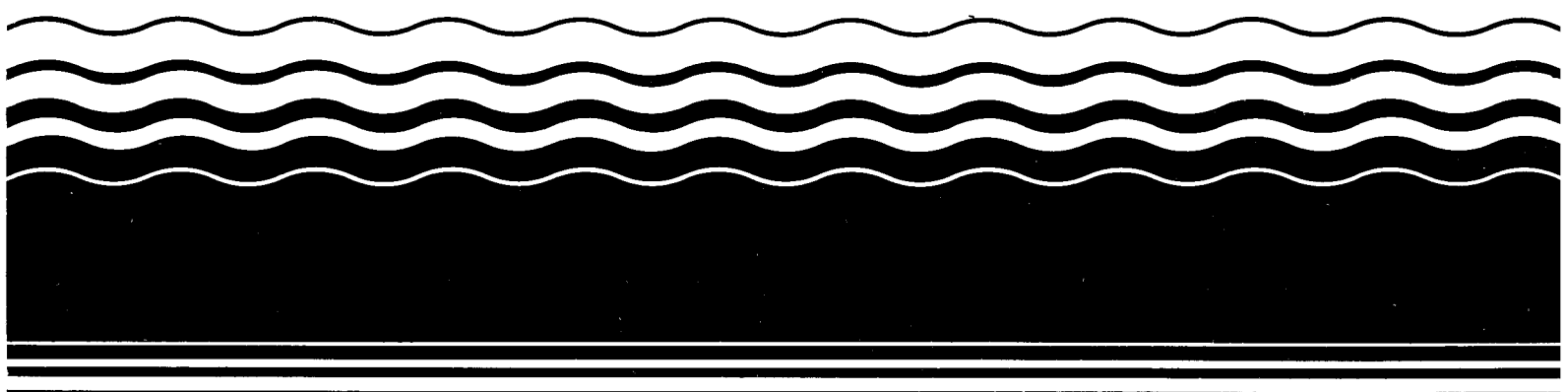

Superfund



Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites



Technological Approaches to the Cleanup of Radiologically Contaminated Superfund Sites

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Abstract

This report identifies technologies that may be useful in removing or stabilizing radiological contamination at those uncontrolled hazardous waste (Superfund) sites that contain radionuclides. The radioactive materials at some Superfund sites consist primarily of waste from radium, uranium, and thorium processing. Twenty existing Superfund sites are known to contain radionuclides, along with seventy-one sites managed by the Department of Energy. This report addresses remediation of contaminated soils; it does not address remediation of contaminated buildings or ground water. This report is not intended to provide any legal or policy basis for the selection or use of technology for cleanup of a hazardous waste site.

Sites contaminated with radionuclides pose a unique problem because, unlike organic wastes, radionuclides cannot be destroyed by physical or chemical means; they can only decay through their natural process. Thus, alteration or remediation of the radioactive decay processes, thereby changing the fundamental hazard, is not possible. Several technologies have potential for eliminating or stabilizing radionuclides at radiologically contaminated sites. These include both on-site and off-site disposal, on-site treatment, radon control, chemical extraction, physical separation, and combined physical separation and chemical extraction technologies. Applicability of these technologies is controlled by site-specific factors, so their suitability must be determined on a site-by-site basis.

Issues of significant concern in attempting to apply remedial techniques include disposal siting, handling of concentrated residuals, public reaction, and cost.

Many of the technologies have not been satisfactorily demonstrated. There is a need for additional assessment studies. Significant research and development activities, including bench-scale and pilot-scale studies, would be necessary prior to full-scale mobilization for site cleanups. These technologies should be evaluated for implementation as they may have the potential for significantly improving cleanup efforts.

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Executive Summary

Introduction

This document identifies potential technologies that possibly can be applied in the control and remediation of radioactive contamination at Superfund sites. This report provides a discussion of the technologies; it does not give a detailed critical evaluation of them. The report does not include in-depth analyses that would be needed to determine the applicability of any of these technologies at a particular site.

The report only addresses treatment and disposal of radiologically contaminated soils, and radon control. It does not address, for example, remediation of radiologically contaminated buildings. The report also does not address treatment of radiologically contaminated ground water, which is of concern at some Superfund sites.

The radioactive materials at many Superfund sites are by-products of uranium, thorium, and radium processing in the form of tailings, contaminated buildings and equipment, and stream sediments.

The primary public health threats from the radioactive materials are through inhalation of radon and radon progeny, external whole body exposure to gamma radiation, and ingestion of radionuclides through food and water. Radon and radon progeny are continuously produced through the decay and decomposition of uranium, thorium, and radium. These hazards will persist throughout the entire decay time if no remedial action is taken. These hazards could include the increased risk of cancers in the exposed whole body and may also increase the risk of genetic damage that may continue to cause inheritable defects in future generations.

It should be noted that the radioactive contaminants are not altered or destroyed by treatment technologies. The volume of contaminated material may be reduced, but the concentration of the contaminants will be much higher in the reduced volume. Some type of containment and/or burial is the only ultimate remedy for materials contaminated at levels above those considered safe for exposure.

Table A on the following page shows the state of the art of the various disposal, on-site treatment, radon

control, chemical extraction, physical separation, and combined physical separation and chemical extraction technologies that are discussed in this report. Since none of the chemical extraction and physical separation technologies has been used in a site remediation situation, their application must be approached cautiously.

Significant research and development activities would be necessary prior to full-scale mobilization for site cleanup. The same holds true for solidification or stabilization processes. Only excavation and land encapsulation have been used to remediate radiologically contaminated sites; ocean disposal has been used for disposal of low level radioactive wastes.

Remediation Sites

Twenty sites that contain man-made radioactive wastes are on or are proposed for inclusion on the National Priorities List (NPL). These Superfund sites are described briefly in Appendix B of this document. (Information provided is accurate as of December 1987.) The sites contain tailings piles and redistributed tailings, solid waste landfills, hazardous waste landfills, fabrication plants and laboratories, and contaminated ground water. Remedial investigation and feasibility studies (RI/FS) have been completed on eight sites and are underway on seven sites. Remediation at none of these sites has been completed. However, the Department of Energy (DOE) has completed remedial actions at vicinity properties associated with DOE NPL sites.

The DOE cleanup projects, which also are described in Appendix B, mainly stem from DOE's inherited responsibilities in the area of nuclear materials production. DOE has four major cleanup projects:

- (1) Formerly Utilized Sites Remedial Action Project (FUSRAP) - 29 sites;
- (2) Uranium Mill Tailings Remedial Action Project (UMTRAP) - 24 sites;
- (3) Grand Junction Remedial Action Project (GJRAP) - 1 site; and
- (4) Surplus Facilities Management Program (SFMP) - 17 sites.

Table A. State of the Art of Remediation Technologies

Technology	Laboratory Testing	Bench Scale Testing	Pilot Scale Testing	Field Demonstration with Radioactive Material	Radiologically Contaminated Site Remediation	Remarks
<i>On-site Disposal</i>						
- Capping				x	x	
- Vertical barriers						
<i>Off-site Disposal</i>						
- Land encapsulation				x	x	
- Land spreading				x		Land spreading of low-level radium sludge from drinking water is an allowed policy in Illinois
- Underground mine disposal				x		DOE currently working on mined repository for radioactive waste
- Ocean disposal				x		Stringent regulations for radioactive waste
<i>On-site Treatment</i>						
- Stabilization or solidification		x		x		Proposed by DOE for low-level radioactive waste
- Vitrification		x		x		Field testing by ORNL
<i>Radon Control</i>						
- In homes					x	As a temporary and interim measure
- ESP			x	x		
- Areal control			x	x		
<i>Chemical Extraction</i>						
- With water	x	x				
- With inorganic salts	x	x				
- With mineral acid	x	x	x	x (from ores)		Used in extraction of radium, thorium, and/or uranium
- With complexing agents	x	x	x	x (from ores)		Used in extraction of uranium
<i>Physical Separation</i>						
- Screening			x	x (from ores)		Used in extraction of radium, thorium, and/or uranium
- Classification			x	x (from ores)		Used in extraction of radium, thorium, and/or uranium
- Gravity concentration			x	x (from ores)		Used in extraction of radium, thorium, and/or uranium
- Flotation		x	x	x (from ores)		Used in extraction of radium, thorium, and/or uranium
<i>Combined physical separation and chemical extraction</i>						
- Soil washing and physical separation		x	x			Pilot-plant development and testing needed for radioactive wastes
- Separation and chemical extraction			x			Various portions of the process have been developed for extraction of uranium from ores. Pilot-plant testing and development needed for radioactive waste
- Separation, washing, and extraction			x			Significant bench-scale and pilot-plant testing needed for radioactive waste

Current DOE projects also involve the cleanup of thousands of vicinity properties, about 4000 in GJRAP alone. The Grand Junction Remedial Action Project has excavated and moved contaminated material to an interim storage site from approximately 700 vicinity sites and is currently evaluating alternatives for remediation of the interim storage site. To date, seven sites administrated by DOE under the FUSRAP project have been remediated. Three of the FUSRAP sites are also on the NPL. The SFMP includes over 30 currently active projects. Two of the SFMP sites are on the NPL.

In addition, DOE's Office of Defense Programs (ODP) has a program similar to SFMP for its sites. ODP conducts selected remedial decontamination activities as required at facilities under their jurisdiction.

In most remedial actions conducted to date, the radioactively contaminated material has been excavated and contained in either permanent or temporary above-ground containment facilities. These facilities have been designed to include perimeter air monitoring, surface water runoff collection and containment features, and ground water monitoring devices.

All methods used to accomplish remedial action on a site contaminated with radionuclides will result in waste materials that require disposal or storage. The final disposal of these waste materials is the single largest problem in remedial action.

Some of the Superfund sites contain various types of hazardous wastes, and the radioactive portion may pose a relatively minor problem. The presence of other hazardous materials may complicate remediation of the radioactive portion of the waste and vice-versa.

Section 121 of CERCLA mandates that remedies must be protective, utilize a permanent solution and alternative treatment technologies or resource recovery options to the maximum extent practicable, and be cost effective. In addition, cleanup standards for remedial actions must meet any applicable or relevant and appropriate requirements (ARARs).

Standards developed under Section 275 of the Atomic Energy Act and Section 206 of the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978 may be applicable or relevant and appropriate on a site-specific basis to the cleanup of radiologically contaminated Superfund sites. The EPA promulgated 40 CFR 192, Health and Environmental Protection Standards for Uranium Mill Tailings in January 1983 under authority of these Acts. The pertinent standards are contained in 40 CFR 192.12, 192.32, and 192.41, and deal with the acceptable levels of radioactivity in residual materials and radiation emission levels from them, and with disposal requirements. The disposal

requirements include a design life of at least 200 years, and preferably 1,000 years where the latter is reasonably achievable. However, standards are applicable to uranium mill tailings only. Relevance and appropriateness must be determined according to specific site conditions.

Disposal

Disposal can be in one of two categories: on-site disposal or off-site disposal. Applicability of these methods to Superfund sites is controlled by site-specific factors; therefore, their usefulness must be determined on a site-by-site basis.

On-Site Disposal

Two methods are available for on-site disposal. These may be applied in situ. They are:

- Capping
- Vertical barriers

Capping is simply covering the contaminated site with a thick layer of low-permeability soil. The design would be chosen to: (1) attenuate the gamma radiation associated with all the radionuclides present, (2) protect the ground water and 3) provide reasonable assurance that release of radon from residual radioactive material to the atmosphere will not exceed acceptable limits. Capping has the advantages of relatively low cost, ease of application, and having been used for remediating radiologically contaminated sites.

Capping has certain drawbacks. It does not eliminate the source of radioactivity; this limits further use of the site. The cap must be maintained as long as the contaminant exists at the site. A cap must not be penetrated for construction or installation of structures and utility hardware. Therefore, existing structures must be removed before capping. Also, horizontal migration of the radionuclides in ground water could still occur.

Vertical subsurface barriers (barrier walls) could serve as barriers to horizontal migration of radionuclides, but perhaps more important, as barriers to the horizontal movement of ground water that may be contaminated with radionuclides. Vertical barriers are relatively simple to install. They perhaps could serve as the container walls for extraction techniques. Disadvantages include the difficulty of obtaining truly low permeability and the possibility of material incompatibility with waste chemicals. Before attempting the installation of a barrier wall, detailed data are required on the physical and chemical characteristics of the soil.

Off-Site Disposal

Off-site disposal can be considered for either temporary storage or permanent disposal. The purpose would be to limit the exposure of people and the environment to the radionuclide. This method can be applied to both untreated materials and materials that have been modified through a volume reduction process. The waste materials could be treated before disposal to reduce their volume or to stabilize them so that they may be transported more easily. Four off-site disposal methods are briefly described in this report:

- Land encapsulation
- Land spreading
- Underground mine disposal
- Ocean disposal

Land encapsulation, either permanent or temporary, has been the disposal method most used so far for low-level radioactive waste materials. Land encapsulation on site can also occur, but this may not be applicable in all situations. It can be as simple as excavating the contaminated material and, without further treatment, hauling it to a secure site designed for land encapsulation. The containment structure technology has been used to remediate radiologically contaminated sites. This technology was originally developed for the disposal of hazardous wastes.

Joint NRC-EPA Design Guidelines and Combined NRC-EPA Siting Guidelines for Disposal of Commercial Mixed Low-Level Radioactive and Hazardous Waste provide guidance on land encapsulation siting and design where chemical contamination is also a problem (see Appendix A).

Selecting a site for a new facility or finding an existing site that will accept the waste can be very difficult. In addition, the problems of handling and transporting the waste must be considered. If the radioactive portion is first concentrated, as in chemical extraction and physical separation, additional disposal issues could result due to higher levels of radioactivity in the concentrated waste. Advantages of land encapsulation include the relative maturity of the technology, the complete removal of the waste from the affected site, and the relative simplicity of the prerequisite information needs.

Land spreading is a technology that has been considered for radiologically contaminated wastes. This technology involves excavation of the contaminated material, transporting it to a suitable site, and spreading it on unused land, assuring that radioactivity levels approach the natural background level of these materials when the operation is completed.

Land spreading might be more appropriate for dry, granular tailings and soils. It would likely be

inappropriate for materials contaminated with both radioactive and nonradioactive hazardous wastes. Another similar method is blending with clean soil prior to land spreading.

Underground mine disposal could provide secure and remote containment. Disposal in underground mines, either new or existing, could be costly. The radiologically contaminated waste could be excavated and transported without treatment to the mine site. Alternatively, it could be pretreated for volume reduction or solidified to facilitate transport and placement.

There would be a tradeoff between costs for treatment or solidification and costs for transportation and placement. Transportation costs and associated risks need to be researched further. Movement of radionuclides into ground water must be considered and prevented.

Ocean disposal could be an alternative to land-based disposal options. This alternative should only be evaluated for low level mill tailing wastes and not considered for enhanced radioactive materials or concentrated residuals.

On-Site Treatment

Two methods are available for treating radiologically contaminated wastes so that the radioactive contaminants may be immobilized. These are:

- Stabilization or solidification
- Vitrification

Stabilization or solidification immobilizes radionuclides (and could reduce radon emanation) by trapping them in an impervious matrix. The solidification agent--for example, Portland cement, silica grout, or chemical grout--can be injected directly into the waste mass or the waste can be excavated, mixed, and replaced. It offers the opportunity to leave the waste materials on site in an immobilized state. It may be used as additional security for a waste mass that will be capped. The presence of other hazardous chemicals could interfere with some solidification processes. Although the radionuclides are not removed in this process, their mobility and spread in the environment are restrained.

Vitrification is another process that can immobilize radioactive contaminants by trapping them in an impervious matrix. The in situ process melts the waste materials between two or more electrodes, using large amounts of electricity while doing so. The melted material then cools to a glassy mass in which the radionuclides are trapped.

Volatilization of waste substances must be contended with; some of the volatiles may be vaporized

radionuclides. Excavation and vitrification in a plant designed for the purpose can be done using an electric furnace or a rotary kiln, but dealing with the resulting solids may pose additional problems. Vitrification is very energy-intensive.

Radon Control Without Source Remediation

As an interim measure, it may be possible to remediate on-site properties through radon removal techniques. In theory, these may include the following:

- Radon reduction in homes
- Electrostatic precipitators
- Areal soil gas venting and areal removal

Radon and its decay progeny do not pose a significant health hazard in an open outdoor environment. However, they can accumulate to harmful concentrations in confined spaces, such as residences where there is an underlying radionuclide source.

Direct radon reduction in homes can be accomplished in a variety of ways. Techniques include sealing entry cracks and holes, forced ventilation of soil and building materials in and adjacent to the foundation, and passive and forced ventilation of indoor airspace. The techniques, properly applied, are effective. These control systems must be maintained as long as the radionuclide source is present. The particular techniques to be applied to a specific situation depend upon the structural characteristics of the building and the nature of the underlying soil.

Electrostatic precipitators may reduce the number of the particles in a room including particles to which radon progeny are attached. The health effects of this are not known.

Areal soil gas venting may be applicable to reduction of radon emanation over a waste site. The technology has been used to remove methane from landfills and organic vapors from soil. The effectiveness will depend in part on the soil characteristics. Areal removal systems would require long-term maintenance.

Chemical Extraction of Radionuclides from Contaminated Soil

The objective of this separation technology is to concentrate the radioactive contaminants by chemical extraction, with the aim of thereby reducing the volume of waste for disposal. The chemical extraction technology ultimately generates two fractions. One fraction contains the concentrated radioactive contaminants and may require disposal; the remaining material is analyzed for residual contamination and

evaluated for replacement at the point of origin or at suitable alternative sites. The various applicable chemical extraction techniques include extraction with:

- water
- inorganic salts
- mineral acids
- complexing reagents

Except for the use of inorganic chlorides to remove radium from liquid effluents at uranium mines, none of the chemical extraction technologies has been field demonstrated to remove radionuclides from waste material at a site. Bench-scale and pilot-scale testing would be needed to determine whether chemical extraction can be used for site remediation.

Water can be used to extract a portion of the radionuclide contaminants. Contaminated soil or tailings could be mixed with large quantities of water. The water, with the soluble radionuclide fraction, could be removed from solids by physical separation. Since many of the soil-cleaning techniques use water as part of their process, this method could be used as pretreatment.

A review of the literature indicates a broad range of results with the use of salt solutions to remove radium and thorium from mill tailings and soils. In many cases the effectiveness of a given salt appears to be related to several obvious variables, such as the nature of the tailings (geochemistry, particle size distribution, and chemical composition); the nature of the soil; the concentration of the salt solution; pH; solid-to-liquid ratio; process time; temperature; and method of extraction.

Mineral acid extraction techniques are being developed and have been used to extract radium, thorium, and uranium from mineral ores. Improvements in these acid extraction processes have been found to be possible in the laboratory and at uranium mills. The results show that the acid extraction processes can remove most of the metals, both radioactive and nonradioactive, and therefore may deserve further study for cleanup of radiologically contaminated sites and tailings. However, different processes may be needed for different radionuclides.

Extraction with complexing agents differs from acid extraction in that complexing agents like EDTA (ethylenediaminetetraacetic acid) are used instead of mineral acids. Radium forms stable complexes with many organic ligands (a molecule that can bind to a metal ion to form a complex) while thorium is not likely to be removed by complexation. Laboratory experiments show that radium forms stable complexes with EDTA, suggesting the potential for

extraction in soils and tailings with low concentrations of thorium.

The above extraction processes produce a pregnant liquor containing the radionuclides. In treating this liquor to concentrate and collect the radionuclides for disposal, the following support techniques are utilized:

- precipitation and coprecipitation
- solvent extraction
- ion exchange

By addition of chemicals, the radionuclides can be precipitated out from leach liquor. The slurry from the precipitation tank is dewatered in thickeners; this is followed by filtration. The filter cake containing the radionuclide fraction is then ready for disposal. Precipitation is a difficult, cumbersome operation requiring complex chemical separation. Close control of operating conditions is required.

Solvent extraction can be an efficient method for separating the radionuclides. In solvent extraction, the dissolved radionuclide fraction is transferred from the feed solution into the organic solvent phase. The loaded organic solvent is stripped of the radionuclides by an aqueous reagent. The barren organic solvent is recycled back to the extraction step. The radionuclide is precipitated out from the aqueous liquor. Solvent extraction offers better selectivity and more versatility than ion exchange.

Ion exchange involves the exchange of ions between the solution and a solid resin. Ion exchange does not extract material from the soil directly. Rather, it separates the constituents in a solution, such as might result from chemical extraction. It has been used extensively in uranium and radium extraction from ore. There are three types of exchange: fixed bed, moving bed, and resin-in-pulp. Any of these are theoretically applicable to radionuclides in liquids as a technique to complete the chemical extraction technology.

Because of the need for a combination of extraction methods to remove uranium, thorium, and radium, the chemical extraction technologies appear to be quite expensive and complex.

Physical Separation of Radioactive Soil Fractions

The radioactive contaminants in soils and tailings in many cases are associated with the finer fractions. This is true for uranium mill tailings and radium processing residue. Thus, size separation may be used to produce a reduced volume of concentrated material for disposal, leaving "cleaner" fractions. These fractions must be disposed as well. Physical separation may be used with chemical extraction to produce fractions of smaller volume with even more

concentrated contaminant. The physical separation technologies may be suitable for removing radionuclides that originally have been deposited as solid particulates on the soil.

Four physical separation technologies may be applicable to the separation of radioactive waste components of soils and tailings:

- Screening - both dry and wet
- Classification
- Flotation
- Gravity Concentration

These processes are already extensively used in the extraction of uranium from ore. They have not been used in the field to further extract other radionuclides from tailings or soils. Pilot plant testing would be needed to determine the ability of physical separation technology to clean radiologically contaminated soils.

Screening separates soil (or soil-like material) on the basis of size. It is normally applied only to particles greater than 250 microns in size. The process can be done dry or by washing water through the screen. Screening is not efficient with damp materials, which quickly blind the screen.

Screening can be applied to a variety of materials, and it is relatively simple and inexpensive. It may be particularly effective as a first operation to remove the largest particles, followed by other methods. Screening is a noisy operation, and dry screening requires dust control. Finer screens clog easily. Information needs include size distribution and moisture content of the feed stream, and throughput required for the equipment.

Classification separates particles according to their settling rate in a fluid. Several hydraulic, mechanical, and nonmechanical configurations are available. Generally, heavier and coarser particles go to the bottom, and lighter, smaller particles (sometimes called slimes) are removed from the top. Theoretically, classifiers could be used to separate the smaller particle fractions, which may contain much of the radioactive contamination in waste sites. Classifiers could be used with chemical extraction in a volume reduction process. Classification is a relatively low-cost, reliable operation. Soils high in clay and sands high in humus, however, are difficult to process this way. Information required for selecting classification includes size distribution, specific gravity, and other physical characteristics of the soil.

