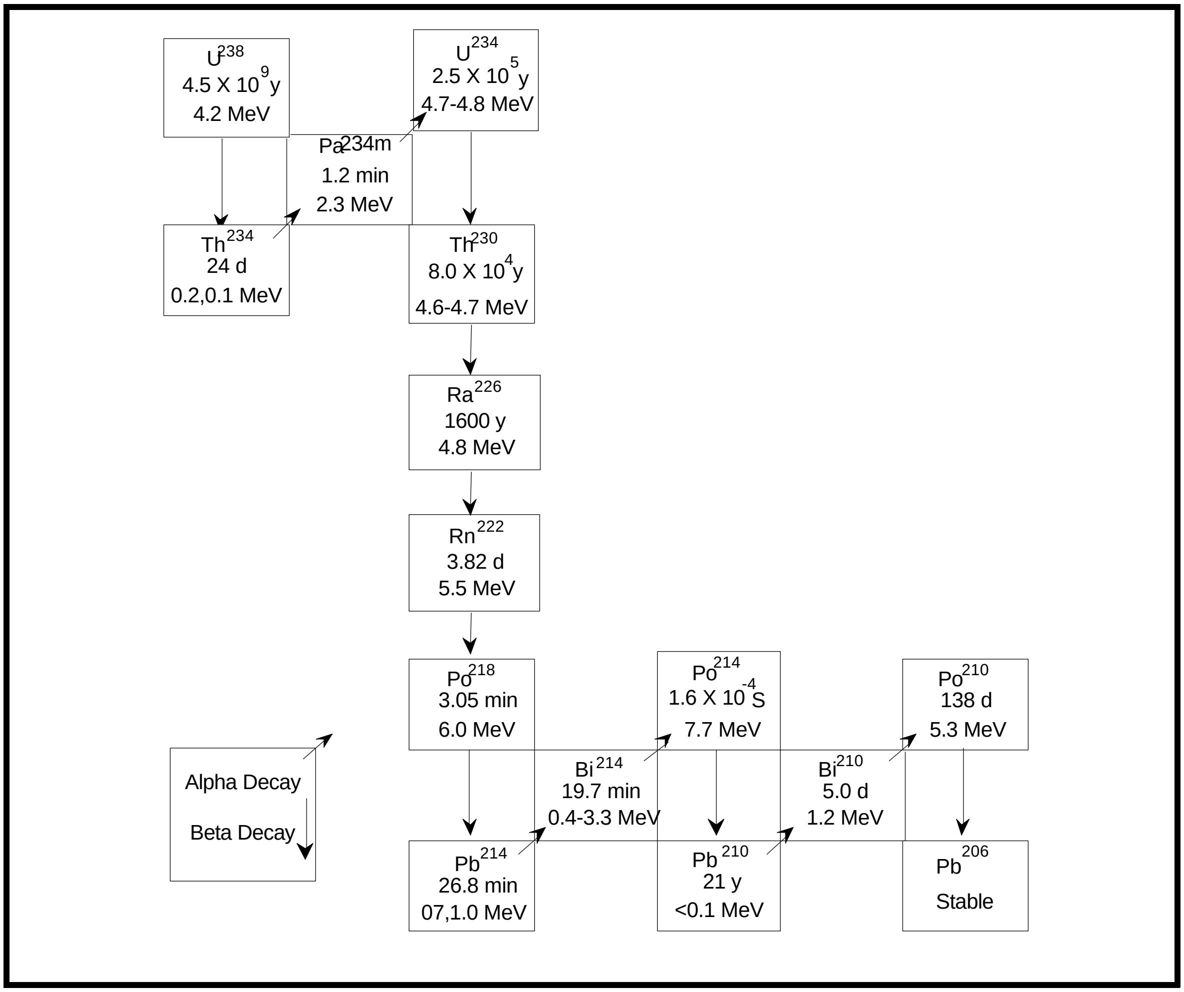

Exhibit A-2: Principal Decay Scheme of the Uranium Series

Each radioactive isotope has a specific rate of decay, known as its <u>half-life</u>, which is the time required for the isotope to decay to half of its original quantity. Carbon-14 has a half-life of 5,730 years, meaning that in that time, one gram of carbon-14 will become one-half gram of C-14 (the other one-half gram would have decayed to nitrogen-14 through beta decay of carbon-14 atoms). In an additional 5,730 years, the amount will be reduced to 0.25 grams of carbon-14 (with 0.75 grams having been transformed to nitrogen-14). Half-lives are unique to each radioactive isotope. Exhibit A-3 presents the half-lives and average radiation energies for alpha, beta and gamma radiation for some of the radionuclides found at Superfund sites.

Exhibit A-3: Radiological Characteristics of Selected Radionuclides Found at Superfund Sites[a]