Flotation is a liquid-froth separation process often applied to separate specific minerals (particularly sulfides) from ores. The process depends more on physical and chemical attraction phenomena between the ore and the frothing agents, and on particle size,

than on material density. If particles can be collected by the froth, flotation is very effective.

Ordinarily, flotation is applied to fine materials; the process often is preceded by grinding to reduce particle size. Process effectiveness has been demonstrated in extracting radium from uranium mill tailings (Raicevic, CIM Bulletin, August 1970). Detailed waste characterization is a prerequisite for application of the flotation process; mineralogy, chemistry, specific gravity, and particle size are all important.

Gravity separation is used in the uranium and radium ore processing industries. This process takes advantage of the difference in material densities to separate the materials into layers of dense and light minerals. Separation is influenced by particle size, density, shape, and weight. Shaking (e.g., a shaking table) and a variety of other motions are employed to keep the particles apart and in motion; this is an integral part of the process. Gravity separation can be used in conjunction with chemical extraction. One drawback to gravity separation is its generally low throughput. Information needs are essentially the same as for flotation.

Additional technologies are required to support separation methods, including sedimentation and filtration, both of which are methods used in waste water treatment. They may be used individually or together.

Combined Physical Separation and Chemical Extraction Technologies

The combined physical and chemical separation techniques that can be applied to decontaminate radioactive soils are:

- Soil washing and physical separation
- Separation and chemical extraction
- Separation, washing and extraction technique

The soil washing and physical separation process involves washing the soil with chemical solution, followed by separation of coarse and fine particles. The type of solution used for washing will depend on the contaminant's chemical and physical composition. In 1972 DOE initiated laboratory-scale studies of soil cleaning techniques; on the basis of these studies, a washing and physical separation process was selected for pilot-plant study of cleaning plutonium-contaminated soil. The results of that pilot-plant testing (at Rocky Flats) show this process to have potential for success.

In pilot-plant test runs, soils contaminated to 45, 284, 7515, 1305, and 675 pCi/g of plutonium were cleaned to contamination levels of 1, 12, 86, 340, and 89 pCi/g, respectively, using different washing

processes. The coarse particle weight fraction ranged from 58 percent to 78 percent. Soil washing has been shown to work in clay soil. This process may not work for humus soil. The process is simple and relatively inexpensive and needs no major process development. It would, however, need further pilot-plant testing and development work to test its applicability to contaminated soil.

In combined physical separation and chemical extraction, the soil is first separated into fine and coarse particle fractions. The coarse particle fractions may be washed or extracted. The fine particle fractions are combined with extracted contaminants and could be sent to a secure disposal site. The "clean" coarse fractions are analyzed for residual contamination and evaluated for placement at the original site or an alternate site. An advantage of this process is that soil containing higher levels of radioactivity could be treated. Also, various sections of the process have been developed for extracting uranium, and laboratory work is underway in Canada for extracting radium from uranium mill tailings. The main disadvantages of this process are that it is expensive and has high chemical usage. In addition, the use of chemicals raises concerns of further contamination to the environment. The process would need further development work in order to better extract radionuclides from soil.

In applying the separation, washing, and extraction technique, the contaminated soils can conceivably be washed with a variety of washing fluids, followed by chemical extraction. The nature of the washing fluids and chemicals depends on the contaminants and on the characteristics of the soil. It could be advantageous to separate the soil into fine and coarse fractions and use the washing system on the coarser soil fraction to reduce the throughput and chemical usage. The treated soil, the finer soil fractions and the collected contaminants would require appropriate disposal.

General Issues

Several issues are of significant concern in attempting to apply remedial technologies at sites contaminated with radioactive materials. They include:

- *Final Disposal and Disposal Siting.* Publicly acceptable sites are difficult to find, and there may be problems in convincing the public that the "clean" fractions of the treated wastes are truly acceptable. Some form of disposal may ultimately be necessary as radioactivity cannot be altered or destroyed by any treatment technology.
- *Handling of concentrated residuals.* Reducing the volume of radiologically contaminated waste will increase the concentration of

radionuclides and may substantially increase the safety hazards of the contaminated fractions.

- *Mixed Wastes.* It is important to note that in some cases there may be two categories of residual contamination: process wastes and soils contaminated with isolated radionuclides or groups of radionuclides. While removal of the radioactive fractions of soils contaminated with single radionuclides such as uranium or plutonium might result in "clean" fractions acceptable for unrestricted disposal, removal of the radioactivity from a soil contaminated with process wastes may not. In this second case, the nonradioactive fractions of the residues could result in an unacceptable product. Therefore, before considering any separation technique, it is necessary that acceptable limits for both the radiological contaminants and the non-radiological contaminants be defined. In some cases multiple treatments or combined technologies could be required to achieve environmental goals.

land. Alternative technologies, which have to be evaluated and discussed further, may have the potential for reducing the mobility, toxicity, or volume of these contaminants. Further studies need to be completed prior to the implementation of these alternatives.

Criteria for Further Studies

The utility of any potential treatment process and the applicability of the overall remedial action depend heavily on the physical characteristics of the contaminated media and the surrounding soils. Since none of the chemical extraction and physical separation technologies have been used in a site remediation situation, their application must be approached cautiously. The same holds true for solidification or stabilization processes. Only land encapsulation and ocean disposal have been used.

It is important to study the patterns in waste characteristics at various sites and develop waste groups with similar major characteristics. Applicability studies can identify promising technologies to be tested for treatment of each waste group. Preliminary screening of the technologies can be accomplished based primarily on the waste characteristics.

When one or more remediation concepts are selected that appear applicable to a site, plans may be made for treatability studies. Success there could lead to pilot-scale testing and eventually to full-scale demonstration of site cleanup. This step-wise procedure is essential for the development of any remediation technology, with carefully developed work plans and quality assurance plans preceding each step.

Conclusions

The remediation of radioactively contaminated sites under Superfund, FUSRAP, and UMTRAP has been hampered by the lack of methods other than temporary storage or permanent encapsulation on

Chapter 1

Introduction

1.1 Study Purpose and Objectives

The Environmental Protection Agency (EPA) has identified twenty Superfund sites in the country that are radiologically contaminated by man-made sources (see Appendix B). These sites, located across the United States, vary greatly in size and may involve radiation exposure to people who reside on and around them. Radionuclides, unlike other hazardous wastes, cannot be altered or destroyed to eliminate their hazard potential.

The principal objective of this document is to identify the full range of technologies that may be useful in reducing to acceptable levels the radioactivity at uncontrolled hazardous waste sites. Many of the technologies discussed would require significant research and development activities before they could be reasonably considered for site cleanup. This report only addresses treatment and disposal of radiologically contaminated soils; it does not deal with, for example, sites whose principal radiological contamination is in building materials. Radiologically contaminated ground water is also a concern at some Superfund sites, but ground water treatment is beyond the scope of this report.

The document is intended as a first review. This report provides a discussion of the technologies, but not a detailed critical evaluation of them. The report does not include in-depth analyses that would be needed to determine the applicability of any of these technologies at a particular site.

In order to better ascertain the applicability of the technologies, descriptive data have been gathered for the twenty sites identified on the National Priorities List (NPL) that are known to contain radioactive waste materials. These data are presented in Appendix B; they are accurate as of December 1987.

1.2 Health Concerns

The radioactive materials at Superfund sites consist primarily of wastes from radium, thorium, and uranium processing. These wastes contain residual quantities of these elements and their radioactive decay products, which have remained as contaminants in

buildings, soil material, and stream channels after operations at the sites have ceased--or have been dumped as waste in on-site or off-site disposal areas. Contaminated soils have sometimes been utilized as fill material on private and public properties for various purposes. There are many other radionuclides that may also be impacted by technologies in this report.

The radioisotopes of concern belong to the uranium 238 and thorium 232 decay series (see Figure 1). Hazards to the general population could occur through several pathways, including:

- (1) inhalation of radon decay products, particularly where radon is concentrated within building structures;
- (2) inhalation of particulates or ingestion of materials containing radioisotopes of the two decay series;
- (3) ingestion of radionuclides via drinking water and food; and
- (4) external body exposure to gamma radiation.

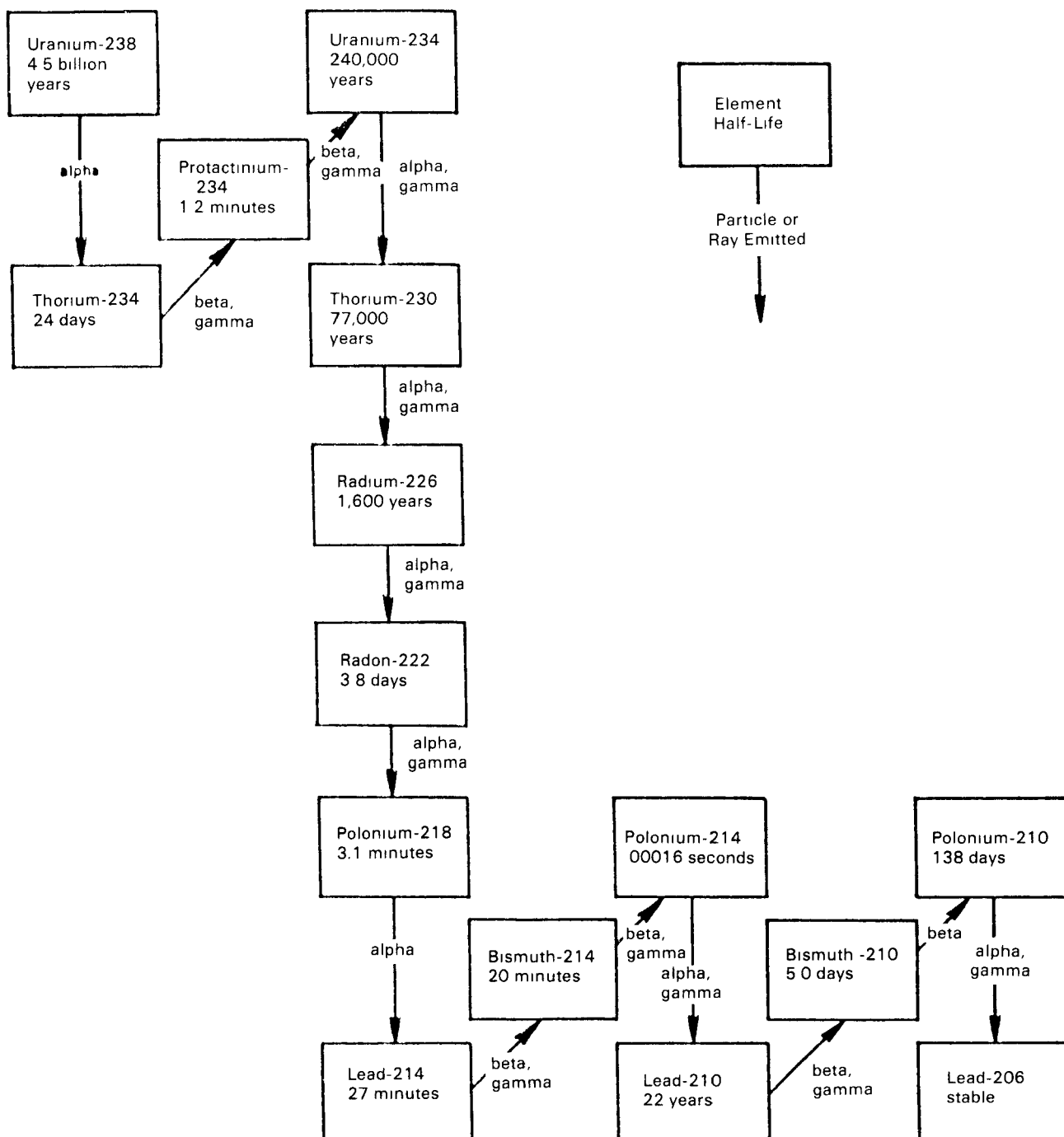
In the absence of remedial action, these potential hazards could persist for extremely long periods (millions of years) because of the long half-lives of the controlling isotopes.

There are three types of radiation generally believed to pose health hazards.

One is the alpha radiation (positively charged nuclear particles) associated with radioactive decay of radon gas and other radioactive elements, such as radium and uranium. Although alpha radiation cannot pass through the outer layers of skin, it can enter the body through inhalation and ingestion. Inhalation of alpha-emitting particles is a major health hazard and may contribute to lung cancer. Ingestion of water, dust, plants, or animals that contain alpha-emitters may contribute to cancer in the various parts of the body where the alpha-emitters lodge.

The second type of radiation that may pose a health hazard is gamma radiation. Gamma emitters can contribute to external exposure, since they can irradiate the human body. Such exposure can

Figure 1. Uranium-238 decay series.



contribute to cancer in various parts of the body. Different measures may be required to reduce exposure to alpha and gamma radiation.

The third type of radiation is beta radiation (electrons). Energetic beta particles can pass through skin. The primary hazard from beta radiation, however, is internal deposition by ingestion or inhalation. Although decay of radium to radon does not produce beta radiation, a subsequent portion of the decay chain produces beta radiation. The beta

radiation is of secondary concern relative to the alpha and gamma radiation, as the associated risks are typically much lower.

The principal health concern at sites containing radioactive wastes has been radon, radon progeny, and gamma radiation from radionuclide decay. The primary gamma radiation source at waste sites is radium in the soil. In addition, radon gas is continually produced by radioactive decay of radium, as indicated in Figure 1. Radon and its decay products (radon

"progeny") are alpha emitters that are potentially injurious if they become lodged in the respiratory system, and gamma emitters. Radon in the soil can make its way through cracks and porous building materials and accumulate in unsafe concentrations within houses and other buildings and enclosures [1].

Radon has a half-life of 3.8 days; its progeny are radioactive particles. They can attach themselves to dust and other particles. If they are inhaled, either attached or unattached to other particles, they may deposit in the respiratory system where they emit alpha particles, which may be damaging to the tissues. Alpha-emitting particles from decay of radon and progeny are considered to be a cause of lung cancer [2].

Residences and other buildings have been built on and around some waste disposal sites contaminated with radioactive materials. The radiation hazard derives from elevated indoor concentrations of radon gas and elevated outdoor and indoor gamma radiation levels that approach and sometimes exceed the radiological standards for the general public. It is important to note that there are average background radiation levels associated with these materials. Typical levels are shown in Table 1; they may not be the same as the average level in any particular location.

Sites that contain radioactive waste materials may also contain other types of hazardous waste. Some of the Superfund sites, for example, contain various types of hazardous wastes, and the radioactive portion may pose a relatively minor threat by comparison. The presence of other hazardous materials may complicate dealing with the radioactive portion of the waste and vice-versa. EPA is developing special regulatory approaches to these "mixed wastes."

1.3 Waste Sources and Contaminated Media

Radioactive wastes at uncontrolled sites have come from a variety of sources. Perhaps the most common, at least at Superfund sites, has been the residual material derived from ore processing to obtain radioactive elements. Examples are wastes from the beneficiation of uranium-, radium-, and thorium-bearing ores and from the process use of these elements. A common use for radium has been luminous watch dials; thorium has been used for mantles for gas lanterns.

It appears that most of the contaminated wastes are in tailings, a soil-like matrix. The radium and thorium wastes exist in relatively small quantities at most sites in comparison to uranium mining and mill tailings and the wastes from nuclear fuel processing and handling.

Table 1. Typical Background Radiation Levels*

Component	Typical Background
Gamma radiation	8-13 μ R/h
Ra-226 or Ra-228 in soil	~ 1 pCi/g
Uranium in soil	~ 1 pCi/g
Th-232 in soil	~ 1 pCi/g
Ra-226 in water with Ra-228	~ 1 pCi/l
U-238 in water	~ 1 pCi/l
Radon in air (outdoor)	0.2 pCi/l
Radon in air (indoor)	~ 1 pCi/l

*These may not be the same as the average level in any particular location.

Fuel processing, handling, and use may result in relatively highly contaminated containers, equipment, and even spent fuel residuals. Nuclear fuel wastes are generally maintained in containers at the use site (e.g., nuclear power and generating plants) until their final disposition. Superfund sites for the most part do not appear to contain these types of materials.

1.4 Scope of Report

Chapters 2 through 7 describe the range of technologies for the removal of radioactive materials from contaminated soil. These sections deal, respectively, with disposal of contaminated materials, on-site treatment, radon control chemical extraction, physical separation, and process combinations to remove contaminants from soil. The descriptions are the result of literature surveys and discussions with experts who have dealt with similar problems. It should be noted that the radioactive contaminants are not altered or destroyed by treatment technologies. The volume of contaminated material may be reduced by treatment, but the concentration of the contaminants will be much higher in the reduced volume. Some type of containment and/or burial is the only ultimate remedy for materials contaminated at levels above those considered safe for unrestricted release.

Chapter 8 briefly points out some of the issues that may inhibit or otherwise affect the remediation of sites containing radioactive waste. The issues include, for example, siting for final disposal, public reaction, and costs.

Chapter 9 looks at potential experimental work (bench-scale studies, for example) to test the applicability of the alternative remediation technologies.

Chapter 10 presents the conclusions of this report.

Appendix A briefly presents some of the laws, regulations, and guidance that are part of the framework within which technologies may be selected for remediation of Superfund sites. This report does

not attempt nor is it intended to provide a complete or detailed analysis of how various laws, regulations, and guidance apply in general or at a specific Superfund site, nor is it intended to set or interpret policy for the selection or use of technologies to clean up any Superfund or other hazardous waste site.

Existing Superfund sites known to contain radioactive materials are briefly characterized in Appendix B. Descriptive data include: the location, size and volume of the site; the character of the matrix materials; proximity to population centers; the degree of contamination; and the status of survey and cleanup activities. Data also have been gathered on sites being managed and remediated by the Department of Energy (DOE) [3]. This information is also presented in Appendix B.

Descriptive data on Superfund sites where radioactivity is a concern were obtained from the EPA Office of Solid Waste and Emergency Response and from each of the pertinent EPA Regional Offices. Information on DOE sites was obtained from literature provided by the Oak Ridge National Laboratory (ORNL) and the EPA Research Library in Cincinnati, from DOE personnel, and from the staff of EPA's Office of Radiation Programs.

Site-specific information is not complete at this time. For example, only limited information has been found on the soil or matrix characteristics at some of the Superfund sites. Detailed information on the physical, chemical, and radiological characteristics is absolutely necessary before attempting to apply any of the alternative technologies.

1.5 References

1. Nero, A. V. Airborne Radionuclides and Radiation in Buildings: A review. LBL-12948. Lawrence Berkeley Laboratory, University of California. 1981.
2. U.S. Environmental Protection Agency. Radon Reduction Techniques for Detached Houses: Technical Guidance (Second Edition). EPA-625/5-87-019 Office of Research and Development, Washington D.C. 1987.
3. U.S. Department of Energy. Office of Remedial Action and Waste Technology Program Summary, DOE/NE-0075, November 1986.

Chapter 2

Disposal

2.1 Introduction

This chapter discusses remediation methods that show potential for use in the final disposal of radioactive waste materials. Final disposal is generally regarded as some sort of containment that separates the materials from any further contact with the public and the environment. The radioactive waste materials may be in the form of tailings or tailings mixed with soil.

If some of the technologies described in this report are applied prior to containment, the contaminated waste volume may be reduced with a concomitant increase in the concentration of the radioactive material. Additionally, the larger fractions of the treated soil may be suitable for replacement at the point of origin without any long-term management, if the treatment technology succeeds in reducing the residual radiation to an acceptable level. No matter what technologies are applied, there will always be some portion of the material that will require long-term disposal.

On the other hand, the radioactive waste materials may not be in a form amenable to volume reduction—e.g., contaminated equipment; these also must be permanently contained if they cannot be cleaned.

Disposal can be in one of two categories: on-site disposal and off-site disposal. The state of the art of on-site and off-site disposal methods is shown in Table 2. Applicability of these methods to Superfund sites is controlled by site-specific factors; therefore, their usefulness must be determined on a site-by-site basis. At present, capping and land encapsulation are the only two methods used for radiologically contaminated site remediation.

2.2 On-Site Disposal

It may be possible to deal with radioactive waste materials, particularly if they are in a soil matrix, by methods that do not remove either the soil or the radionuclides from the site. Methods include: capping and vertical barriers.

2.2.1 Capping

2.2.1.1 Description and Development Status

This concept involves covering the contaminated site with a barrier sufficiently thick and impermeable to minimize the diffusion of radon gas. Barrier materials can be either natural low-permeability soils (e.g., clay) or synthetic membrane liners, or both. Both types of materials are generally available. A barrier might consist of several feet of compacted clay, depending upon radiation levels, and extending a few feet beyond the perimeter of the contaminated area.

Cap design and construction should consider the need to: 1) confine radon until it has essentially decayed to its progeny (for normal soils, the depth of cover required is about 150 cm for Rn-222 and 5 cm for Rn-220); 2) attenuate the gamma radiation associated with all the radionuclides present (for normal soils, the depth of cover required for gamma radiation shielding is on the order of 60 cm); 3) provide long-term minimization of water infiltration into the contaminated material; 4) function with minimum maintenance; 5) promote drainage and minimize erosion; and 6) have a permeability less than or equal to the permeability of any bottom liner system present or the natural subsoils.

Radon is continually produced from the radium source, but the radon itself decays in a few days. A schematic diagram of one potential cap design is shown in Figure 2 [1]. A number of DOE facilities have been constructed using the criteria contained therein. The technology of caps is well developed, and several good references are available [2-7]. However horizontal migration of radium or other radionuclides in ground water could still occur.

2.2.1.2 Potential Applicable Situations

Capping a waste mass in situ is applicable over a large, discrete, contaminated area or as a continuous cover over several smaller areas that are close together. Since there is a greater likelihood of penetration through the cover if structures are built upon it, capping is best used when no structures are planned for the site. All reasonable steps should be

Table 2. State of the Art of Disposal Methods

Method	Laboratory Testing	Bench Scale Testing	Pilot Plant Testing	Field Demonstration with Radioactive Material	Radiologically Contaminated Site Remediation	Remarks
<i>On-site Disposal</i>						
- Capping				x	x	
- Vertical barriers						
<i>Off-site Disposal</i>						
- Land encapsulation				x	x	
- Land spreading				x		Land spreading of radium sludge from drinking water is an allowed policy in Illinois
- Underground mine disposal				x		DOE currently working on mined repository for radioactive waste
- Ocean disposal				x		Stringent regulations for radioactive waste

taken to prevent or prohibit construction of buildings on capped wastes as long as possible.

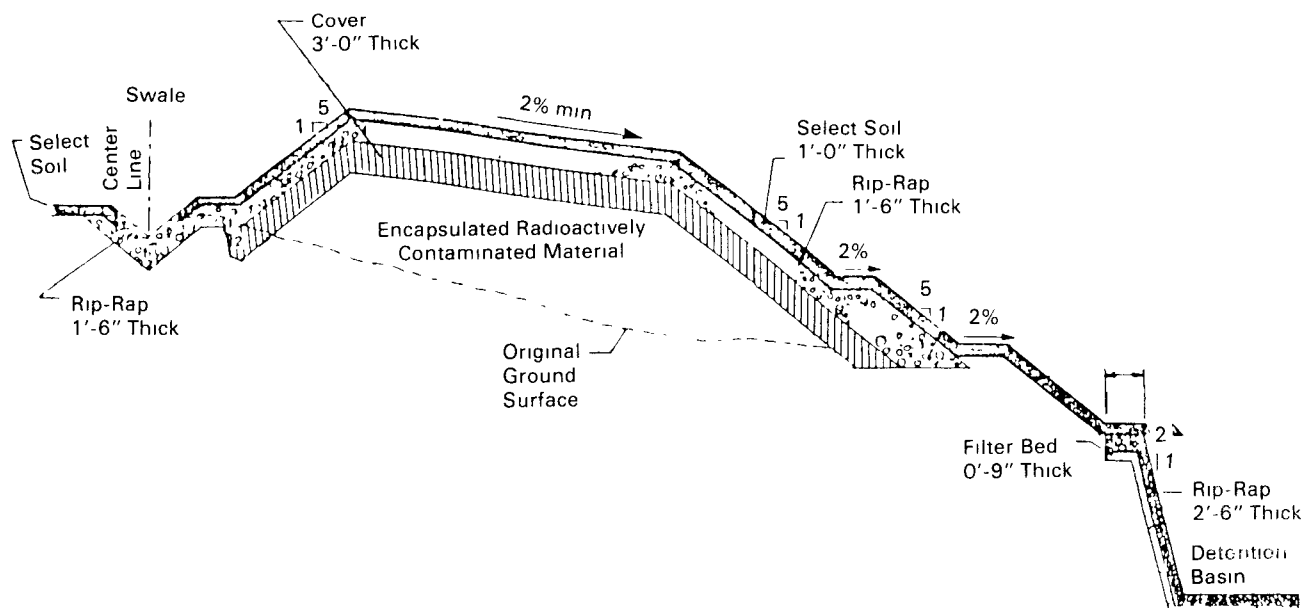
2.2.1.3 Advantages and Disadvantages

Advantages – The advantages of capping are ease of application, the fact that it is a well-known technology, and its high reliability when maintained properly. Another advantage of in situ capping is its

relatively low cost. Covers that are effective Rn-222 barriers may be effective gamma radiation shields. The soil characteristics are not as critical as they may be for stabilization or other treatment technologies.

Disadvantages – Capping the radon-emitting site does nothing to eliminate the source of radioactivity from the area of concern. It simply impedes release by shielding and trapping. Thus, the cap must remain

Figure 2. Schematic of a cover profile. (Reprinted from [1].)



intact, without penetrations, indefinitely. Tree roots, excavations for various purposes, such as utilities repair, and unwitting excavations or penetrations (e.g., post holes) could result in significant leaks. Building construction, as indicated above, is a clear threat to a cap. In addition migration of uranium and radium in the ground water could still occur.

2.2.1.4 Information Needs

As noted above, capping probably can be applied without the detailed site materials characterization necessary for most other types of remediation. However, it must be determined whether other hazardous materials are present; remediation requirements for nonradioactive hazardous materials may take precedence.

2.2.2 Vertical Barriers

2.2.2.1 Description and Development Status

Vertical barrier walls may be installed around the contaminated zone to help confine the material and any contaminated ground water that might otherwise flow from the site. The barrier walls, which might be in the form of slurry walls or grout curtains [8,9], would have to reach down to an impermeable natural horizontal barrier, such as a clay zone, in order to be effective in impeding ground-water flow. A barrier wall in combination with a surface cap could produce an essentially complete containment structure surrounding the waste mass.

Slurry walls are constructed by excavating a trench under a slurry. The slurry could be bentonite and water or it could be Portland cement, bentonite and water. In cases where strength is required of a vertical barrier, diaphragm walls are constructed with pre-cast or cast-in-place concrete panels [9].

An illustration of the slurry wall construction process is shown in Figure 3.

Grout curtains [9] are constructed by pressure-injecting grout directly into the soil at closely spaced intervals around the waste site (Figure 4).

The spacing is selected so that each "pillar" of grout intersects the next, thus forming a continuous wall or curtain. Various kinds of grout can be used, such as Portland cement, alkali silicate grouts, and organic polymers.

2.2.2.2 Potential Applicable Situations

Vertical barriers could be considered for use to prevent or delay escape of liquids and perhaps gases (if installed in combination with a cap), until a more

Figure 3. Slurry trench construction operations. (Reprinted from [9].)

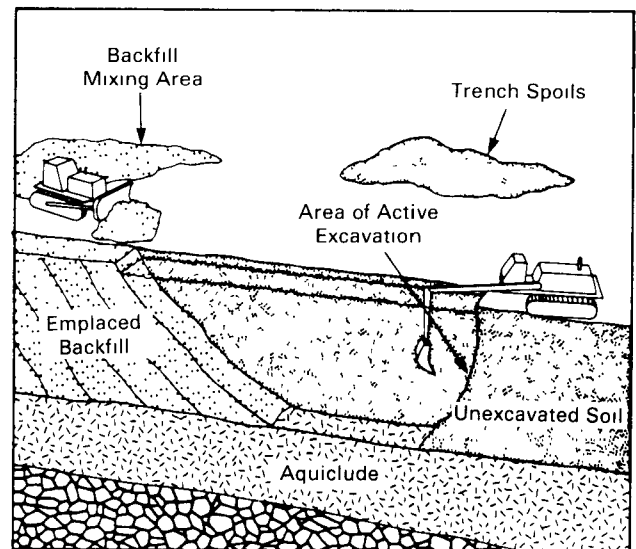
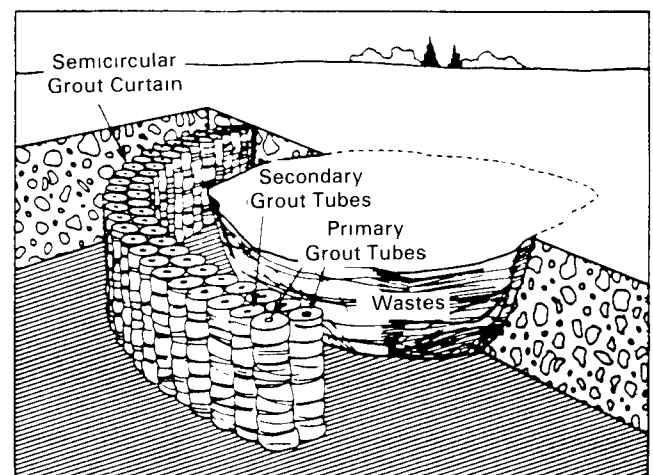


Figure 4. Grout curtain around waste site. (Reprinted from [9].)



desirable permanent remediation technology is adopted.

Barrier walls could be considered only for large discrete masses of waste materials or around several smaller masses close together. Barrier walls are not totally impermeable to water.

2.2.2.3 Advantages and Disadvantages

Advantages – Vertical barriers in soil and soil-like materials are relatively simple to install. They may save the expense of excavating and removing the contaminated material. In addition, they might serve as a vessel within which an in situ treatment process, such as contaminant extraction, could be carried out.

Disadvantages – It is difficult to obtain truly low permeabilities in grout curtains constructed in

unconsolidated materials [6]. Neither slurry wall nor grout curtain does anything, in itself, to eliminate the problem of radioactivity or any other contaminant. Each simply improves the confinement of the contaminants to the site.

Another potential disadvantage is the possible deterioration of the barrier walls resulting from the chemicals contained in the waste, particularly organic chemicals. A vertical barrier would not stop vertical contamination to ground water below.

As with caps, barrier walls do not eliminate the radioactive contents of the enclosed waste. They can only inhibit the spread of the contaminants. They do not inhibit the release of radon as a cap would.

2.2.2.4 Information Needs

The successful installation of a vertical barrier wall by the slurry wall or grout curtain technique requires detailed prior knowledge of the soil's physical and chemical characteristics [9]. As a minimum, the characterization of any liquid contaminants is required. Many common chemical (particularly organic) contaminants at uncontrolled waste sites can destroy certain grout materials or prevent them from setting.

2.3 Off-Site Disposal

Off-site disposal, as the term is used here, means controlled disposal at a site that is engineered or chosen for the purpose because of certain characteristics. Hydrogeological conditions at the site is one of the factors that must be considered in selecting off-site land disposal sites. Disposal may be very near the contaminated site or it may be very remote. The choice may depend upon site availability, security, public acceptance, cost, safety, and other factors. Off-site disposal is considered here to be a final stage of remediation, whether it is applied to untreated waste or to the extracted, encapsulated, or solidified wastes. Land encapsulation, land spreading, underground mine disposal, and ocean disposal are the off-site disposal methods reviewed in this chapter.

In the case of radioactive waste it is not clear that disposal with treatment will be superior to disposal without treatment. The off-site disposal technologies are discussed here without attempting to judge their relative acceptability. Given the length of time that the radioactive waste will be a hazard, the design must include greater attention to degradational characteristics of construction materials than has been normally considered for hazardous waste disposal sites.

2.3.1 Land Encapsulation

2.3.1.1 Description and Development Status

Land encapsulation is a proven, well-demonstrated technology. EPA has produced many publications dealing with the technology of hazardous waste land encapsulation (all of the Technical Resource Document series) [10]. Figure 5 is a cross-section of a conceptual design of a land encapsulation structure [1,11]. Nuclear Regulatory Commission (NRC) and EPA have jointly developed guidance on land encapsulation siting and design for commercial mixed low-level radioactive and hazardous waste disposal facilities [6,7] (see Appendix A, Addenda).

Land encapsulation is a technology that is likely to be considered at some stage in every site remediation case, especially with radioactive wastes, because the radioactivity cannot be altered or destroyed. Alternative technologies may be applied to the waste, as described later, to reduce its volume, but the concentrated contaminants must still be contained. DOE has used land encapsulation or some variant of it at the FUSRAP sites that have been remediated (see Appendix B).

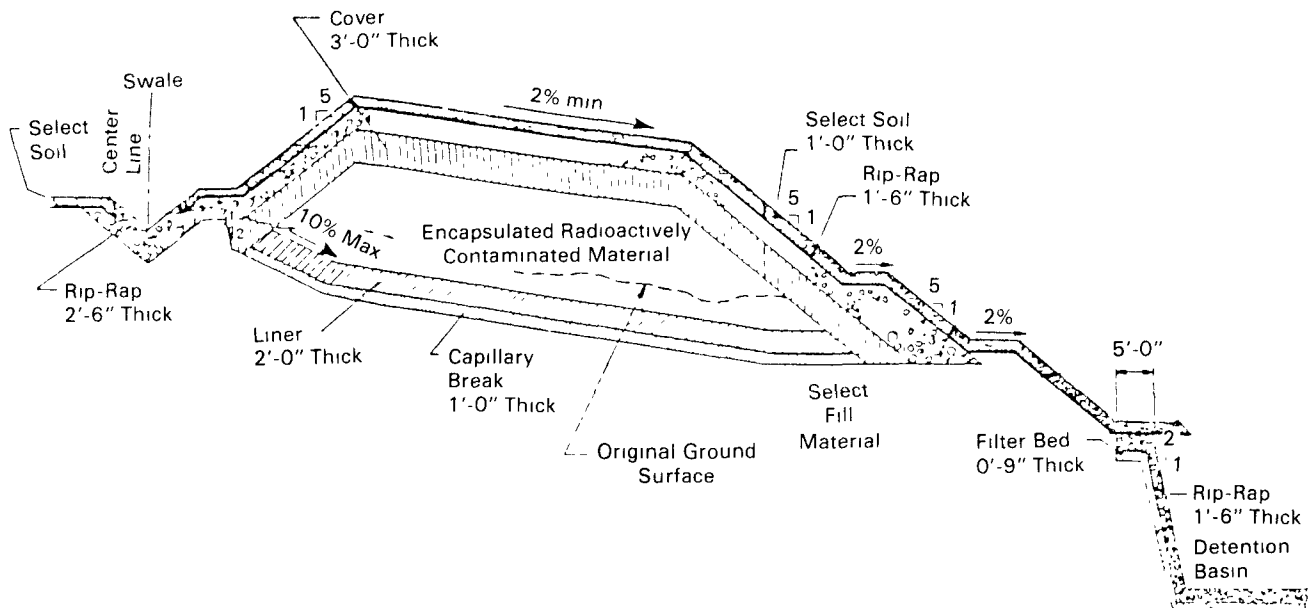
Land encapsulation can occur on site, but this may not be an option in all situations. If a radioactive material processing plant is the source of the waste and is near the contaminated area, the plant site could be a prime possibility for the land encapsulation location.

Alternatively, a remote site dedicated by a state or other government entity to radioactive waste containment, possibly could receive waste from any number of sources within the state. The control inefficiencies associated with operating diverse sites over long periods could thus be minimized.

A variation of the in-state concept might be the placement of the radioactive waste in the base of a new municipal solid waste landfill. The landfill would require a low-permeability liner. The solid waste atop the radioactive waste would delay the emission of radon until it had decayed and would absorb gamma radiation. Since the eventual land encapsulation cover would not be breached, at least for many years, the radioactivity would not be of significant concern. There is potential for problems if landfill leachates were to mobilize the radionuclides buried below the garbage. Another possible problem with this concept is methane generation in the municipal waste. If the methane should escape, radon might escape with it.

There are three existing NRC-licensed (by states) commercial low-level radioactive waste sites, at Hanford, WA; Beatty, NV; and Barnwell, SC. The Barnwell site cannot accept radium waste. Although probably capable of safely containing the waste from

Figure 5. Schematic of a land encapsulation system. (Reprinted from [1].)



Superfund sites, the other two may be reluctant to accept the wastes for many reasons, not the least of which is the scarcity of containment space. States in which these facilities are found are beginning to refuse wastes from outside their state or outside their compact states, and are permitted to do so under LLRWPA. Disposal at such remote out-of-state sites may well be the most difficult, and the most expensive, of the land encapsulation options [1].

2.3.1.2 Potential Applicable Situations

Land encapsulation may be appropriate for wastes that have not been treated, as well as for radionuclides extracted from a soil or other type of matrix. In fact, it may be the most appropriate final disposal method in most situations. To date, DOE has been utilizing either temporary storage or permanent encapsulation as the most viable remedial alternatives.

2.3.1.3 Advantages and Disadvantages

Advantages – Land encapsulation is a proven, workable technology for the disposal of low-level radioactive wastes. It can be a viable solution at a reasonable cost. The radionuclides would be removed from the site and would not be a significant problem at that site.

Disadvantages – Finding an appropriate site for construction of a land encapsulation may be difficult due to the current public aversion to this technology. Finding an existing secure site outside the containment property that will accept radioactive

wastes may also be difficult. Outside the contaminated property the wastes will require transportation and handling. Transportation of large volumes of radioactive materials also carries certain costs and risks. There will be considerations of safety and permitting in any case, but if the radionuclides have been concentrated by extraction and separation processes, these problems may become more difficult. Longevity is a consideration in the design of the disposal site. An appropriate site will have to be found for the radionuclide concentrated fraction of the material. In any case, the disposal site issue will have to be faced at some future date.

2.3.1.4 Information Needs

Relative to other technologies, minimal information about the site soil characteristics is required prior to land encapsulation. The levels of radioactivity and quantities of nonradioactive hazardous materials are certainly important, but soil grain size and other physical characteristics do not have a significant impact on applicability of encapsulation. Other characteristics of the potential disposal site, however, must be fully analyzed.

2.3.2 Land Spreading

2.3.2.1 Description and Development Status

A disposal option not often considered for radioactive waste is spreading on land [12]. This could be an option for untreated soil with low radioactivity levels. The material could be transported to an appropriately selected and sufficiently large expanse of remote

open land and spread to a degree that the soil radioactivity level approaches the natural background radiation level of these materials. The material can also be blended with clean fill for dilution and then spread over the land or disposed under road beds. This technology has not been demonstrated for radioactive waste. Land spreading of radium sludge from drinking water treatment systems has been an allowed policy in Illinois since 1984.

2.3.2.2 Potential Applicable Situations

Land spreading appears to be more appropriate for dry, granular, soil-like materials or tailings that are not mixed with other contaminants.

2.3.2.3 Advantages and Disadvantages

Advantages – The technology appears simple and relatively inexpensive; it could result in a permanent remedy for the contaminated sites involved.

Disadvantages – Selecting a site to receive the materials would likely be a politically and socially sensitive issue. The types of materials that could be accepted would probably fall within a very narrow range of physical and chemical characteristics. The technology has not been demonstrated. Convincing the public of its safety would be very difficult. A potential problem may be emitting respirable particles into the air. Land spreading could contribute to a non-point source pollution problem generated by native soil.

2.3.2.4 Information Needs

Because this technology is an untried concept, information needs have not been worked out. However, there seems to be no doubt that detailed physical and chemical characteristics of the waste matrix would need to be gathered. Site selection criteria would have to be developed for the receiving site.

2.3.3 Underground Mine Disposal

2.3.3.1 Description and Development Status

Abandoned mines could provide sites for the permanent disposal of radiologically contaminated wastes. A conceptual layout of a mine disposal facility is shown in Figure 6. This is one way to plan for distance between the radioactively contaminated material and the human population, although ground water could provide a route for the contaminated material to reach the population. Some research has been done on the possibility of using mines for the disposal of hazardous waste [12-14] and, more specifically, for dioxin-contaminated wastes in Missouri [15]. In the latter case, abandoned mines in that state were examined. The results were

encouraging from a technical standpoint, but the concept has never been implemented in the United States.

The DOE is currently working on a mine repository for radioactive waste called the Waste Isolation Pilot Project (WIPP) in New Mexico. While this repository is designed for higher activity materials than most of the Superfund material, the concept might be applicable, particularly in light of the possibility of volume reduction. Mine containment of hazardous waste in Europe has been successful [16]. Multipurpose use of a mine for hazardous waste and for low-level radioactive waste might be considered and would likely reduce the per-unit costs of waste disposal.

Underground mine disposal would not be appropriate for radiologically contaminated bulk liquids or noncontainerized waste.

For mine disposal, as for any off-site disposal, excavation of the contaminated materials would be necessary, and they would have to be transported to an appropriate site.

Any of the waste volume reduction and solidification or vitrification techniques described in this document might be used prior to mine disposal. Solidification or vitrification of the material, whether or not the volume has been reduced, could provide even more security for final containment in the mine.

The principal drawback to the mine disposal option may be cost. The use of an existing abandoned mine might overcome that obstacle. With appropriate site selection, there are few, if any, technical disadvantages to this option.

2.3.3.2 Potential Applicable Situations

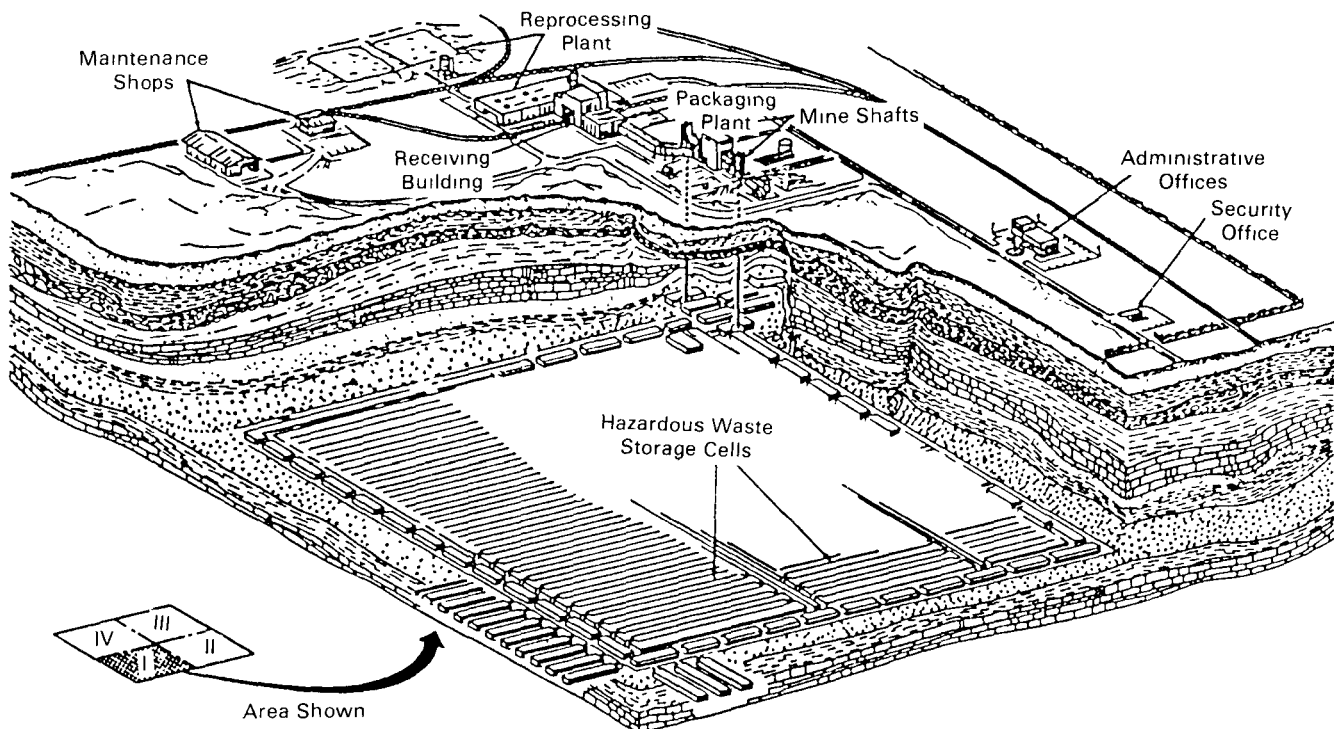
Mine disposal might be considered for use for a variety of radionuclide and matrix types. As noted above, it could be used to dispose of wastes with or without prior treatment, although volume reduction and/or solidification or vitrification might facilitate the process. Wastes that have been concentrated by extraction or separation techniques may be particularly appropriate for mine disposal, since they are likely to be more radioactive, requiring disposal that is more remote and more secure.

2.3.3.3 Advantages and Disadvantages

Advantages – Mine disposal, if done properly, should provide a very secure and remote containment of radioactive wastes. This technology has been used successfully in Europe for hazardous waste.

Disadvantages – The mine disposal of hazardous radioactive waste may be among the more costly

Figure 6. Conceptual view of a mine storage facility. (Reprinted from [13].)



disposal alternatives, particularly if a mine must be excavated for only that purpose. Wastes must be excavated and transported with the associated permit and safety concerns. The use of an abandoned mine would involve the cost of reconstruction and may pose safety hazards. Also, the ground water must be protected.