Radio-		Average Radiation Energies (MeV/decay)[b]		
Nuclide	Half-life[c]	Alpha	Beta	Gamma
Am-241	4.32×10^{2} y	5.57×10^{0}	5.21×10^{-2}	3.24×10^{-2}
Am-243	7.38×10^{3} y	5.36×10^{0}	2.17×10^{-2}	5.61×10^{-2}
C-14	5.73×10^{3} y	--	4.95×10^{-2}	--
Cs-134	2.06×10^{0} y	--	1.64×10^{-1}	1.55×10^{0}
Cs-135	2.30×10^{6} y	--	6.73×10^{-2}	--
Cs-137	3.00×10^{1} y	--	1.87×10^{-1}	--
H-3	1.23×10^{1} y	--	5.68×10^{-3}	--
K-40	1.28×10^{9} y	--	5.23×10^{-1}	1.56×10^{-1}
Pu-238	8.77×10^{1} y	5.59×10^{0}	1.06×10^{-2}	1.81×10^{-3}
Pu-239	2.41×10^{4} y	5.24×10^{0}	6.74×10^{-3}	8.07×10^{-4}
Pu-240	6.54×10^{3} y	5.24×10^{0}	1.06×10^{-2}	1.73×10^{-3}
Pu-241	1.44×10^{1} y	1.22×10^{4}	5.25×10^{-3}	2.55×10^{-6}
Pu-242	3.76×10^{5} y	4.97×10^{0}	8.73×10^{-3}	1.44×10^{-3}
Ra-226	1.60×10^{3} y	4.86×10^{0}	3.59×10^{-3}	6.75×10^{-3}
Ra-228	5.75×10^{0} y	--	1.69×10^{-2}	4.14×10^{-9}
Th-230	7.70×10^{4} y	4.75×10^{0}	1.42×10^{-2}	1.55×10^{-3}
Th-232	1.41×10^{10} y	4.07×10^{0}	1.25×10^{-2}	1.33×10^{-3}
U-234	2.44×10^{5} y	4.84×10^{0}	1.32×10^{-2}	1.73×10^{-3}
U-235	7.04×10^{8} y	4.47×10^{0}	4.92×10^{-2}	1.56×10^{-1}
U-238	4.47×10^{9} y	4.26×10^{0}	1.00×10^{-2}	1.36×10^{-3}

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[a] Source ICRP 1983.
[b] Computed as the sum of the products of the energies and yields of individual radiations.
[c] Half-life expressed in years (y).

Basic Terms, Types and Units of Radiation

Basic Terms

Activity

The number of nuclear transitions occurring in a given quantity of radioactive material per unit time.

Background Radiation

The radiation in man’s natural environment, including cosmic rays and radiation (which may vary from location) from the naturally radioactive elements, both outside and inside the bodies of humans and animals. It is also called natural radiation.

Decay Constant

The fraction of the amount of a radionuclide that undergoes transition per unit time.

Dose

A general term denoting the quantity of radiation or energy absorbed. For special purposes it must be appropriately qualified. If unqualified, it refers to absorbed dose.

Ion

Atomic particle, atom, or chemical radical bearing an electric charge, either negative or positive.

Ionization

The process of adding one or more electrons to, or removing one or more electrons from, atoms or molecules, thereby creating ions. High temperatures, electrical discharges, or nuclear radiations can cause ionization.

Ionizing radiation

Ionizing radiation is radiation with enough energy so that during an interaction with an atom, it can remove tightly bound electrons from their orbits, causing the atom to become charged or ionized. Examples are gamma rays and neutrons.

Isotope

One of several nuclides having the same number of protons in their nuclei, and hence having the same atomic number, but differing in the number of neutrons, and therefore, in the mass number. Almost identical chemical properties exist between isotopes of a particular element. The use of this term as a synonym for nuclide is to be discouraged.

Non-ionizing radiation

Nonionizing radiation is radiation without enough energy to remove tightly bound electrons from their orbits around atoms. Examples are microwaves and visible light.

Radiation

Radiation is energy in transit in the form of high speed particles and electromagnetic waves. We encounter electromagnetic waves every day. They make up our visible light, radio and television waves, ultra violet (UV), and microwaves with a spectrum of energies. These examples of electromagnetic waves do not cause ionizations of atoms because they do not carry enough energy to separate molecules or remove electrons from atoms.

Radioactive Decay

The process by which a spontaneous change in nuclear state takes place. This process is accompanied by the emission of energy in various specific combinations of electromagnetic and corpuscular radiation and neutrinos.

Radioactivity

Radioactivity is the spontaneous transformation of an unstable atom and results in the emission of energy. This process is referred to as a transformation, a decay or a disintegrations of an atom.

Radiotoxicity

Potential of an isotope or mass of radioactive material to cause adverse health effects to living tissue by absorption of energy from the decay of the radioactive material.

Common Units of Radiation

Becquerel (Bq)

The Becquerel is a unit used to measure a radioactivity. One Becquerel is that quantity of radioactive material that will have 1 transformations in 1 second. Often radioactivity is expressed in larger units like: thousands (kBq), millions (MBq) or even billions (GBq) of becquerels. As a result of having 1 Becquerel being equal to one transformation per second, there are 3.7 X 10^{10} Bq in 1 curie.

Curie (Ci)

The curie is a unit used to measure a radioactivity. One curie is that quantity of a radioactive material that will have 37,000,000,000 transformations in 1 second. Often radioactivity is expressed in smaller units like: thousandths (mCi), millionths (uCi) or even billionths (nCi) of a curie. The relationship between becquerels and curies is: 3.7 X 10^{10} Bq in 1 curie.

Rad (radiation absorbed dose)

The rad is a unit used to measure a quantity called absorbed dose. This relates to the amount of energy actually absorbed in some material and is used for any type of radiation and any material. One rad is defined as the absorption of 100 ergs per gram of material. The unit rad can be used for any type of radiation, but it does not describe the biological effects of the different radiations.

Rem (roentgen equivalent man)

The rem is a unit used to derive a quantity called equivalent dose. This relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is often expressed in terms of thousandths of a rem, or mrem. To determine equivalent dose (rem), you multiply absorbed dose (rad) by a quality factor (Q) that is unique to the type of incident radiation.

Roentgen

The roentgen is a unit used to measure a quantity called exposure. This can only be used to describe an amount of gamma and X rays, and only in air. One roentgen is equal to depositing 2.58 E-4 coulombs per kg of dry air. It is a measure of the ionizations of the molecules in a mass of air. The main advantage of this unit is that it is easy to measure directly, but it is limited because it is only for deposition in air, and only for gamma and x rays.

Appendix B

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BIBILOGRAPHY

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