2.3.3.4 Information Needs

As with most technologies, the waste being dealt with must be carefully characterized. The mine site must also be carefully described and judgments made as to feasibility or applicability on the basis of the information gathered. For example, the hydrogeology must be known in detail, so that any ground water contamination may be prevented.

2.3.4 Ocean Disposal

2.3.4.1 Description and Development Status

The concept of ocean disposal of low-level radioactive wastes is not new. As shown in Table 3, a sizable amount of these wastes was disposed at sea between 1946 and 1970 [17].

The radioactive wastes that have been disposed at sea were usually in concrete-filled drums or

containers. Three sites were used in the Atlantic Ocean. One was 12-15 miles from the coast in 300 feet of water near Massachusetts Bay. The other two were in water deeper than 6,000 feet, one 150 miles off Sandy Hook, NJ, and the other 105 miles off Cape Henry, VA.

Two sites were used in the Pacific about 48 miles west of San Francisco [17].

2.3.4.2 Potential Applicable Situations

Ocean disposal could be considered for tailings and other radiologically contaminated soils that are free of other hazardous wastes. This alternative should not be considered for enhanced radioactive materials or concentrated residuals. Stabilization techniques could be applied to the waste before emplacement to provide for more security against leaks. For those materials contaminated with hazardous chemicals, the potential danger to marine biota must be evaluated.

2.3.4.3 Advantages and Disadvantages

Advantages – Ocean disposal offers the opportunity for extreme isolation of low-level radioactive waste.

Disadvantages – Transportation of the contaminated materials will involve transfer between land and sea. If

Table 3. Ocean-Disposed Low-Level Radioactive Waste, 1946-1970

Year	Number of Containers	Estimated activity at time of disposal (in curies)
1946-1960	76,201	93,600
1961	4,067	275
1962	6,120	478
1963	129	9
1964	114	20
1965	24	5
1966	43	105
1967	12	62
1968	0	0
1969	26	26
1970	3	3
Totals	86,758	94,673

the radioactive contaminants should be released, the potential for dispersal and dilution is immense.

2.3.4.4 Information Needs

Detailed characterization of the matrix, including other hazardous materials, would be required before ocean disposal could be considered. If solidification or vitrification, as used in past disposal of radioactive materials, were first applied to the waste, the chemical compatibility of the solidification agents and the waste would need to be determined. However, solidification or vitrification is not required; all that is needed is an assurance that the material will reach the bottom and will not stay suspended in the water.

2.4 Typical Costs of Disposal Methods

The cost of the application of any of the disposal methods described in this chapter will depend upon many factors, including waste and site characteristics. Thus the costs cannot be estimated reliably for any method and for any site at this stage, because most of the prerequisite information is not available. It also must be cautioned that many, if not most, of the controlling factors will be site-specific. The cost for a method at one site may be vastly different than for the same method applied at another site, especially when transportation costs are involved. Costs for off-site disposal would include transportation as well as disposal costs, and all but in situ options must take into account excavation costs for the contaminated materials. Those disposal methods requiring waste treatment will involve treatment costs as well.

Despite the limitations and cautions, some typical costs of disposal methods are presented in Table 4. These costs are not intended to be applicable to any particular site. Costs of returning "clean" treated material to a site are not included.

Table 4. Typical Costs of Various Disposal Methods*

These costs are presented to give some typical costs under the referenced conditions. They are not intended to be applicable to any particular site. Costs of returning "clean" treated material to a site are not included.

Remediation Method	Costing Units	Materials & Installation*	First Year O&M*	Comments
Capping with clay ^a	cu m	\$13-200	\$0.44	
Vertical barrier slurry wall ^b	sq m	\$33-377	–	Area units for vertical face
Grout curtain ^c	cu m	\$208-403		Cost for grouted soil volume
Excavation and secure land encapsulation ^d	cu m	\$276-895	\$0.45	–
Land spreading	–	No data found	–	–
New underground mine ^e	cu m	\$399-942	\$2.50-18.00	–
Existing underground mine ^e	cu m	\$185-523	\$2.50-18.00	–
Ocean disposal ^f	cu m	\$332-401	–	

* Costs are mid 1980s. Costs are from different sources and may be derived from different assumptions and therefore may not be directly comparable.

^a Low cost includes cost of capping only [11]. The material consists of radiation residues from uranium processing and contaminated soil. The high cost includes cost of excavation, transportation, and legal assistance. Cost for site acquisition is not included. The material consists of contaminated soils.

^b Low costs are for soft soil with 9m depth of excavation, and the high costs are for hard soil with 37m depth of excavation [3,9]. These costs are for hazardous waste. Specific soil conditions have not been identified.

^c Low costs are for Portland cement grout and high costs are for 40% sodium silicate grout in rocky soil [9]. These costs are for hazardous waste; the specific soil conditions have not been identified.

^d Low cost includes cost of excavation and transportation, but does not include cost for disposal site acquisition [1]. Transportation costs are from Montclair/West Orange and Glen Ridge to a land encapsulation cell in Glen Ridge. High cost includes cost of transportation and excavation, etc., but does not include cost of disposal site acquisition. Transportation cost is from Niagara Falls, NY to Hanford, WA [11].

^e Costs are for storage of nonradioactive hazardous waste. Specific conditions could not be identified [15].

^f Low cost includes cost of excavation and transportation to ocean dump site off New Jersey/New York shore [11]. High cost includes cost of excavation and transportation to an undetermined ocean dump site [1]. Material is radiologically contaminated soil.

2.5 References

1. Camp, Dresser & McKee et al. Draft Final Feasibility Study for the Montclair/West Orange and Glen Ridge, New Jersey Radium Sites, Volume 1. USEPA Contract 68-01-6939, 1985.
2. Lutton, R. J. Design, Construction, and Maintenance of Cover Systems for Hazardous Waste: An Engineering Guidance Document EPA-600/2-87-039 Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, 1987.
3. McAneny, C. C., P. G. Tucker, J. M. Morgan, C. R. Lee, M. F. Kelley, and R. C. Horz. Covers for Uncontrolled Hazardous Waste Sites. EPA-540/2-85-002, Office of Emergency and Remedial Response, Washington, DC, 1985.
4. Lutton, R. J., G. L. Regan, and L. W. Jones. Design and Construction of Covers for Solid Waste Landfills. EPA-600/2-79-165, Municipal Environmental Research Laboratory, Cincinnati, OH, 1979.
5. Lutton, R. J. Evaluating Cover Systems for Solid and Hazardous Waste. SW-867, USEPA, Municipal Environmental Research Laboratory, Cincinnati, OH, 1980.
6. Combined NRC-EPA Siting Guidelines for Disposal of Commercial Mixed Low-Level Radioactive and Hazardous Wastes, 1987.

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7. Joint NRC-EPA Guidance on a Conceptual Design Approach for Commercial Mixed Low-Level Radioactive and Hazardous Waste Disposal Facilities, 1987.
 8. U.S. Environmental Protection Agency. Slurry Trench Construction for Pollution Migration Control. EPA 540/2-84-001, Municipal Environmental Research Laboratory, Cincinnati, OH, 1984.
 9. U.S. Environmental Protection Agency. Handbook - Remedial Action at Waste Disposal Sites (Revised). EPA-625/6-85/006, Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, 1985.
 10. U.S. Environmental Protection Agency. Technical Resource Documents on Hazardous Waste Land Disposal. SW860 and SW870 Series. Office of Solid Waste, Washington, DC, 1979-1987.
 11. U.S. Department of Energy. Long Term Management of the Existing Radioactive Wastes and Residues at the Niagara Falls Storage Site, DOE/EIS-0109D, Washington, DC, 1984.
 12. Gilbert, T. L., J. M. Peterson, R. W. Vocke, and J. K. Alexander. Alternatives for Management of Wastes Generated by the Formerly Utilized Sites Remedial Action Program. ANL/EIS-20, Argonne National Laboratory, Argonne, IL, 1983.
 13. Stone, R. B., P. L. Aamodt, M. R. Engler, and P. Madden. Evaluation of Hazardous Wastes Emplacement in Mined Openings. EPA-600/2-75-040. Municipal Environmental Research Laboratory, Cincinnati, OH, 1975.
 14. Stone, R. B., K. A. Covell, T. R. Moran, L. W. Weyand, and C. U. Sparkman. Using Mined Space for Long-Term Retention of Nonradioactive Hazardous Waste. EPA-600/2-85-021, Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, 1985.
 15. Esposito, M. P., W. E. Thompson, and J. S. Greber. Using Mined Space for Long-Term Placement of Dioxin-Contaminated Soils. EPA Contract 68-02-3693, 1985.
 16. Jacoby, C. H. Inspection Visit of the Hazardous Waste Storage at Herfa-Neurode, Germany, of Kali & Salz. Prepared for EPA under Bechtel Subcontract. 1977.
 17. Council on Environmental Quality. Ocean Dumping - A National Policy. A Report to the President. U.S. Government Printing Office, 1970.

Chapter 3

On-Site Treatment

3.1 Introduction

This chapter discusses on-site treatment technologies that may immobilize radioactive contaminants. These technologies include:

- stabilization or solidification
- vitrification

These technologies do not reduce the amount of the contaminated material. However, they immobilize the contamination in the waste material and limit the spread of radioactive material.

Each of these is discussed below. The state of the art of these on-site treatment technologies is shown in Table 5.

3.2 Technologies of Potential Interest

3.2.1 Stabilization or Solidification

3.2.1.1 Description and Development Status

Solidification is a process that produces a monolithic block of waste with high structural integrity. The contaminants do not interact chemically with the solidification agents but are mechanically bonded. A stabilization process usually involves addition of reagents, which limit the solubility or mobility of the waste constituents. Solidification and stabilization techniques are often used together [1].

The intent of solidification and/or stabilization of the contaminated soil materials would be to limit the spread of radioactive material via leaching, etc., and to trap and contain radon within the densified soil mass. While the contaminants would not be removed and would remain active, the mobility of the contaminants would be eliminated or reduced.

Waste materials at Superfund sites could be solidified in two ways. One is to inject the solidifying agent into the materials in place. The other is to dig up the materials and machine-mix them with the solidifying agent. The solidified materials from the latter process

could then be re-deposited on or off site in engineered containment systems [1,2].

In situ solidification utilizing grout injection technology, grout would be injected directly into the soil containing the radioactive source materials (Figure 7). This technique has been proposed by DOE for by-product radioactive wastes [3]. If successful, the materials would be solidified and radon would be contained long enough to decay to its daughters. The solidified material also might reduce mobility of radioactive and nonradioactive constituents; if not, the material would require isolation. The solidification technique thus might be better suited to materials that are already buried and/or capped.

In situ grouting for stabilization purposes requires extensive and detailed characterization of the waste matrix before the process is undertaken [Oak Ridge National laboratories, staff, personal communications, May 19, 1987]. Chemical grouts are better suited to fine-grained soil with small pores, while cement grouts are best for coarse-grained materials. Greater effectiveness might be achieved if both techniques are used together: cement grouting first, followed by chemical grouting. Lime and fly ash have been injected together to stabilize abandoned solid waste sites [4].

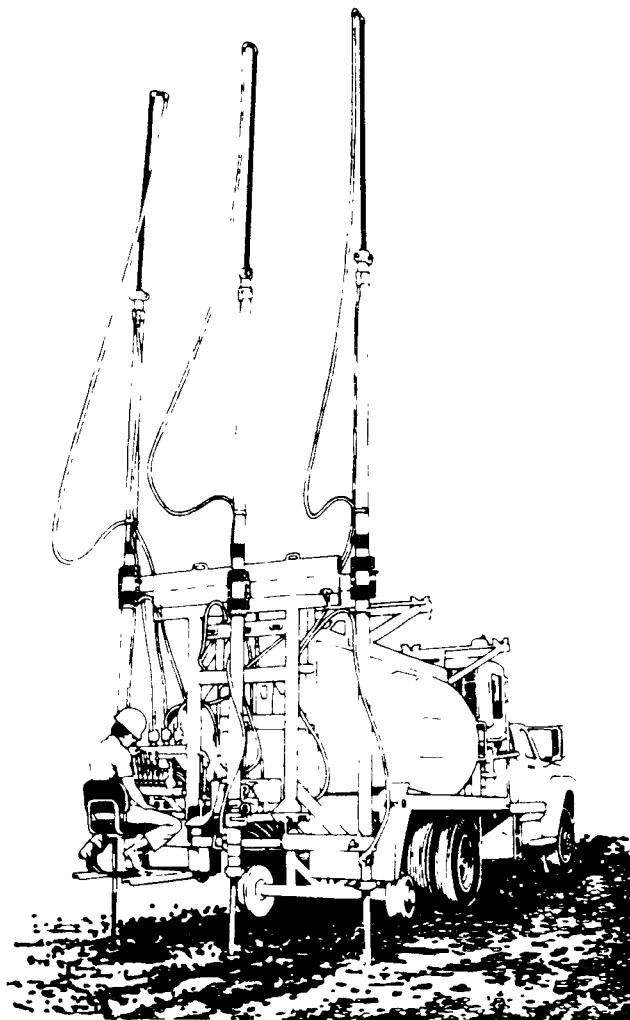
The second way to solidify the waste materials is to excavate and mix the waste with solidifying agents in either a continuous or batch process [4]. Portland cement, pozzolanic fly ash, or any of a number of chemical fixation agents can be used in the process. Bitumen (asphalt), because of its excellent binding and sealing properties, and its weatherability, can be an effective solidifying agent.

Excavation and mixing would be followed either by placing the solidified soil in containers or by burial on the site. The use of containers provides greater assurance against release of radioactive materials and allows for flexible storage, either on- or off-site. On-site burial with or without containers would require a soil cover of sufficient thickness to absorb the gamma radiation.

Table 5. State of the Art of On-Site Treatment Technologies

Technology	Laboratory Testing	Bench Scale Testing	Pilot Plant Testing	Field Demonstration with Radioactive Material	Radiologically Contaminated Site Remediation	Remarks
Stabilization or solidification			x	x		Proposed by DOE for low-level radioactive waste
Vitrification			x	x		Field testing by ORNL

Figure 7. Subsurface injection machine. (Reprinted from [3].)



3.2.1.2 Potential Applicable Situations

Solidification could be considered for use in a variety of situations. It offers the opportunity of leaving the waste materials on-site in a relatively immobilized state. It could be applied to materials with a range of physical characteristics, and is particularly applicable to highly porous and permeable matrices. Solidification may be useful where increased material

strength is desired, such as in a matrix of municipal solid waste.

For residential sites, the in situ method may not be suitable, since maintenance of utilities would be difficult. Also, it probably is insufficient to reduce gamma radiation exposure substantially.

The injection solidification technique is best suited to materials that are already buried and/or capped and may provide more security against the escape of radioactive material entering the environment.

3.2.1.3 Advantages and Disadvantages

Advantages – 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.

Solidification may also facilitate transportation and off-site disposal of radioactive contaminants with the use of containers, especially where volume reduction or extraction techniques have been applied previously.

Disadvantages – While solidification may work initially, its long-term effectiveness is not known. Working against the in situ solidification technique may be the location and configuration of the contaminated masses. If they are thin, discontinuous, and at or near the surface, injection grouting would obviously face significant difficulties. In situ solidification would be impractical for residential areas. In situ solidification, as with other disposal technologies, may trap the radioactivity, but does not eliminate it. If other types of hazardous waste are included in the waste, they may interfere with the solidification process. Organic chemicals could be particularly troublesome and could eliminate solidification processes from further consideration. Excavation coupled with solidification may be more costly than excavating and land encapsulation.

3.2.1.4 Information Needs

Before a decision can be made concerning the usefulness of the process for the site being considered, detailed information on the matrix (e.g.,

soil) and associated waste characteristics must be known.

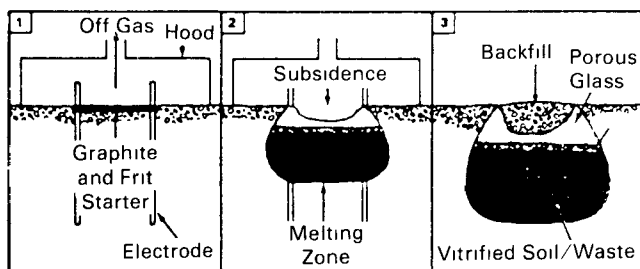
3.2.2 Vitrification

3.2.2.1 Description and Development Status

Vitrification is a process in which the contaminated material is heated to its melting temperature, then is allowed to cool and solidify to a glassy mass. In the sintering process the contaminated material is heated to produce a coherent mass without melting. The process may be applied in situ or it may be applied to material excavated and transported to a fixed process site.

The in situ vitrification process has been experimentally applied to soils by Battelle Pacific Northwest Laboratories [5] with the intent of potentially applying it to radioactive waste sites and/or Superfund hazardous waste sites. The concept is depicted in Figure 8. Presumably, the radionuclides would be trapped, and some radiation would be attenuated by the resulting material.

Figure 8. In situ vitrification process. (Reprinted from [5].)



Vitrification is a high energy consuming process. In the in situ vitrification process, electricity is applied to electrodes placed in the ground over the waste mass. The ground and waste mass heat and melt, and the melting zone grows downward. A hood to catch gases is placed over the zone, and the gases are treated or removed to prevent air pollution.

In the full-scale concept, electrode spacing would be 3.5 to 5 m, and the power required would be 3750 kW, for an expected vitrified mass of 400 to 800 tons [5].

An in situ pilot-scale experiment was completed in the summer of 1987 at ORNL on natural soil spiked with cesium and strontium to simulate the radioactive contaminants. Results of this experiment are under evaluation. In July 1987 an in situ vitrification process was field demonstrated on a transuranic waste site at Hanford, Washington. The results of this field demonstration are being evaluated [Battelle Northwest Laboratories, Personal Communication,

February 1988; and ORNL, Personal Communication, May 17, 1987].

The vitrification also could be performed on excavated materials on site or off site in an electric furnace or in a rotary kiln [6]. In the first, the materials would be melted and poured into molds. In the second, the contaminated materials are sintered in a rotary kiln. While sintering may not necessarily produce a solid monolithic mass, it may reduce availability of the radioactive constituent for leaching and therefore may be appropriate for containing the radioactivity.

The products in either case are likely to require an engineered final disposal method.

3.2.2.2 Potential Applicable Situations

The in situ vitrification process has been developed specifically for application to low-level radioactive waste sites, particularly to be used by DOE in its remediation programs. In situ vitrification works on a variety of materials to a limited extent.

The effectiveness of the process is very different for different radionuclides and different chemicals. The volatility and mobility of the element or compound are important factors in the applicability of the method.

3.2.2.3 Advantages and Disadvantages

Advantages – In in situ vitrification the materials do not require excavation; the process could be applied to materials with minimal prior preparation. The radioactive material is trapped in the vitrified mass, and releases to the environment are reduced.

Electric furnace vitrification on excavated material would produce a glassy mass, which can be poured into molds of some convenient size. The glassy blocks might supplant waste containers or solidification blocks. Such treatment might be a preprocessing step to mine or ocean disposal. The rotary kiln is significantly more energy-efficient than the electric furnace.

Disadvantages – Many substances would probably volatilize in the process, requiring gas collection and treatment devices. Radon trapped in the material matrix could be released during the process, and radium may volatilize. The use of the process in residential areas may pose difficulties, including problems in future underground utility repair work. Even if this were to be successful, the vitrified material will remain radioactive. Additional shielding may be required for protection from gamma radiation. The vitrified material, if near the surface, may still require removal from residential areas.

Fixed plant vitrification on or off site would require excavation and transport of the waste materials to the vitrification site. This would add to the cost. The rotary kiln may not be suitable for radioactive wastes, as it does not produce a secure, solid, monolithic mass.

3.2.2.4 Information Needs

Detailed waste characterization will likely not be required to make the process work. However, the characteristics of the materials, including the matrix and the contaminants, need to be known in some detail in order to determine the volatilization characteristics, so that control of off-gases may be planned correctly.

3.3 Typical Costs of On-Site Treatment Technologies

The cost of the application of any of the treatment technologies described in this section will depend on many factors, including waste and site characteristics. Thus, the costs cannot be estimated reliably for any technology and for any site at this stage, because most of the prerequisite information is not available. It also must be cautioned that many, if not most, of the controlling factors will be site-specific.

Despite the limitations and cautions, some typical costs for treatment technologies that immobilize the radioactive contaminants are presented in Table 6. These costs are not intended to be applicable to any particular site.

3.4 References

1. U.S. Environmental Protection Agency. Handbook – Remedial Action at Waste Disposal Sites (Revised). EPA-625/6-85-006, Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, 1985.
2. U.S. Environmental Protection Agency. Handbook – Remedial Action at Waste Disposal Sites. EPA 625/6-82-006, 1982.
3. Tamura, T., and W.J. Boegly, Jr. In Situ Grouting of Uranium Mill Tailings Piles: An Assessment. ORNL/TM-8539, Oak Ridge National Laboratory, Oak Ridge, TN, 1983.
4. Blacklock, J. R., and P. J. Wright. Stabilization of Landfills, Railroad Beds and Earth Embankment by Pressure Injection of Lime/Fly Ash Slurry. Proceedings – Ash Tech 84, Second International Conference on Ash Technology and Marketing, London, England, 1984.
5. Fitzpatrick, V. F., J. L. Buelt, K. H. Oma, and C. L. Timmerman. In Situ Vitrification – A Potential Remedial Action Technique for Hazardous Wastes. Proceedings of the Fifth National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, DC, 1984.
6. Camp, Dresser & McKee et al. Draft Final Feasibility Study for the Montclair/West Orange and Glen Ridge, New Jersey Radium Sites, Volume 1. USEPA Contract 68-01-6939, 1985.
7. U.S. Department of Energy. Long Term Management of the Existing Radioactive Wastes and Residues at the Niagara Falls Storage Site, DOE/EIS-0109D, Washington, DC, 1984.

Table 6. Typical Costs of On-Site Treatment Technologies*

These costs are presented to give some costs under the referenced conditions. They are not intended to be applicable to any particular site. Costs of returning "clean" treated material to a site are not included. Costs are mid 1980s.		
Treatment Technologies	Costing Units	Materials & Installation*
Stabilization/solidification (chemical fixation) ^a	ton	\$ 33 - 248
In situ vitrification ^b	cu m	\$161 - 224
On-site vitrification ^c	-	\$400 - 600

* Costs are from different sources and may be derived from different assumptions and therefore may not be directly comparable.

^a Costs provided are for hazardous waste [1]. Specific soil conditions could not be determined. Low costs are for in situ mixing; high costs are for in-drum mixing. The solidification agent is silicate and cement. The cost includes labor, equipment and material.

^b These are typical estimated costs for hazardous waste [1]. Soil moisture and electricity cost can increase the cost. Specific soil conditions have not been identified..

^c Cost includes excavation and on-site vitrification, but does not include cost for disposal of slag [7]. The material is radioactive residue from uranium ore processing. Cost increases with increasing moisture and electricity cost.

Chapter 4

Radon Control

4.1 Introduction

Although the main intent of this report is to summarize technologies that might be used to remove, contain, or immobilize the radioactive source materials in Superfund sites, where radioactivity has resulted from material processing or waste disposal operations, there may be sites where it is more desirable or logical not to disturb these materials, at least for an interim period.

Control processes using ventilation are already used to some extent to lower the radon concentration in residences contaminated with naturally occurring radon. Radon control from soil can be approached in three ways: (1) radon reduction in homes through soil gas ventilation; (2) electrostatic precipitator control; and (3) areal ventilation from the soil above the contaminated source mass. Each of these is discussed below. Table 7 shows the state of the art of radon control technologies.

4.2 Methods

4.2.1 Radon Control and Reduction in Buildings

4.2.1.1 Description and Development Status

Radon may accumulate to unacceptable concentrations indoors. EPA has provided guidance that recommends action at levels above 0.02 WL (4 pCi/l) to reduce annual average exposure to below those levels. Note in Table 8 that the average indoor concentration is estimated to be 0.005 WL. Although exposures between 0.005 and 0.02 WL do present

some risk of lung cancer, reductions of these levels may be difficult and sometimes impossible.

EPA has developed and implemented a program to evaluate various methods to reduce radon concentrations in residences [1]. The program is aimed at developing cost-effective technologies for reducing radon from naturally occurring sources in existing and new homes of all structural types. The first demonstration projects are underway in homes located in Pennsylvania, New York, New Jersey, Maryland, Tennessee, Alabama, and Ohio.

Radon reduction in homes is simple in concept. The EPA program recognizes three basic methods:

- (1) diversion of soil gas flow away from the house;
- (2) barriers to prevent entry to the house; and
- (3) reduction of concentration once it has entered the house.

The techniques that may be used to implement these methods are described in reference 2. The techniques include sealing entry cracks in foundations, forced ventilation of soil in and adjacent to the foundation, and natural and forced ventilation of the airspace inside the house. Examples of the techniques that may be used are depicted in Figures 9 and 10. However, each house must be addressed individually.

A variety of soil parameters influence radon movement, including thickness, densities, specific gravities, permeabilities, porosities, and moisture

Table 7. State of the Art of Radon Control Technologies

Technology	Laboratory Testing	Bench Scale Testing	Pilot Plant Testing	Field Demonstration with Radioactive Material	Radiologically Contaminated Site Remediation	Remarks
<i>Radon Control</i>						
- in homes				x	x	Requires maintenance
- ESP control			x	x		Requires maintenance
- areal control			x	x		Requires maintenance

Table 8. Representative Exposure to Radon-222 Progeny

Location	Average WL*	Average pCi/l*
Outdoors	0.001	0.2
Indoors	0.005	1.0

* WL = Working Level = a measure of exposure rate to radon progeny. Under equilibrium conditions of radon and its progeny, 1 WL equals the activity of 100 pCi/l of air. At the equilibrium (50%) generally considered representative of most indoor environments, 1 WL equals 200 pCi/l [2].

content. These parameters in turn affect the diffusion and emanation coefficients of radon [3].

4.2.1.2 Potential Applicable Situations

Site-specific house remediation techniques for radon levels are currently being demonstrated. The techniques apply to radon emanating from the underlying soil, whether the source is natural or a man-made waste mass. Radon control from buildings may be a viable interim technique while considering and implementing source removal alternatives.

4.2.1.3 Advantages and Disadvantages

Advantages – Radon reduction techniques for existing homes can be simple, effective, and relatively inexpensive. They may be temporary alternatives while awaiting removal of the source radionuclides, if this is being considered. However, in many instances, the solutions can be relatively difficult and expensive when the problem is not completely understood. Costs can run into thousands of dollars for a house if 90+ percent reductions are needed, especially for large highly-finished houses with poor sub-slab permeability.

Disadvantages – Radon reduction techniques do not affect the source of the radon, and therefore radon production at current rates can be expected to continue indefinitely. Thus, the reduction system must be maintained for as long as the building is occupied or the source is present. Radon removal systems do not address gamma radiation problems, potential ingestion pathways, or the potential for unearthing existing contaminated material.

4.2.1.4 Information Needs

Information needs include the levels of radon concentration inside the structure, an inventory of all the avenues of radon entry, the characteristics of the soil underlying the building, and the structural characteristics of the building.

4.2.2 Electrostatic Precipitators (ESPs)

4.2.2.1 Description and Development Status

Electrostatic precipitators (ESPs) are a form of indoor air cleaner. ESPs work on the principle that when particles suspended in air enter an electrostatic field they become charged and migrate under the action of the field to the positive electrode, where they are collected. The collected material is removed by rapping the collecting surface to slough off the particles. An ESP would be installed in a room or area so as to maximize the air contact. The ESP may reduce the number of particles (e.g. dust and smoke) to which radon progeny may be attached, resulting in a reduction of radon progeny in the air. The health effects of using ESPs in reducing radon progeny are not known.

4.2.2.2 Potential Applicable Situations

ESPs have been used to reduce the radon progeny levels in a store built with contaminated adobe bricks [4]. The technique could be applied for buildings where the source of contamination is building materials or the underlying soil.

4.2.2.3 Advantages and Disadvantages

Advantages – ESPs are easy to install in rooms or enclosed areas.

Disadvantages – ESPs do not affect the source of the radon. The reduction system must be maintained for as long as the building is occupied or the source is present. The ESPs do not reduce gamma radiation. The health effects of using ESPs are not known.

4.2.2.4 Information Needs

Information needs include the level of radon and radon progeny concentrations inside the room or area; the structural characteristics of the building; and air flow, volume, and pattern.

4.2.3 Soil Gas Venting and Areal Control

4.2.3.1 Description and Development Status

The term "soil gas venting," as used in this section, refers to techniques that may be applied across the entire area of gas production. For example, the gas extraction that is now relatively common in and around municipal solid waste landfills fits in this category.

Soil gas venting has been used to remove methane from municipal waste landfills and to remove organic vapors from underground leaks of organic compounds. Both active systems, where a fan or pump is used to induce gas flow, and passive

Figure 9. Tile ventilation where tile drains to sump. (Reprinted from [2].)

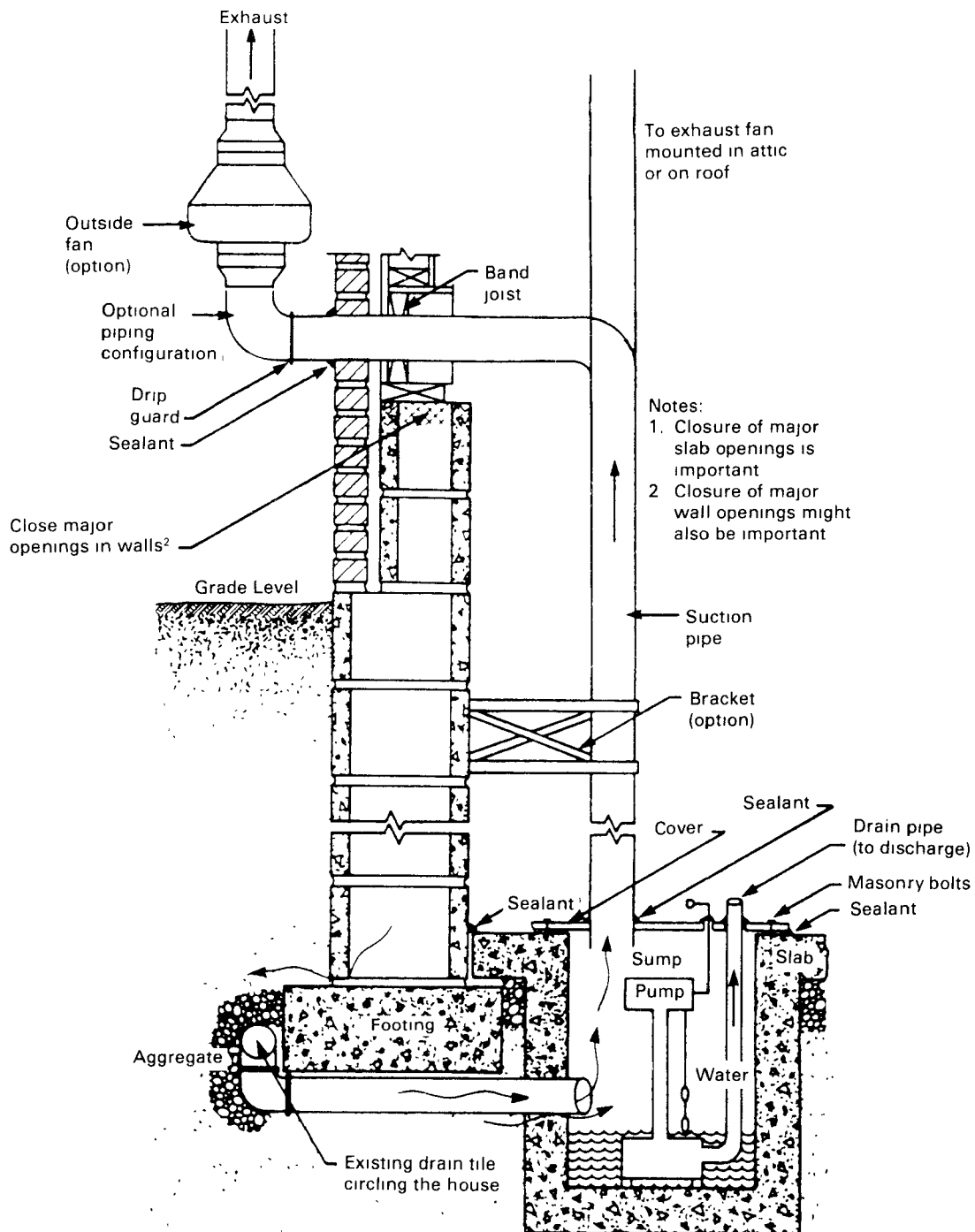
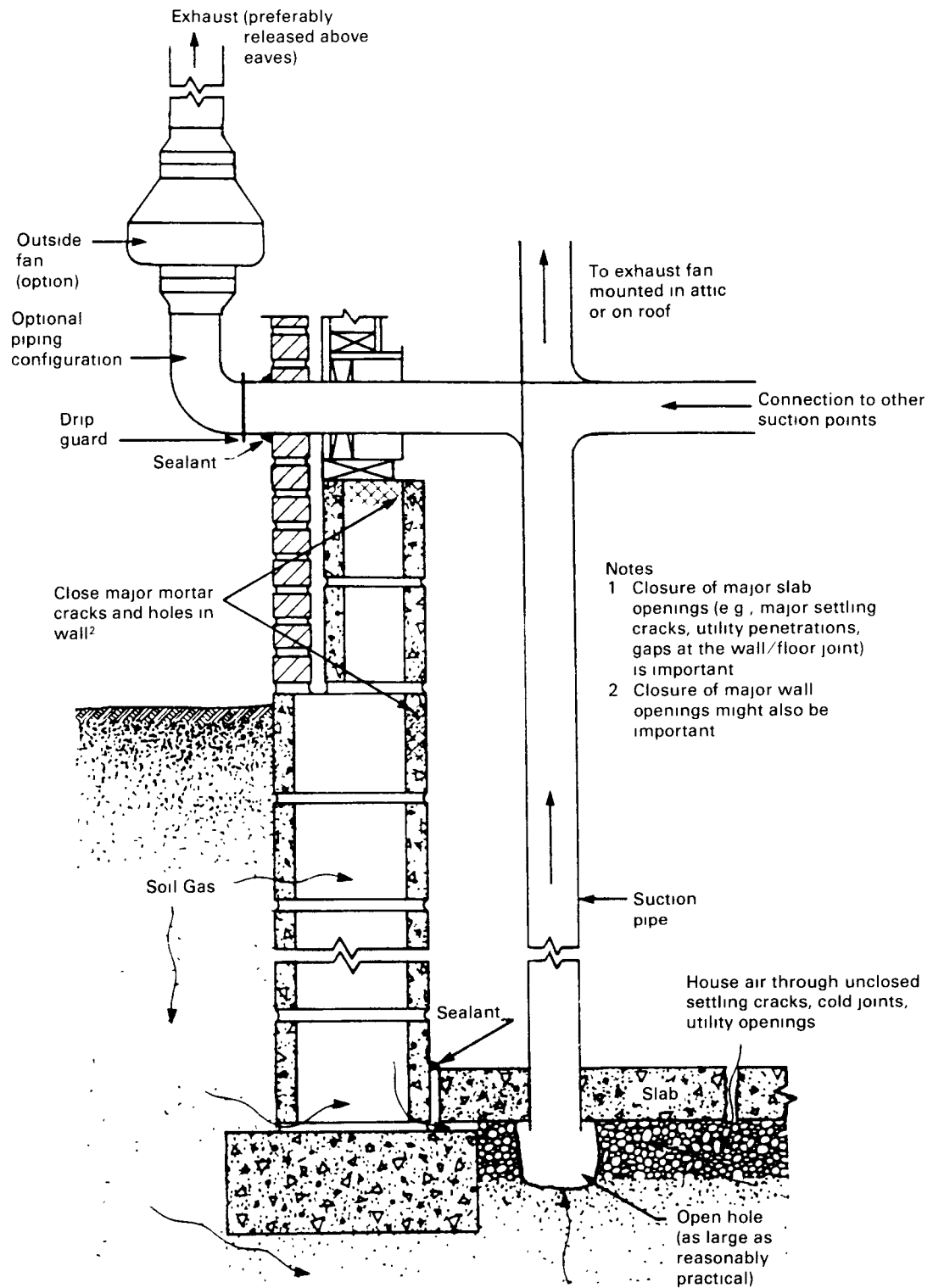


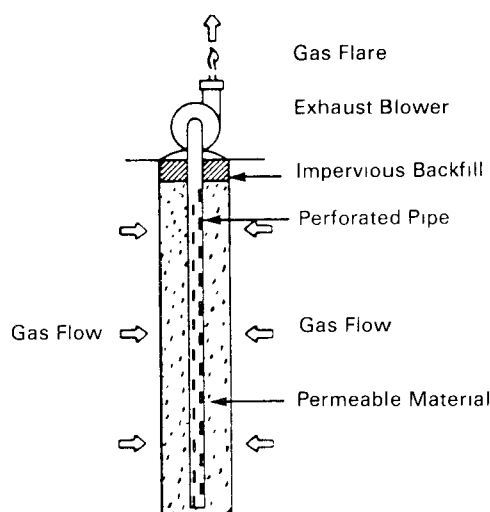
Figure 10. Sub-slab ventilation. (Reprinted from [2].)



systems, which rely on the natural flow, have been used to vent soil gases. These types of systems might be applied to vent radon from soils where radon diffusion and migration occur.

In landfill soil gas venting, a narrow perforated pipe is installed in the center of the extraction well and backfilled with coarse rock. The upper part of the well is sealed around the pipe with impervious material to prevent air from being pulled into the well, as shown in Figure 11. The perforated pipe is connected to a header system and fan to extract the gas. Gas withdrawal rates vary widely from site to site depending on the rate of methane and carbon dioxide generation and the landfill's porosity [5].

Figure 11. Gas extraction well for landfill gas control. (Reprinted from [4].)



Based on the same general principle, Terra Vac has successfully removed volatile organics from the soil at several sites in the United States. Terra Vac utilizes a vacuum pump to apply vacuum to the soil through wells, causing an in situ air stripping of volatile organic compounds. The extracted gases are discharged to the atmosphere through an activated carbon bed which adsorbs most volatile organics [6].

If used for radon removal, direct venting to the atmosphere may be appropriate. In some cases, the highly concentrated radon in the vented gas may be of such quantity that it cannot be released to the air immediately. In this case, the gas can be passed through a packed bed of activated carbon. Since soil gas tends to be saturated with moisture (1 - 2% by volume) the retention capacity of the carbon is somewhat reduced. At 20°C, activated carbon can adsorb 5000 to 9000 cc of radon-bearing air per gram of carbon depending on the type of carbon, temperature, and flow rates [7]. However, over years this could cause the carbon to become a low-level radioactive waste.

Active soil gas venting has also been applied to remove organic vapors from soil. In this remedial technology, soil gas is drawn from a well or set of wells constructed near one edge of the contaminated zone. To better induce the flow of vapor and to dilute the vapors, another well or set of wells is constructed on the opposite edge of the zone. By drawing air from one set of wells, a flow gradient is established across the contaminated zone, and vapors are drawn off [8].

Another type of active gas ventilation system, which relies upon pumping air into the soil at one location and pumping gases out at another location, may be more effective than other methods [9]. Figure 12 is a schematic diagram of this system.

Passive soil vent systems are relatively simple and inexpensive to construct and operate. However, they may be less effective than active systems in removing soil gas since much less gas flow occurs. The passive flow would be caused by barometric pressure changes and diurnal temperature changes that affect soil gas movement.

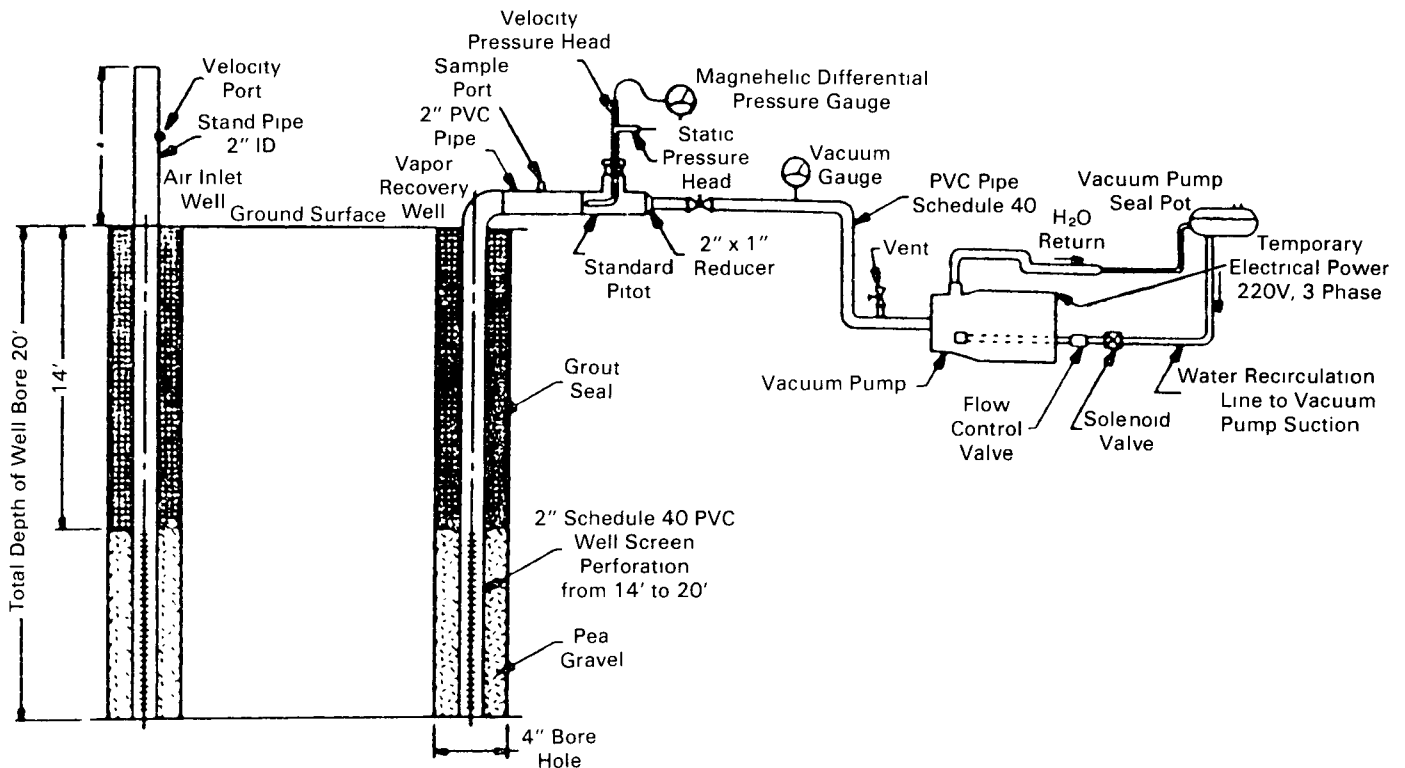
The effectiveness of any soil radon removal system is likely to be very site-specific, depending largely on the porosity of the soil, soil moisture content, the distribution of radium in the soil, and the chemical/physical matrix containing the radium. For example, if the radium were contained in a tightly compacted and/or wet matrix, the radon would not diffuse readily and probably would remain trapped until it decayed to its progeny. It should be noted that radon should not be removed from soil gas unless it is a proven source of indoor radon for an on-site or a nearby occupied structure. Radon in subsurface soil, unlike methane, presents no fire or explosion potential.

Even though soil gas venting is a popular methodology for dealing with volatile organic chemicals (VOC) in the soil and/or ground water, it has some large potential problems in radioactive applications. This method has been shown to be in violation of some State radiation emission standards, and charcoal beds may collect more than exempt quantities of radon decay products, making them licensable or registerable under State radiation statutes. Moreover, when these charcoal beds are incinerated to remove the VOC, they may impact Department of Transportation (DOT) regulations for radioactive materials (transport to out-of-state incinerator) and may impact a second state's radionuclide emission standards (at the incinerator).

4.2.3.2 Potential Applicable Situations

Radon gas venting from a radioactive waste site could be applied where the materials are highly porous (high permeability) and the radon could move freely to the extraction point. Sweden has used soil

Figure 12. Schematic diagram of a forced air venting system. (Reprinted from [9], Courtesy of American Petroleum Institute).



gas venting for radon removal in small areas for venting naturally occurring radon.

4.2.3.3 Advantages and Disadvantages

Advantages – Radon venting might supplant other remediation techniques. The entire operation could take place on the site without disturbing surrounding properties. It may be relatively low in cost.

Disadvantages – The radionuclide source material would remain in place. As long as it does, the radon removal system would have to operate, since radon would be produced indefinitely. The system would require a long-term maintenance program.

The soil, if it is not totally uniform and highly porous, would probably not be vented uniformly. Also, absence of sufficient data on this approach makes it somewhat unpredictable. This method does not address gamma radiation. Adsorbing radon onto carbon in large quantities may be unworkable. Areas with a high water table may generate large quantities of radioactively contaminated ground water, which must be treated and/or disposed.

4.2.3.4 Information Needs

The waste site would require detailed physical characterization in order to determine if the areal venting concept is practical and feasible.

4.3 Typical Costs of Radon Controls

Rough estimates of costs are provided in "Radon Reduction Techniques for Detached Houses - Technical Guidance" [2] for various radon reduction techniques for residences. The cost estimates are based upon the experience of EPA and a number of investigators. A summary of these rough estimates is included in Table 9.

Typical capital costs for soil gas venting systems range from \$10 - \$12 per cu m for shallow VOC deposits (at less than 20 feet) [10]. The cost includes site preparation, drilling, piping, blowers, electricals, decontamination and demobilization. The typical operating cost for a soil gas venting system is \$12 - \$14/cu m/yr. The operating cost includes cost of electricity, carbon, water, and labor.

Table 9. Typical Costs of Various Radon Reduction Techniques in Existing Homes [2]

Reduction Technique Operating	Installation Cost (\$)	Annual Cost (\$)
Natural ventilation	0	1.1 to 3 × normal heating cost
Forced ventilation	50-1000	1.1 to 3 × normal heating cost + \$275/yr for electricity
Forced ventilation with heat recovery	800-2500	1.1 to 2.0 × normal heating cost + \$30/yr for electricity
Avoidance of appliance depressurization	100-300 (install ducts)	small
Sump ventilation	800-2500 (contractor-installed) 300 (home owner-installed)	\$130/yr
Sealing entry routes	300-500*	low
Drain tile ventilation	700-1500 (contractor) 300 (home owner)	\$130/yr\$
Active wall ventilation	1500-250	\$230-460/yr\$
Sub-slab ventilation	900-2500	\$130/yr\$

* For average sealing. A comprehensive sealing job would run much higher.

4.4 References

1. U.S. Environmental Protection Agency. Report to Congress on Radon Mitigation Demonstration Programs under Section 118(k) of the Superfund Amendments and Reauthorization Act of 1986, 1987.
2. U.S. Environmental Protection Agency. Radon Reduction Techniques for Detached Houses - Technical Guidance. Second Edition EPA-625/5-87-019. Office of Research and Development, Washington, DC, 1987.
3. Nuclear Regulatory Commission. Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers. (Draft) 1987.
4. Nichols, F. D., J. M. Brink, and P. C. Nyberg. Cleanup of Radiation Mill Tailings from Properties in Monticello, Utah. Presented at the Hazardous Materials Control Research Institute Superfund Conference, November 1984.
5. Shafer, R. A., A. Renta-Babb, J. T. Bandy, E. D. Smith, and P. Malone. Landfill Gas Control at Military Installations. Technical Report N-173, U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, 1984.
6. Malot, J.J., and P.R. Wood. Low-Cost, Site-Specific Total Approach to Decontamination. Presented at the Environmental and Public Health Effects of Soils Contaminated with Petroleum Products Conference. University of Massachusetts, Amherst, 1985.
7. A. D. Little, Inc. Advanced Techniques for Radon Gas Removal. Bureau of Mines Publication PB-243898. 1975.
8. Benneds M. B. Vacuum VOCs from Soil. Pollution Engineering, 1987.
9. Crow, W. L., E. P. Anderson, and E. Minugh. Subsurface Venting of Hydrocarbon Vapors from An Underground Aquifer. API Publication 4410, pp. 3-10, Washington DC, 1984.
10. Roy F. Weston, Inc. Task II, In Situ Air Stripping of Soils Pilot Study. U.S Army Toxic and Hazardous Materials Agency, Final Report, October 1985.

Chapter 5

Chemical Extraction

5.1 Purpose

There are several separation techniques that have the potential to clean radiologically contaminated soils and tailings. The objective of these technologies would be to concentrate the radioactive contaminants, thereby reducing the volume of soil for disposal. Chemical extraction is one type of separation technology, which uses chemicals to extract the radionuclides from soils and tailings. Other separation technologies that might be used to clean soils and tailings are discussed in Chapters 6 and 7 of this report.

The chemical extraction technology generates several soil fractions. One or more fractions contain the concentrated radioactive contaminants; the other "cleaner" soil fractions may contain unextractable traces of radioactive contaminants.

The concentrated radionuclide-contaminated soil fractions would require off-site disposal. The intent could be to return the "cleaner" soil fractions, which would be a major portion of the soil by volume, to the point of origin (the original excavation). Standards for returning the cleaner soil fractions to the point of origin do not currently exist.

It should be emphasized that none of the chemical extraction techniques have been demonstrated at full scale to remove radionuclides from waste masses. Many of these techniques are used in ore beneficiation processes to remove a single constituent. The waste soils often contain radium, thorium and uranium, which must all be removed. The real practicability of these techniques to remove radionuclides in a field application remains to be demonstrated. The various potential chemical extraction techniques are discussed in this section.

5.2 State of the Art

Concern about environmental and health problems related to uranium mill tailings has resulted in an extensive study of methods for extracting radionuclides from soils and uranium mill tailings. These studies were initiated in order to examine the migration characteristics of radium in contaminated soils and uranium mill tailings, and to examine

chemical extraction as a potential method for tailings remediation [1-4].

References at the end of this section contain reviews of those techniques with the potential for cleaning radiologically contaminated soils and mill tailings. These include extraction with:

- water
- inorganic salts
- mineral acids
- complexing reagents

There are notable differences in the extractability rates of these methods. These extractability differentials are caused by the types of soils, ores, and tailings studied as well as varying conditions within and between the methods. There also have been occasional inconsistencies in results obtained under similar experimental conditions. In spite of these differences and inconsistencies, significant trends in each method are evident and are reported here.

Though the chemical extraction technologies have been extensively used in extraction of uranium from mineral ores, their use in cleaning contaminated soils and tailings to acceptable limits has been limited to laboratory and pilot plant testing. Table 10 shows the state of the art of the chemical extraction technologies. The applicability of these technologies would be controlled by site-specific factors, and their capability must be determined on a site by site basis. Research and development activities would be necessary prior to full scale mobilization of these technologies for site cleanup.

5.3 Technologies of Potential Interest

This section discusses the four chemical extraction techniques listed previously. These technologies produce an extractant containing a radionuclide, which must be treated to concentrate and collect it for disposal. This section also discusses the following chemical methods for separation and collection of extracted radionuclides from the extractant:

- Precipitation and coprecipitation

- Solvent extraction
- Ion exchange

Membrane filtration, which is a physical method used to separate and collect the radionuclide from the extractant, is briefly discussed in Chapter 6 of this report.

5.3.1 Extraction of Radionuclides from Soil or Tailings with Water

5.3.1.1 Description and Development Status

This process would use water to extract the radionuclide contaminants. Contaminated soil or tailings would be mixed with large quantities of water. The water, with the soluble radionuclide, could be separated from solids by a combination of physical separation methods described in Chapter 6.

The radionuclide would then be extracted from the liquid by coprecipitation, solvent extraction, or by ion exchange (discussed later in this chapter).

Water solubility studies have been performed primarily to examine the leachability of radionuclides from soils and mill tailings [5-9]. Extraction of uranium from water is also being studied [10-13], even for uranium concentration less than 3 ppb.

The water solubility of radium salts varies. Chloride, bromide, nitrate, and hydroxide are water soluble, while fluoride, carbonate, phosphate, biphosphate, and oxalate are only slightly soluble.

The sulfate is essentially insoluble in water and dilute acids but is soluble in concentrated sulfuric acid (H_2SO_4). Radium sulfate is the least water soluble of the alkaline earth sulfates and probably the least water soluble radium compound known. Barium sulfate is only slightly more soluble than radium sulfate. The water soluble salts of thorium include nitrate, sulfate, chloride, and perchlorate. Most prominent of the insoluble thorium salts are hydroxide, oxide, fluoride, oxalate, phosphate, peroxide, and hydride. Uranium salts that are soluble in water include bromide, chloride, carbide, sulfate,

and hexafluoride. The key insoluble uranium salts are oxide, tetrafluoride, and tribromide.

The extraction of radium from soil is dependent on the liquid to solid ratio and optimum time for leaching. Reference materials in this area [5-7] indicate that a 15-minute leaching time removes the optimum amount of radium; the incremental amount extracted declines after that time to almost no extraction after 2 hours.

Generally, the extraction of radium with deionized water removes less than 10 percent of the cation from the samples studied. As little as 0.1 percent [8] has been extracted, but as much as 40 percent has been removed [6] under exceptionally high liquid to solid ratios (10,000:1). In one study [9] water removed 75 percent of the $RaSO_4$ from very fine (-150 mesh) slime solids. The removal of thorium with water was reported to be 3 percent in a study of uranium mill tailings (4.5 percent radium and 22 percent uranium were removed), but the water was probably acidic as a result of H_2SO_4 in the mill pond from the uranium leaching process [12]. Soil samples from the sites of former radium extraction companies in Denver, Colorado and East Orange, New Jersey that were extracted with water released only 0.1 to 2.3 percent of the radium present and less than 1.5 percent uranium [8].

A detailed investigation of corresponding experiments carried out in Japan, West Germany, and the U.S. has led to the development of specific plant concepts for extracting uranium from sea water [10,11,13].

The typical cost of extracting uranium from sea water is around \$300/lb. However, enormous cost differentials, ranging from \$11 to \$1,400/lb, have been reported [13].

5.3.1.2 Potential Applicable Situations

This method of extraction has not been demonstrated in the field for cleaning soil or mill tailings. Laboratory testing is needed to identify an applicable situation. Since many of the soil cleaning techniques use water as part of their process, this method can be used as

Table 10. State of the Art of Chemical Extraction Technologies

Technology	Laboratory Testing	Bench Scale Testing	Pilot Plant Testing	Field Demonstration with Radioactive Material	Radiologically Contaminated Site Remediation	Remarks
<i>Chemical Extraction</i>						
- With water	x	x				
- With inorganic salts	x	x				
- With mineral acid	x	x	x	x		Used in extraction of radium, thorium and uranium from ores
- With complexing agents	x	x	x	x		Used in extraction of uranium from ores

pretreatment. Presence of sulfate in the soil will decrease the amount of radium that can be extracted.

5.3.1.3 Advantages and Disadvantages

Advantages – The main advantages of using water are that it is very inexpensive, completely nontoxic, uses ambient temperatures, and utilizes simple extraction vessels. The technique can be used to dissolve some radionuclide salts. It can be used as a pretreatment technique to reduce interference at subsequent extractions.

Disadvantages – This method requires a large quantity of water. The process is relatively ineffective for removing radioactivity from soils; less than 10% removal for radium and virtually none for thorium has been demonstrated.

5.3.1.4 Information Needs

Extraction with water requires the following information:

- Physical, chemical, and mineralogical characteristics of the soil.
- Radionuclide concentration for each particle size fraction.
- Amount of water available.
- Water analysis for total suspended solids, pH, hardness, background radiation, etc.

5.3.2 Extraction of Radionuclide from Soil and Tailing with Inorganic Salts

5.3.2.1 Description and Development Status

Radionuclide contaminants can be extracted by thoroughly mixing soil and mill tailings in a solution containing inorganic salt. The slurry is filtered, separating the extractant from the solid. The radionuclide contaminant is separated from the extractant by ion exchange, coprecipitation, or membrane filtration [4]. No field demonstration of soil cleaning using this process has yet been attempted; all the research work so far consists of laboratory experiments.

A review of the literature indicates a broad range of results with the use of salt solutions to remove radium and thorium from mill tailings and soils. In many cases the effectiveness of a given salt appears to be related to several obvious variables, such as the nature of the tailings or soil (geochemistry, radionuclide concentration, method of extraction, particle size distribution, and chemical composition), the concentration of the salt solution, temperature, pH, solid to liquid ratio, time, and temperature [3-7,9,12,14-16].

An increasing ratio of salt solution to solid, as with water, plays a positive role in the effectiveness of the

salt solution in removing radionuclides from ore tailings and soils [3,5,9]. Multistage extraction increases the effectiveness of the radium extraction essentially by increasing the ratio of solution to solid [4,5,15]. One study [12] reported as little as 0.4 percent of radium removed from radium mill tailings with 0.1 M sodium chloride (NaCl). On the other hand, another study [4] reported 94 percent removal with a 3 M NaCl solution at room temperature in a three-stage process using 20 liters of solution per kilogram of tailings, and 90 percent with 1 M NaCl. In another study 50 percent of the radium was removed in a single-stage extraction with a 3 M NaCl solution [5]. Using 3 M potassium chloride (KCl), 91 percent of the radium-226 was removed in a two-stage leaching process at room temperature [16].

The extraction of thorium by salt solutions has received less attention than the extraction of radium. One study [12] reported that, while 13 percent of the radium was removed from uranium mill tailings with a 0.1 M NaCl solution, only 0.02 percent of the thorium was removed. In another experiment, no thorium was removed by a 3 M NaCl solution, while 62 percent of the radium was extracted. However, a study of various inorganic phosphates [17] indicates that 60-80 percent of both radium and thorium can be removed by sodium hexametaphosphate ((NaPO₃)₆) from a fine particle fraction (-200 mesh) of uranium tailings that were produced by leaching with H₂SO₄. The study also indicated that salt interferes with the removal of uranium during the H₂SO₄ extraction process. Other phosphate salts (orthophosphate, pyrophosphate, tripolyphosphate) were not effective in extracting thorium from the tailings.

The ability of the salt to extract radium or thorium is primarily reflected in the solubility of the compound or complex that it forms with radium and thorium. The presence of sulfate in soil greatly affects the ability of the inorganic salts to extract radium, since the radium sulfate that is formed is the least soluble radium compound encountered in mill tailings. Hydroxide is the analogous anion in thorium chemistry since thorium hydroxide is the least soluble thorium compound encountered. It is reported in one study of uranium mill tailings [3] that the radium-leaching power of several anions decreases as follows: Cl⁻ > NO₃⁻ > HCO₃⁻ > HO₄⁻ > PO₄⁻³. It was also found that washing to remove soluble sulfates before radium leaching helps dissolve the radium.

The effectiveness of aluminum salts in dissolving radium and thorium is minimal, probably as a result of the hydrolysis of the cation, producing a gelatinous precipitate that retains radium by adsorption. This is particularly important since many soils and tailings contain aluminum and similar cations. The barium cation also was found to be less effective than sodium in solubilizing radium, supporting the hypothesis that an insoluble barium radium sulfate

(Ba(Ra)SO₄) salt is a major form of radium in most mill tailings. [5]

The barium cation would be expected to be effective in releasing radium bound by adsorption on particles containing metal hydroxides, silicas, and clays but ineffective in solubilizing the Ba(Ra)SO₄.

The effectiveness of cations of various salts in releasing radium decreases in the following order [3]: Cs⁺ > Ca⁺² > Mn⁺² > NH₄⁺ > K⁺ > Na⁺ > Li⁺.

5.3.2.2 Potential Applicable Situations

Inorganic salt extraction has not undergone field demonstration for cleaning radiologically contaminated sites. Laboratory or pilot plant testing will be needed to identify applicable situations. The presence of sulfates in the soil will greatly affect radium removal, as sulfates will form radium sulfate, the least soluble radium compound. The presence of hydroxide in soils and tailing will similarly affect thorium removal. The use of salts interferes with the removal of uranium by sulfuric acid. This process should not be used as pretreatment to an acid extraction process.

5.3.2.3 Advantages and Disadvantages

Advantages – A high percentage of radium and thorium may be removed. Processes may operate at ambient temperatures. Most salts are relatively innocuous. Simple extraction vessels are required. Recycling of salts may be possible.

Disadvantages – Large amounts of salts may be required with large solution-to-solid ratios. Some salts, such as chloride, may be environmentally undesirable.

5.3.2.4 Information Needs

For extraction by salt solution, the following information is required.

- Physical, chemical, and mineralogical characteristics of the soil.
- Amount of water available.
- Water analysis for total suspended solids, pH, hardness.
- Background radiation, etc.

5.3.3 Extraction of Radionuclide from Soil and Tailings with Mineral Acids

5.3.3.1 Description and Development Status

Historically, radium has been extracted from carnotite ores with mineral acids – H₂SO₄, hydrochloric acid (HCl), or nitric acid (HNO₃) [18,19]. Under favorable conditions, up to 97 percent of the radium was removed. Thorium ores are extracted industrially with

(among other reagents) fuming H₂SO₄ or HNO₃ [20]. Uranium is also extracted from mineral ores by acid leaching [21].

Sulfuric acid, rather than hydrochloric or nitric acid, is commonly utilized for leaching in uranium extraction due to its less corrosive nature and lower costs.

In all these processes the ores are ground to 28 mesh and mixed with water to form a slurry. The slurry is pumped into a leach circuit, maintaining a pulp consistency of 50 percent solids. The solids are separated from the leach liquid by physical methods. The radionuclides are removed from the leach solution by ion exchange, solvent extraction, or precipitation [21].

It appears from a survey of recent reports on the extraction of radium and thorium that these metals are readily extracted by several mineral acids from soils and soil components [3,5,7,22], ores, and ore tailings [8,9,14,15,23-28]. Although fuming H₂SO₄ is used in industrial processes for the removal of thorium from ores as soluble thorium sulfate Th(SO₄)₂ [20], one would not expect the acid to be useful for the extraction of radium, considering the insolubility of radium sulfate (RaSO₄). However, RaSO₄ is somewhat soluble in concentrated H₂SO₄ [29], and several studies have indicated that the hot acid will remove between 70-80 percent of the radium and 80-90 percent of the thorium from uranium mill tailings [24,28]. A recent study [25] demonstrated that between 14-40 percent radium can be removed from uranium ores by dilute H₂SO₄ in a countercurrent process at 72°C, in the presence of oxidizing agents; approximately 86 percent of the thorium was removed.

Nitric acid has proved to be very efficient in the extraction of radium and thorium [9,26,30]. Generally, the best results with ores and ore tailings have been achieved with approximately 3 M HNO₃ solution at temperatures between 70° and 80°C for about 5 hours in two- or three-stage processes with liquid-to-solid ratios of 2:1 to 4:1. For example, 97 percent radium and 99 percent thorium were removed from uranium ore or ore tailings (H₂SO₄ or carbonate leached) with 3 M HNO₃ at 70°C in a two-stage process, with a reaction time of 5 hours [26]. Over 99 percent of the uranium was also removed from the ores. The resulting Ra-226 level was as low as 17 pCi/g, and the thorium level was 7 pCi/g [26]; the tailings before nitric acid extraction contained 716 pCi/g Ra-226 and 88 pCi/g Th-230, respectively.

Similar results were achieved using HNO₃ with ores, slimes, solids, and sand tailings [9], with 89 percent removal of radium in a one-stage process with 6 percent solid loading. A six-stage, batch crosscurrent process [31] removed 98 percent of the radium from ores and tailings with a final Ra-226

level of 10 pCi/g. Remarkably similar results have been obtained with HCl solutions [9,8,23,25]. Like HNO₃ extractions, the best results occur with 1.5 to 3 M HCl at about 70°- 85°C with multiple extractions. Ninety-three percent of radium (< 28 pCi/g) and 86 percent of thorium removal was achieved in a four-stage, countercurrent process in the presence of other oxidants [25].

More than 95 percent of the radium was removed with 3 M HCl at 85°C in one hour with a liquid-solid ratio of 4:1 [9] and 92 percent radium-226 was removed with 1.5 M HCl at 60°C in a three-stage leaching process with a 4:1 solid to liquid ratio [23]. Depending on the size of the soil particles and the nature of the soil, 27% to 100% of Ra-226 extraction has been demonstrated in the laboratory from soil contaminated with radium mill tailings using 0.1 M HCl.

Combining dilute acids with inorganic salts has produced leaching solutions that achieve results similar to those of the more-concentrated acid solutions [9,14,15,27]. Mixed NaCl and HCl solutions were used to extract radium from mill tailings [9,14]. In a three-stage process (30 minute stage) 94 percent of radium was removed with 0.3 M NaCl in 0.1 M HCl at 25°C [14]. Calcium chloride (CaCl₂) in HCl has produced very good results even at room temperature. Removal of 96 percent of the uranium, 97 percent of the radium, and 75 percent of the thorium with 0.045 M CaCl₂ in 0.125 M HCl at room temperature in a two-stage leaching process has been reported [27]. A 91 percent removal of Ra-226 and 79 percent removal of Th-230 were obtained from tailings with 1 M CaCl₂ in 0.1 M HCl at 21°C and a 2:1 liquid-to-solid ratio with 30 minutes contact time.

An acidic environment would be expected to have a positive influence on the release of cations such as radium and thorium from soils and tailings that have the potential to bind metal ions. This is especially important in determining the extracting power of various acid solutions on ores and tailings, since most of these materials contain soil particles with a large amount of amorphous silica (up to 90 percent) and hydrated metal oxides such as aluminum and iron oxides.

Adsorption on surfaces of amorphous silica or hydrated metal oxides is strongly affected by the acidity of the environment [2,3]. The surface charge of silica is positive at pH <1, is zero between pH 1 and 3, and becomes progressively more negative above pH 3 [2].

Hydrated metal oxides that have aged will not readily dissolve in acid solutions, but an increase in acid concentration will diminish the number of oxide sites available for binding [3], thus enhancing the

dissolution of radium and thorium. Natural organic acids, such as humic and fulvic acids found in soils, tend to decrease their binding capacity thus increasing the dissolution of radium and thorium. Increased concentrations of HNO₃ and HCl also will promote the dissolution of Ba(Ra)SO₄. With increased concentration, the salt dissolves in water with the formation of barium hydroxide (Ba(OH)₂), a slightly soluble base, and the more soluble radium hydroxide (Ra(OH)₂), which are converted by the acids to more soluble salts, barium chloride (BaCl₂) or barium nitrate (Ba(NO₃)₂) and radium chloride (RaCl₂) or radium nitrate (Ra(NO₃)₂) [25].

5.3.3.2 Potential Applicable Situations

Mineral acid extraction techniques are being developed and have been used to extract radium, thorium, and uranium from mineral ores. Improvement to these acid extraction processes has been demonstrated in the laboratory. These demonstrations show that the acid extraction processes can remove most of the metals, both radioactive and nonradioactive, and therefore may be applicable for cleaning radiologically contaminated sites.

5.3.3.3 Advantages and Disadvantages

Advantages – An advantage of extraction with acids is that a high percentage of radium and thorium removal is possible. Uranium and other metals would also be removed. These processes require relatively small liquid-to-solid ratios compared to extraction with water or inorganic salts, thus requiring less pumping power and smaller holding and reaction vessels. Costs can be reduced if the acids are recycled.

Disadvantages – The main disadvantage of this process would likely be the increased operating and capital costs due to expensive reagents, higher operating temperatures, and the stainless steel reaction vessels and pipes needed because of the corrosiveness of acid. A multistage process is needed, which adds to the costs. A major disadvantage of these techniques is that the anions, such as NO₃⁻ or Cl⁻, are environmentally undesirable. The resulting chemically leached material may create a waste stream that is more harmful than the original tailing mixture.

5.3.3.4 Information Needs

The analyses and requirements listed below are required in implementing treatment procedures.

- Physical, chemical, and mineralogical characteristics of the soil.
- Radionuclide concentration in each particle size fraction.
- Amount of water available.

Water analysis for total suspended solids, pH, hardness, background radiation, etc.

5.3.4 Extraction of Radionuclides from Soil and Tailings with Complexing Agents

5.3.4.1 Description and Development Status

This process differs from acid extraction in that complexing agents like EDTA (ethylenediamine-tetraacetic acid) are used instead of mineral acids.

Radium forms stable complexes with many organic ligands (a molecule or anion that can bind to a metal ion to form a complex). For that reason, several complexing agents have been investigated as potential candidates for extraction of radium from uranium mill tailings [3,9,31-34] and, in one case, from soils [35]. Thorium is not likely to be removed by complexation.

Several successful radium extraction tests with complexing agents have been reported. Up to 92 percent (to 40 pCi/g) of radium content was removed from mill tailings using 0.15 M Na₂ EDTA at 60°C, pH 10, and a liquid-to-solid ratio of about 7/1 in a three-stage process [23]. After collecting the Ra as Ba(Ra)SO₄, the EDTA was recovered for reuse by lowering the pH. Another study [33] removed 80-85 percent of the Ra with a 0.04 M EDTA solution at pH 10, 23°C, and a liquid-to-solid ratio of 2:1. A pre-wash with water (25 l/kg) removed calcium sulfate (CaSO₄), which tends to interfere with the extraction. Using 6.65% sodium diethylenetriaminepentaacetic acid complex (Na₅ DTPA), another study [34] reported removing up to 85 percent of the radium. The crosscurrent or countercurrent process used in this study obtained maximum yields after 2 hours at 20°-25°C with a liquid-to-solid ratio of about 9:1.

A recent study [32] described a reducing-complexing treatment for the leaching of radium from uranium mill tailings. A reducing agent, sodium hydrosulfite (Na₂S₂O₄), is added in order to reduce Fe⁺³ and similar cations. Using 0.04 M Na₂ EDTA, 0.04 M Na₂S₂O₄ and 1 M KCl (to mask the adsorption sites on silica) for 1 hour at pH 10 with a liquid-to-solid ratio of 10:1, 87 percent of the radium was removed, leaving 44 pCi/g in the residue.

Adopting a procedure of keeping the liquid-to-solid ratio initially high and slowly adding the tailings to the leach solution had a major effect on radium extraction, reducing the residue from 44 to 31 pCi/g radium. A comparison with several other complexing agents using 0.1 M solutions of the agents under the same conditions was made: Citrate removed 67 percent to 120 pCi/g, and nitrilotriacetic acid (NTA) removed 85 percent to 48 pCi/g. Note that these solutions are 2.5 times more concentrated than the Na₂ EDTA solution (0.04 M). This study also reported

the recovery of 92 percent of the Na₂ EDTA by bringing the leach solution to pH 1.8.

Most of the studies of radium extraction with complexing agents have been with EDTA. Radium extraction during leaching is improved by keeping the radium concentration low in the solution, particularly in order to shift the equilibrium representing the dissolution of Ba(Ra)SO₄ [3].

One would expect thorium extraction to be assisted by complexing with EDTA or another suitable complexing agent. Leaching of radium with EDTA is generally performed at pH 8 and 10. Unfortunately, above pH 3 thorium forms a very insoluble hydroxide whose formation competes with the formation of the thorium EDTA complex. Thus, at a pH where the formation of an EDTA complex with thorium would be favored, the thorium cation is not available for complexation.

Other cations found in soils and tailings, such as Fe⁺³ and Ti⁺⁴, behave in a similar fashion and compete with Ra⁺² dissolution by forming insoluble hydroxides that adsorb the cation. Studies [3] have determined that the result of these competing equilibria will prevent the dissolution of radium with EDTA. But with the appropriate reducing agent, Fe⁺³, Ti⁺⁴, and similar cations will be reduced to lower oxidation states that tend to form more soluble hydroxides.

The radium EDTA complex formation will then compete favorably with hydroxide formation, causing the hydroxides to be solubilized, releasing radium adsorbed on these materials [2,3]. Thorium cations are not reduced to lower oxidation states, subsequently forming more soluble hydroxides. Therefore, radium extraction would be assisted by prior extraction of thorium.

5.3.4.2 Potential Applicable Situations

This method of extraction has not been field demonstrated for radiologically contaminated soils and tailings. Laboratory experiments show that radium forms stable complexes with EDTA, suggesting its potential for application in cleaning radium from soils and tailings with low concentrations of thorium. Soils and tailings with high concentrations of thorium may require prior extraction of thorium before using this technique to extract radium.

5.3.4.3 Advantages and Disadvantages

Advantages – One of the main advantages of extraction of radionuclides with a complexing agent would be the expected high percentage of radium removal. Low reagent concentrations are required, and the reagent can be recycled, thus reducing operating costs. The process works at ambient

temperatures, and many of the reagents are innocuous. Therefore, expensive materials such as stainless steel for vessels and piping would not be needed.

Disadvantages – Complexing reagents are very expensive. This process would not remove thorium, therefore, other processes might be required to remove thorium prior to the removal of radium by complexing agents. A multiple-stage process is probably required, adding to the capital and operating cost.

5.3.4.4 Information Needs

The following information is required prior to extraction with complexing agents.

- Physical, chemical, and mineralogical characteristics of the soil.
- Radionuclide concentration in each particle size fraction.
- Amount of water available.
- Water analysis for total suspended solids, pH, hardness, total dissolved solids, background radiation, etc.

5.3.5 Technologies for Separating Radionuclides from Extractant

The previous section discussed the leaching and extraction technologies that produce a pregnant liquor containing the radionuclides.

Radium and thorium extracted from soils and mill tailings will be in solution with many other molecular and ionic compounds. Some of the ions may be simple, while others will be complex, depending upon the nature of the sample to be extracted and the leaching solution(s). Other molecular substances and material will probably be present as colloids. Still other fractions will be in suspension and will separate upon settling or filtering.

The support technologies utilized in treating the extractant to remove the radionuclides for disposal are:

- precipitation and coprecipitation
- solvent extraction
- ion exchange
- membrane filtration

The first three technologies are chemical methods and are discussed in this chapter. The last, membrane filtration, is a physical separation method and is discussed in Chapter 6.

5.3.5.1 Description and Development Status

Precipitation and Coprecipitation – By addition of chemicals the radionuclides can be precipitated. Several stages of precipitation at controlled pH are used. The pH is readjusted in the precipitation tank near the end of the circuit. The slurry from the precipitation tank is dewatered in thickeners and followed by filtration (see Chapter 6 for description of dewatering technologies). The filter cake, containing the concentrated radionuclide, is then ready for disposal. Precipitation, however, produces products with impurities. This may not be a problem on cleaning soils and tailings. However, in extraction of uranium from ore, solvent extraction or ion exchange is used before precipitation to obtain a purer product.

Radium forms a very insoluble salt with sulfuric acid. Sulfuric acid is commonly used to form a precipitate of RaSO_4 , but sodium sulfate (Na_2SO_4) is also used [29]. Thorium may be precipitated as a highly insoluble, gelatinous hydroxide with alkali or ammonium hydroxide [1]. Thorium is also precipitated by sodium oxalate/oxalic acid solutions at a pH of 1.2 from acid solutions [36]. The concentration of radium and thorium cations in the extractant from soil and mill tailings may be low enough that a direct precipitation process would not be appropriate to the collection of these radionuclides. Radium and thorium may be coprecipitated by the addition of a simple precipitating agent such as H_2SO_4 .

Small quantities of radium cations can be coprecipitated from solution with many different carrier compounds [29,37].

The use of the classical radium carrier, BaSO_4 , to precipitate radium from leach solutions has been reported by several investigators [4,23,31,32,38,39]. A review [36] of other natural organic carriers (such as tannin and gelatin) reported that these carriers removed 90 to 100 percent of the radium in coprecipitation processes. In a study [4] it was found that BaSO_4 is slightly soluble in a HNO_3 leach solution (0.07 g/l in 3 M HNO_3); however, 95 to 100 percent of radium may be coprecipitated from nitric acid leach solutions using very dilute (<10 mM) BaCl_2 solutions in the presence of sulfate ions [4,31]. The use of a silica-bed filter to remove $\text{Ba}(\text{Ra})\text{SO}_4$ has also been suggested for the removal of radium from uranium mill tailings [32].

Thorium coprecipitates with a wide variety of insoluble hydroxides such as iron, zirconium, and lanthanum as well as zirconium iodate or phosphate from acid solutions [20]. Calcium fluoride and calcium oxalate are also used as coprecipitants [38]. One study [40] reported that 60 to 100 percent of the thorium coprecipitates with BaSO_4 solution; lower concentrations of thorium (<0.09 mM) removed the largest amount of the cation. Another study [39] used

an oxalate to remove thorium from a 3.6 M HNO_3 leach solution. The oxalate is very insoluble in HNO_3 ; no radium was carried by the coprecipitate. Using 20 percent NaOH , more than 96 percent of the thorium was coprecipitated in the presence of Fe at a pH of 4.2 as ferric hydroxide ($\text{Fe}(\text{OH})_3$) [38].

Uranium is precipitated from solution by addition of sodium hydroxide, gaseous ammonia, hydrogen peroxide, or magnesia. Precipitation using sodium hydroxide, sulfuric acid, and gaseous ammonia produces purer uranium with little sodium.

For a plant processing 10,000 tons of uranium ore per month, the typical capital and operating cost of precipitation circuits are estimated to be \$750,000 and \$0.50 per ton of ore processed, respectively. [41,42,47]. These costs are in 1985 dollars. These costs are for uranium ore processing and are not intended to be applicable to any particular site.

Solvent Extraction – Solvent extraction is an efficient method for separating uranium on a commercial scale [42]. There are no commercial solvent extraction processes to extract radium or thorium. The solvent extraction, as applied to uranium extraction plants, consists of a two-step process. In the first step, termed "extraction," the dissolved uranium is transferred from the feed solution (or aqueous phase) into the organic or solvent phase. The second step, called "stripping," recovers the purified and concentrated uranium product into a second aqueous phase after which the barren organic is recycled back to the extraction step. The aqueous and organic solutions flow continuously and countercurrently to each other through the required number of contacting stages in the extraction and stripping portions of the circuit. The uranium is recovered from the second aqueous solution by precipitation.

The extraction of metal from the aqueous solution and its eventual transfer to another aqueous solution (the strip liquid) involves the use of various reagents (extractants, diluents, and modifiers) and requires a suitable vessel to bring about intimate contacts between the different liquids. The extractants are the reagents in the solvent that extract the metal ions. Extractants that are used in recovery of uranium from acid leach solutions are alkylphosphoric acid, amines, tri-n-butyl phosphate (TBP) and trioctyl phosphine oxide (TOPO).

The diluents comprise the bulk of solvent and are inert ingredients whose principal function is to act as carrier for the relatively small amount of extractant. Kerosene is the most commonly used diluent, although other organics such as fuel oil, toluene, and paraffins are also used. The most commonly used modifiers for increasing the solubility of the extracted

species are long chain alcohols such as isodecanol [41,42].

Radium compounds have very low solubilities in organic solvents [43]. In most extraction procedures for separating radium from other elements, those other elements are usually extracted into the organic phase [29]. For example, the use of 2-thenoyl-trifluoroacetone (TTA) or tributylphosphate (TBP) has been successful in the separation of radium from other elements. However, a mixture of TTA and TBP in carbon tetrachloride (CCl_4) has been used to extract radium for quantitative analysis [29]. Radium tetraphenylborate has been removed by nitrobenzene from an alkaline solution, and solutions of 8-hydroquinoline (HOQ) and some of its derivatives will also remove radium from an alkaline solution [43,44,45]. This extraction characteristic may be significant in the separation of radium from thorium in leach solutions. There is no reported use of these solvent systems for the removal of radium from soils, ores, or mill tailings.

Organic solvents are used extensively for the extraction of thorium from ore and mill tailings leach solutions [31,36,38,39] and for the extraction of the cations in analytical procedures [20,43,29]. Generally, these procedures take advantage of the solubility of inorganic complexes such as thorium chlorides, thorium nitrates, or thorium sulfates in organic solvents. Thorium sulfates are formed during leaching of the ore with H_2SO_4 and thorium nitrates, and thorium chlorides are produced by the HNO_3 or HCl dissolution, respectively, of precipitated thorium hydroxide. The most common organic solvent used in these extractions is TBP. For example, a 30 percent TBP in kerosene was used in the extraction of thorium from the H_2SO_4 [38] liquor. In another study [39] 30 percent TBP in normal-hexane was used. Still another study [31] used 30 percent TBP in normal- dodecane for HNO_3 solutions of thorium from leach solutions. A review of the extraction of thorium [36] listed over two dozen organic solvent systems involving TBP, other organophosphates, and various amines, which are applied to remove thorium and actinides from leaching acids such as H_2SO_4 , HCl , and HBr .

Primary amines and straight-chain secondary amines have also been used to extract thorium in the processes for the recovery of uranium and thorium from ores. After the extraction of uranium with triisooctylamine, thorium is removed with 5 percent sec-dodecyl or 5 percent di(tridecyl)amine in kerosene.

For processing of uranium ore at a rate of 10,000 tons of ore per month, the typical capital and operating costs for a solvent extraction circuit were estimated as one million dollars and \$1.00/ton of ore processed, respectively [42,47]. These costs are in

1985 dollars. These costs are based on uranium ore processing and are not intended to be applicable to any particular site.

Ion Exchange – Leaching used in extraction of uranium and other minerals is a nonselective process resulting in the dissolution of elements in addition to the desired constituents. Ion exchange is one process used for concentrating the desired constituents from the leached solutions. The resin ion exchange technique involves the interchange of ions between the aqueous solution and a solid resin. This provides for a highly selective and quantitative method for recovery of uranium and radium. The process of removing dissolved ions from solution by an ion exchange resin is usually termed adsorption in the uranium industry [4,21,42,46,47].

There are several resins available for extraction of both radium and uranium. For uranium extraction by ion exchangers, strong and intermediate base anionic resins are loaded from either sulfuric acid or a carbonate leach feed solution. The loaded resin is stripped with a chloride, nitrate, bicarbonate, or an ammonium sulfate-sulfuric acid solution to remove the captured uranium. These resins are semirigid gels prepared as spherical beads. Radium can be extracted by using synthetic zeolites.

The total amount of uranium that may be adsorbed is a function of the quantity of anionic complex in solution. Two to five pounds of U_3O_8 can be captured for each cubic foot of resin. Higher capacity is not possible because of competition for ion sites in the resin by other anions present.

The other anions present in the acid solution that compete with uranium for resin sites include HSO_4^- , SO_4^{2-} , and various impurities that dissolve along with the uranium during leaching. The extent to which one of these anions adsorbs on the resin is influenced by its concentration in solution relative to other ions, pH, and by the relative affinity of the resin for the anion.

Removal of the uranium from the saturated resin is termed elution. It is customary to refer to the eluting solution as the eluant and to the final effluent as the eluate. Chloride elution is best accomplished in acid circuits with concentrations of from 0.5 to 1.5 M Cl^- . Nitrate elution can also be used at a 1 M NO_3^- content.

The ion exchange process is, in most plants, a semicontinuous series of operations integrating the adsorption and elution steps with various stages of washing, resin regeneration, etc.

There are three types of ion exchange systems: fixed bed, moving bed, and resin-in-pulp.

For a fixed bed ion exchange system, cylindrical pressure vessels with dished ends are usually constructed of steel and lined with rubber for corrosion resistance. The resin bed rests upon a bed of crushed and sized rock, which is in turn supported either by a flat rubber-covered steel false bottom or the dished bottom of the column.

For a moving bed ion exchange system, the resin is transferred to separate columns for adsorption, backwashing, and elution. This procedure has been performed in six Canadian plants, one U.S. processing plant, and two U.S. mine water recovery plants. The major plant installations utilize ten columns per set, with two groups of three on adsorption, one group of three on elution, and one special column for transfer and backwashing. This arrangement eliminates the danger of mixing leached solution and eluate solution due to improper operation.

The moving bed processing cycle does not vary significantly from that in the fixed bed plants, except that either two or three columns are continuously on adsorption without interruption, and elution is conducted with three columns in series.

For a basket resin-in-pulp ion exchange system, the resin is contained in cube-shaped baskets formed of stainless steel and covered with either stainless steel or plastic screen cloth.

The baskets are moved up and down at a rate of between six and twelve strokes per minute in rectangular shaped tanks containing flowing slurry or eluting solution. The basket movement consolidates the resin bed during an up stroke, thereby squeezing out residual solution, and expands the bed for free solution access during the down stroke. From six to eight stages are employed in adsorption and from seven to fourteen in elution, with more stages required when sulfuric acid is used for elution.

Some of the new developments in ion exchange equipment are:

- Porter and Stanton contactor. Resin passes downward and solution flows upward.
- Higgins contactor. A single column divided into two sections by rotating valves.
- Jigged bed ion exchange. Uses jigged action in the resin to cause more dense uranium loaded resin. Department of Defense is investigating the use of the equipment to clean a missile site in New Jersey.
- Winchester Fixed Bed. Pulp flow is introduced through an oscillating distributor.

- Bureau of Mines ion exchange. Divides the adsorption column into compartments separated by orifice plates.

Based on an ion exchange system with a capacity of 200 tons per day, the typical capital cost estimates range between \$300,000 and \$1,000,000. The operating cost estimates for that tonnage capacity range between \$1 and \$3 per ton of soil processed. [42,47] These costs are for processing of uranium ore and are not applicable to any particular site.

5.3.5.2 Potential Applicable Situations

Precipitation and Coprecipitation – Precipitation and coprecipitation have been used in some extraction schemes to separate uranium from the leach liquor. All currently operated uranium extraction plants, with the exception of a few using a carbonate leaching circuit, employ precipitation to recover the uranium from the solvent extraction stripping liquor or from the ion exchange eluate. Precipitation could be used directly to extract the radionuclide from the water and inorganic salt extraction pregnant liquor.

Solvent Extraction – Solvent extraction is the preferred technology for extracting uranium from acid leach liquor circuits. However, it has not proved feasible to apply solvent extraction to carbonate leach liquors or to slurries containing appreciable amounts of solids [42].

Ion Exchange – The use of ion exchange has been documented in a number of applications. These include:

- Decontamination of uranium mill processing water and water pumped from the mine. Ion exchange also has been used to remove radium from uranium mill tailings [47].
- The Mining Science Laboratory in Canada has demonstrated ion exchange extraction as a means of cleaning the leach liquor from tailings for uranium, thorium, and radium [48].
- Extraction of uranium in several plants in the U. S. [42].
- An alkaline leaching process in which ion exchange is used to extract the impurities and produce a high grade liquor for precipitation and recovery of uranium [21].

5.3.5.3 Advantages and Disadvantages

Advantages – Precipitation and coprecipitation are used extensively in uranium recovery operations. They can be operated in both batch and continuous operation mode, and involve low capital cost.

Since solvent extraction technology involves only liquid-liquid contacts, it is readily adaptable to other systems and can be performed as a continuous

operation. Solvent extraction is also readily adaptable to efficient and economical automatic continuous operation. Other advantages of solvent extraction are better selectivity and greater versatility than ion exchange.

Ion exchange is an excellent and economic method for removing very fine radioactive contaminants from liquids. In the absence of ion exchange equipment, more expensive ultrafiltration or solvent extraction techniques are used. Ion exchange is less sensitive to the volume or grade of liquor than the solvent extraction techniques. Ion exchange has been extensively used in cleaning radioactive contaminants from nuclear power plant water streams, providing a valuable database for the development of ion exchange equipment to clean contaminated soils.

Disadvantages – Precipitation and coprecipitation involve a difficult, cumbersome, and costly operation requiring complex chemical separation. Close control of operating conditions is required. The pH must be monitored and controlled to have better product recovery. The precipitation procedure is not adaptable to automatic control, and most plants currently operate on manual.

The main disadvantage of solvent extraction is that the feed solution must be essentially free of solids. It has not proved economically feasible to apply solvent extraction to carbonate leach liquors. Emulsion formation in solvent circuits causes trouble. The small loss of solvent to tailings is not only costly, but may be a source of stream pollution. Solvent reagents are also very costly. The solvent extraction process is more sensitive to the volume and grade of liquor than the ion exchange process. Molybdenum is strongly extracted by amines and builds up in the amine, acting as poison.

In using ion exchange, impurities in the liquor can overload the ion exchange resins. Trace metals such as molybdenum, vanadium, radium, and sulfate in the leached liquor can poison the resin, reducing its life.

5.3.5.4 Information Needs

The analyses listed below must be considered in preparing to implement precipitation, solvent extraction, and ion exchange procedures.

- Chemical composition and trace ion analysis of the leach liquor.
- Solid content and pH of the liquor.
- Trace element content

5.4 Typical Costs of Chemical Extraction Technologies

It is estimated that the typical cost for chemical extraction would range from \$50-150 per ton of soil,

assuming that the waste is in a form suitable for the use of these technologies. Transportation and disposal costs for the concentrated and "clean" fractions are not included in the above figure. Because of lack of process data, the costs of some of the chemical extraction technologies are based on profitable ore processing techniques and not on the costs of removing enough radioactivity from the contaminated material to render it "clean." As such, these costs could be much higher. Since more detailed process information is lacking, these figures represent an educated guess. These costs are not intended to be applicable to any particular site.

5.5 References

1. Landa, E. R. Isolation of Uranium Mill Tailings and Their Component Radionuclides from the Biosphere - Some Earth Science Perspectives. Circular 814, U.S. Geological Survey, Arlington, Virginia, 1980.
2. Shoesmith, D. W. The Behavior of Radium in Soil and in Uranium Mill Tailings. AECL-7818, Whiteshell Nuclear Research Establishment, Pinawa, Canada, 1984.
3. Nirdosh, I., S. V. Muthuswami, and M. H. I. Baird. Radium in Uranium Mill Tailings - Some Observations on Retention and Removal. Hydrometallurgy, 12:151-176, 1984.
4. Ryan, R. K., and D. M. Levins. Extraction of Radium from Uranium Tailings. CIM Bulletin, October, 1980, pp. 126-133.
5. Levins, D. M., R. K. Ryan, and Strong. Leaching of Radium from Uranium Tailings, OECD Nuclear Agency Publication. In: Proceeding of the OECD/NEA Seminar on Management, Stabilization and Environmental Impact of Uranium Mill Tailings, pp. 271-286, Albuquerque, New Mexico, 1978. OECD, Paris, France, 1978.
6. Shearer, S. D., Jr., and G. F. Lee. Leachability of Ra-226 from Uranium Mill Solids and River Sediments. Health Physics, 10:217-227, 1964.
7. Havlik B., J. Grafova, and B. Nycova. Radium-226 Liberation from Uranium Ore Processing Mill Waste Solids and Uranium Rocks into Surface Streams. Health Physics, 14:417-422, 1968.
8. Landa, E. R. Geochemical and Radiological Characterization of Soils from Former Radium Processing Sites. Health Physics, 46:385-394, 1984.
9. Seeley, F. G. Problems in the Separation of Radium from Uranium Ore Tailings. Hydrometallurgy, 2:249-263, 1977.
10. Best, F. R., and M. J. Driscoll (Eds.), Proceedings of a Topical Meeting. Energy Lab. Rep. MIT-EL80-031, 1980.
11. Kanno, M. Energy Developments in Japan, Vol. 3. Rumford Publishing Company Inc., 1980. pp. 67-89
12. Landa, E. R. Leaching of Radionuclides from Uranium Ore and Mill Tailings. Uranium, 1:53-64, 1982.
13. Organization for Economic Cooperation and Development (OECD). Uranium Extraction Technology - Current Practice and New Development in Use Processing. OECD, Paris, 1983.
14. Torma, A. E. A New Approach to Uranium Mill Tailings Management. NMERDI 2-69-1308, New Mexico Energy Research and Development Institute, Santa Fe, New Mexico, 1983.
15. Torma, A. E., N. R. Pendleton, and W. M. Fleming. Sodium Carbonate - Bicarbonate Leaching of a New Mexico Uranium Ore and Removal of Long Half-Life Radionuclides from the Leach Residue. Uranium, 2:17-36, 1985.
16. Torma, A. E. Extraction of Radionuclides from Low-Grade Ores and Mill Tailings. EMD 2-68-3620, New Mexico Energy Research and Development Institute, Santa Fe, New Mexico, 1981.
17. Hawley, J. E. Use of Phosphate Compounds to Extract Thorium-230 and Radium-226 from Uranium Ore and Tailings. NSF/RA-800528, Hazen Research Corp., Golden, Colorado, 1980.
18. d'Aguiar, H. D. Radium Production in America I. Chemical and Metallurgical Engineering, 25:825-828, 1921.
19. Landa, E. R. A Historical Review of the Radium-Extraction Industry in the United States (1906-1926) - Its Processes and Waste Products. In: Proceedings of the Fourth Symposium on Uranium Mill Tailings Management. Fort Collins, Colorado, 1981. pp. 3-32.
20. Albert, R. E. Thorium: Its Industrial Hygiene Aspects. Academic Press, New York, 1966.

21. Clark, D. A. State of the Art: Uranium Mining, Milling and Refining Industry. USEPA/600/2-74-038, 1974.
22. Nathwani, J. S., and C. R. Phillips. Rates of Leaching of Radium from Contaminated Soils: An Experimental Investigation of Radium Bearing Soils from Port Hope, Ontario. Water, Air, and Soil Pollution, 9:453-465, 1978.
23. Borrowman, S. R., and P. T. Brooks. Radium Removal from Uranium Ores and Mill Tailings. RI-8099, U.S. Bureau of Mines, Salt Lake City Research Center, Salt Lake City, Utah, 1975.
24. Dreesen, D. R., M. E. Bunker, E. J. Cokal, M. M. Denton, J. W. Starner, E. F. Thode, L. E. Wangen and J. M. Williams. Research on the Characterization and Conditioning of Uranium Mill Tailings 1. Characterization and Leaching Behavior of Uranium Mill Tailings. LA-9660-UMT, Vol. 1, DOE/DMT-0263, Los Alamos National Laboratory, Los Alamos, New Mexico, 1983.
25. Haque, K. E., and J. J. Laliberte. Batch and Counter-Current Acid Leaching of Uranium Ore. Hydrometallurgy, 17:229-238, 1987.
26. Ryon, A. D., F. J. Hurst, and F. G. Seeley. Nitric Acid Leaching of Radium and Other Significant Radionuclides from Uranium Ores and Tailings. ORNL/TM-5944, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1977.
27. Torma, A. E., and S. Y. Yen. Uranium Ore Leaching with Brine Solutions Containing Hydrochloric Acids. Erzmetall, 37:548-554, 1984.
28. Williams, J. M., E. J. Cokal, and D. R. Dreesen. Removal of Radioactivity and Mineral Values from Uranium Mill Tailings. In: Proceedings of the Fourth Symposium on Uranium Mill Tailings Management, Fort Collins, Colorado, 1981. pp. 81-95.
29. Vdovenko, V. M., and Dubasov, Yu. V. Analytical Chemistry of Radium, Analytical Chemistry of the Elements. D. Malament, ed. John Wiley and Sons (Halstead Press), New York, 1975.
30. Seeley, F. G. Removal of Radium and Other Radionuclides from Vitro Tailings. Memo to A.D. Ryon, Oak Ridge National Laboratories, Oak Ridge, Tennessee, 1976.
31. Scheitlin, F. M., and W.D. Bond. Removal of Hazardous Radionuclides from Uranium Ore and/or Mill Tailings: Progress Report for the Period October 1, 1978, to September 30, 1979. ORNL/TM-7065, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1980.
32. Nirdosh, I., S. V. Muthuswami, M.H.I. Baird, C.R. Johnson, and W. Trembley. The Reducing-Complex Treatment for the Leaching of Radium from Uranium Mill Tailings. Hydrometallurgy, 15:77-92, 1985.
33. Nixon, A., D. Keller, K. Fritze, A. Didruczny, and A. Corsini. Radium Removal from Elliot Lake Uranium-Mill Solids by EDTA Leaching. Hydrometallurgy, 10:173-186, 1983.
34. Yagnik, S. K., M.H.I. Baird, and S. Banerjee. An Investigation of Radium Extraction from Uranium Mill Tailings. Hydrometallurgy, 7:61-75, 1981.
35. Taskayev, A. I., V. Ya. Ovchenkov, R.M. Altkashin, and I. I. Shuktomova. Effect of pH and Liquid Phase Cation Composition on the Extraction of ²²⁶Ra from Soils. Pochvovedeniye, 12:46-50, 1976.
36. Phillips, C. R., and Y. C. Poon. Status and Future Possibilities for the Recovery of Uranium, Thorium, and Rare Earths From Canadian Ores, with Emphasis on the Problem of Radium Part I: Ores, Special Problem, and Leachings. Minerals Science Engineering, 12:53-72, 1980.
37. Sedlet, J. Radon and Radium. pp. 219-316. In: Treatise on Analytical Chemistry, Vol. 4. I. M. Kolthoff, and P. J. Elving, eds. John Wiley and Sons (Interscience Publishers), New York, 1966.
38. Kluge, E., K. H. Lieser, I. Loc, and S. Quandt. Separation of ²³⁰Th (Ionium) from Uranium Ores in Sulfuric Acid and in Nitric Acid. Radiochemica Acta, 24:21-26, 1977.
39. Ryon, A. D., W. D. Bond, F. J. Hurst, F. M. Scheitlin, and F.G. Seeley. Investigation of Nitric Acid for Removal of Noxious Radionuclides from Uranium Ore or Mill Tailings. In: Proceedings of Two OECD/NEA Workshops on Uranium Mill Management, OECD Nuclear Agency Publication, OECD, Paris, France, 1982. pp 139-147.
40. Ambe, S. and K. H. Liefer, Coprecipitation of Thorium with Barium Sulfate, Radiochemica Acta, 25:93-98, 1978.
41. Buskin, A.R. The Chemistry of Hydrometallurgical Processes. Span Limited, London, 1966.

-
42. Merritt, R. C. Extraction Metallurgy of Uranium, Colorado School of Mines Research Institute, 1971.
 43. Kirby, H. W., and M. L. Salutsky. The Radiochemistry of Radium, NAS-NS-3057, National Technical Information Service, Springfield, Virginia, 1964.
 44. Sebesta, F., J. John, and V. Jirasek. Extraction of Radium and Barium Phosphomolybdates into Nitrobenzene in the Presence of Polyethyleneglycol. Radiochem, Radioanal, Letters, 30:357-364.
 45. Sebesta F., E. Bilkova, and J. Sedlacek. Extraction of Radium and Barium into Nitrobenzene in the Presence of Polyhedral Borate Anions. Radiochem, Radioanal, Letters, 40:135-144, 1979.
 46. Raicevic, D. Decontamination of Elliot Lake Uranium Tailing. CIM Bulletin, 1970.
 47. Logsdail, D.H. Solvent Extraction and Ion Exchange in the Nuclear Fuel Cycle. John Wiley & Sons, New York, 1985.
 48. Rulkens, W.H., and J.W. Assink, et. al. Development of an Installation for On-Site Treatment of Soil Contaminated with Organic Bromine Compounds. Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, DC, 1982.

Chapter 6

Physical Separation Processes

6.1 Purpose

Radioactive contaminants in soils and in uranium mill tailings may be associated with fine soil particles [1-3]. Separation of the fine soil particles should concentrate the radioactive contaminants in fine soil fractions, and thus reduce the volume of soil for disposal, permitting more manageable soil disposal.

The physical separation techniques that can be utilized to separate out or concentrate radioactive contaminants within soils are discussed in this chapter. These separation techniques are also utilized in the pre- or post-treatment phases of chemical extraction treatment schemes. Physical separation techniques are mechanical methods for separating mixtures of solids to obtain a concentrated form of the desired constituents. Chemical agents are added in some cases to enhance the separation process. Methods for separation by mechanical rather than by chemical means are usually low in cost and trouble-free. There are a variety of physical separation techniques, each with a particle size range; they are shown in Table 11 along with the physical attributes that govern the separation processes [4-6]. In any given process a combination of these physical separation techniques is employed to achieve the required concentration of the desired constituents.

6.2 State of the Art

Most of the radium in uranium mill tailings occurs in very fine particles, or slimes. Borrowman and Brooks used physical separation techniques to separate tailings into sand (coarse particle) and slime [1]. Physical separation of the tailings, which contained radium levels of 500 and 450 pCi/g, resulted in coarse particle fractions with 50 and 140 pCi/g radium, respectively.

Garnett et al. scrubbed plutonium-contaminated soil with wash solution and then used physical separation techniques to separate the clean sand [2]. Results from a few of the tests showed that coarse particle fractions of the soil can be cleaned to contamination levels of <1, 12, and 86 pCi/g for soils contaminated with 45, 284, and 7515 pCi/g of plutonium, respectively.

Treatment of Elliot Lake uranium mill tailings in Canada showed that much of the radium, thorium, and uranium can be removed using physical separation techniques [3]. The laboratory test at CANMET and bench-scale testing at the Denison Mill employing physical separation techniques reduced the radium contamination levels in tailings from 290 and 266 pCi/g to 57 and 45 pCi/g, respectively.

Based on a literature review, the following physical separation technologies show potential for cleaning soils contaminated with radioactivity:

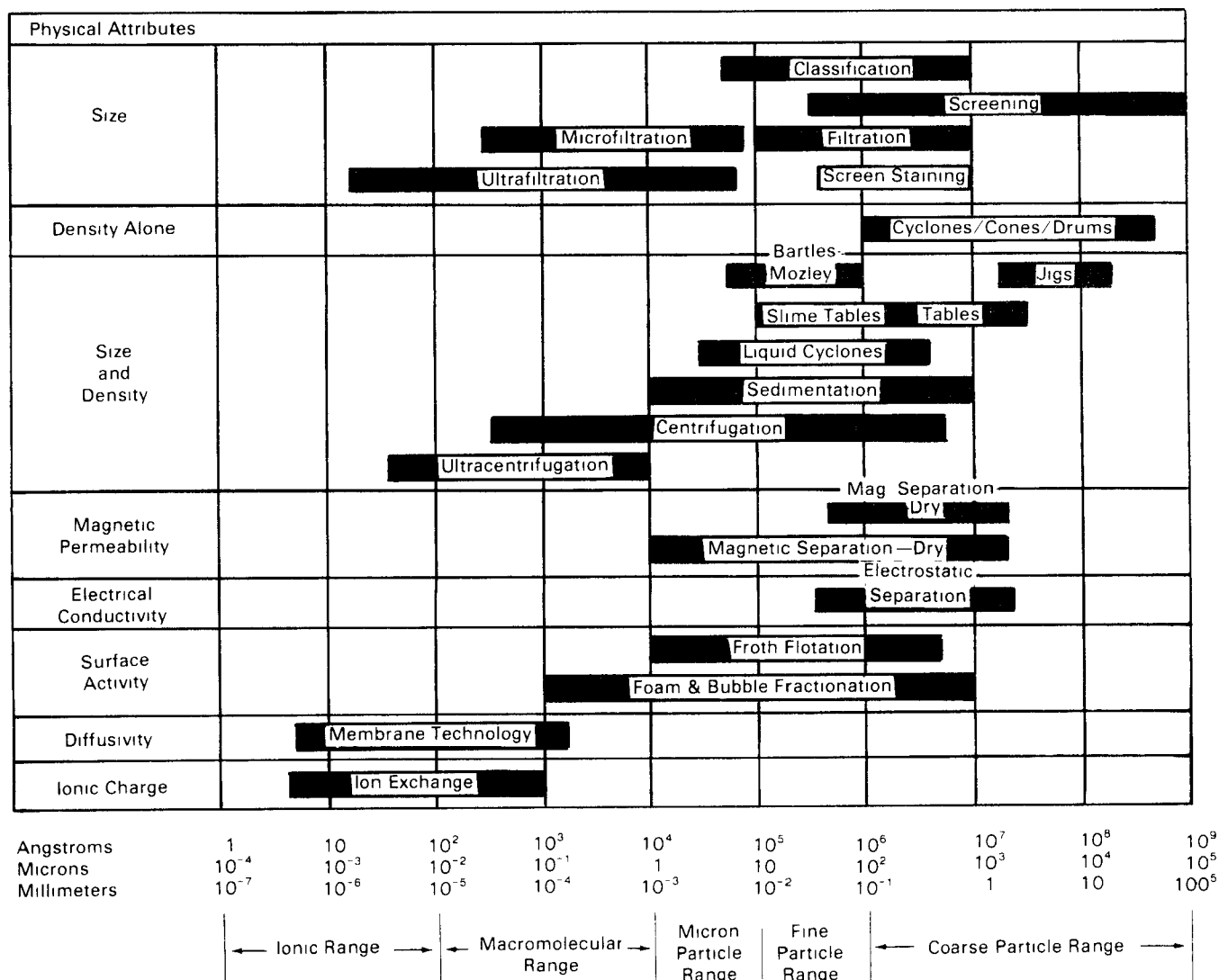
- screening, both dry and wet
- classification
- flotation
- gravity concentration

Sedimentation and filtration supplement these techniques.

All the above physical separation processes are used extensively in uranium extraction. Screening, gravity concentration, and flotation comprise part of the physical separation methods used in preparing the uranium ore for extraction. The prepared ore is then normally acid-leached, and the particles are separated using classification and ion exchange. References 7-10 discuss the physical separation techniques used in many uranium processing operations. Shown in Figure 13 is a process used to clean plutonium-contaminated soil using physical separation techniques. In this process a variety of technologies, including screening, classification, sedimentation, and filtration are employed to separate the soil into different size fractions and to separate out the water. Other processes used to decontaminate soil probably would include some combination of these.

The state of the art physical separation technologies are shown in Table 12. As can be seen from this table, although these technologies have been field demonstrated for radioactive material extraction from ores, they have not been used in remediating any radiologically contaminated sites. Pilot plant testing

Table 11. Physical Separation Technology and Particle Size



would be needed to determine their capability for radiologically contaminated site cleanup.

Selection of the physical separation technology for soil cleaning is dependent on the properties of the contaminated soil and concentration of radionuclides in each particle size fraction.

There are several other separation techniques used in the mining industry, which will be described briefly but not in detail because of their limited applicability for removing radioactive contaminants from soils and tailings. These techniques include:

- heavy media separation
- magnetic separation
- electrostatic separation

Heavy media separation techniques use heavy liquids of suitable density to separate light and heavy

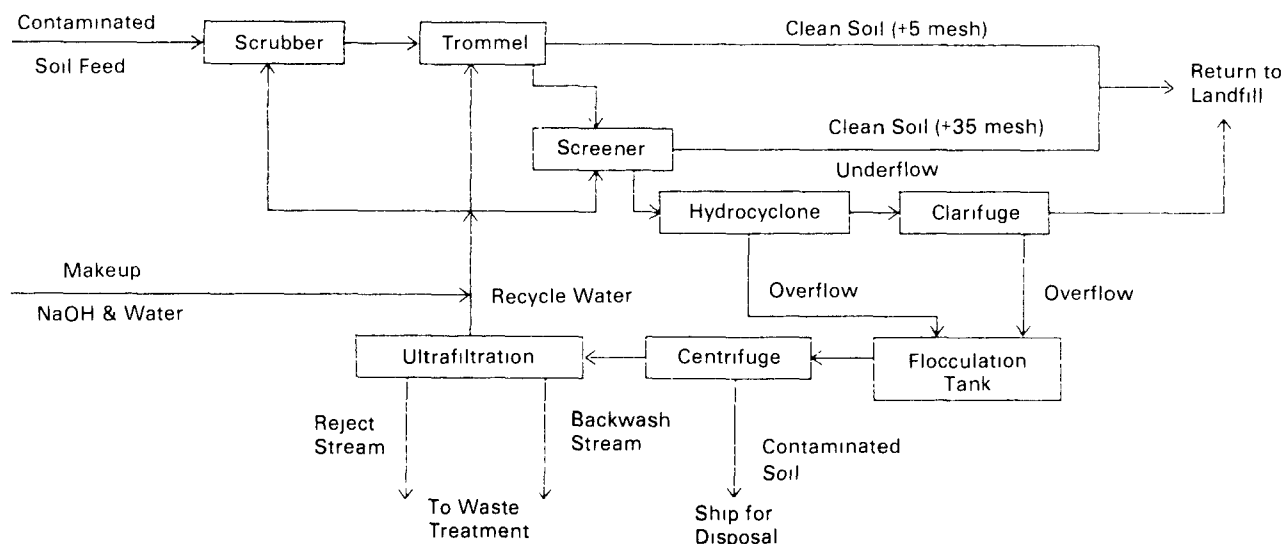
particles [6,11,12]. Heavy media separation is possible if the contaminant is in loosely aggregated coarse particles. If the contaminant is finely disseminated throughout the soil, then this technique will not work. Also, the heavy liquids used give off toxic fumes.

Magnetic separation [6,11-13] and electrostatic separation [6,11,12,14] exploit the difference in magnetic and conductive properties between the radioactive contaminants and the soil to effect the separation. As with heavy media separation, if the contaminant is finely disseminated throughout the soil, these separation techniques are not likely to work.

6.3 Technologies of Potential Interest

This chapter discusses the physical separation technologies mentioned above. With the exception of

Figure 13. Pilot-scale equipment test for soil decontamination. (Reprinted from [2].)



dry screening, all technologies--screening, classification, flotation, and gravity concentration--use substantial quantities of water as part of the process. The final concentrate must be separated from the water before disposal. The separated water is normally purified and recycled, thereby reducing the water usage. The solid/liquid separation techniques, sedimentation and filtration, are also discussed in this chapter.

In general, one has to be concerned with dust control for dry physical separation processes and the treatability of liquid wastes which are generated in wet physical separation processes. These are important issues that need to be addressed carefully before technology selection.

6.3.1 Screening

6.3.1.1 Description and Development Status

Screening is the mechanical separation of particles on the basis of size. Such separations are achieved using a uniformly perforated surface. Particles larger than the screen openings are retained on the surface, while smaller particles pass through. Material retained on the surface is the *oversize* or *plus* (+) material; that passing through is the *undersize* or *minus* (-) material; and material passing one surface but retained on a subsequent surface is *intermediate* material. Perfect separation is seldom achieved. There are always some undersize particles left in the oversize fraction. Nevertheless, an almost complete separation can be achieved with the use of a slow feed and a consequently long screening period [6-8,11,15-17].

Table 12. State of the Art of Physical Separation Technologies

Technology	Laboratory Testing	Bench Scale Testing	Pilot Plant Testing	Field Demonstration with Radioactive Material	Radiologically Contaminated Site Remediation	Remarks
Physical Separation						
- Screening			x	x		Used in extraction of radium, thorium, and uranium from ores
- Classification			x	x		Used in extraction of radium, thorium, and uranium from ores
- Gravity concentration			x	x		Used in extraction of radium, thorium, and uranium from ores
- Flotation		x	x	x		Used in extraction of radium, thorium, and uranium from ores

Screening is normally limited to materials larger than 250 microns, with finer sizing obtained by classification. In addition to size, there are many factors affecting the passage of the particle through the screen, including screening efficiency, particle shape, angle of approach, and particle orientation to the screen. The closer to the perpendicular the angle of approach, the higher the chance of passage. Taggart gives some probabilities of passage related to the particle size [8].

The amount of moisture in the feed also affects screening efficiency, as does the presence of clays and other sticky materials. Damp feeds screen very poorly as they tend to agglomerate and blind (plug) the screen apertures. Screening must always be performed on either dry or wet material, but never on damp material. For best screening efficiency, wet screening is always superior: Finer sizes can be processed, adhering fines are washed off by large particles, and the screen is cleaned by the flow of pulp. There is no dust problem. There is, however, the increased cost of dewatering and drying, and for this reason dry screening is preferred.

Particle size separation achievable by the basic screen types is illustrated in Figure 14. A common problem with screens is the blinding of the screen apertures with particles that are just slightly oversize. The problem increases as aperture size decreases, and it can result in a significant reduction in capacity. Blinding can often be minimized by correct screen motion or by a suitable surface material.

Problems caused by small amounts of moisture can be alleviated by using electrically heated screen cloths. Although this increases the capital cost of the screen, operating costs may decrease because of longer surface life. Another approach is to use a gas flame underneath and parallel to the screen surface. With screens having apertures between 0.5 and 5.0 mm, ball decks are sometimes employed for cases of severe blinding.

Screening equipment can be classified as either stationary or dynamic. Figure 15 shows the various screen types, and Table 13 describes them.

6.3.1.2 Potential Applicable Situations

Table 14 describes the typical situations in which the basic screen types are used. Grizzly screens are normally used for separating large pieces like stones. The size of particles screened on grizzly screens can range from 20 mm to 300 mm. In most applications a grizzly is used to separate large particles, followed by other screens for finer separation. Sieve bends can be used for separation as low as 50 microns, since these devices give sharper separation than can be achieved by wet classifiers.

6.3.1.3 Advantages and Disadvantages

Advantages and disadvantages of the various screen types are included in Table 14.

Advantages – Screens are an inexpensive method for separating coarse and fine particles.

Disadvantages – Screens are subject to plugging, thus decreasing their efficiency. Fine screens are very fragile and clog easily with retained particles. High throughput reduces particle dwell time on the screen and generally produces a thick bed of materials through which fines must travel to reach the screen surface. This results in decreased efficiency. Screens are noisy, and dry screening requires dust control. To control dust emissions, dust covers are used. Most manufacturers can supply fully enclosed screening, which can be connected to a dust extraction system.

6.3.1.4 Information Needs

The information listed below must be gathered and considered in selection of the screens and implementation of a screening process.

- Particle size distribution of the feed.
- Radionuclide distribution with particle size.
- Moisture content.
- Mineralogical composition.
- Dust control requirement.
- Throughput required.

6.3.2 Classification

6.3.2.1 Description and Development Status

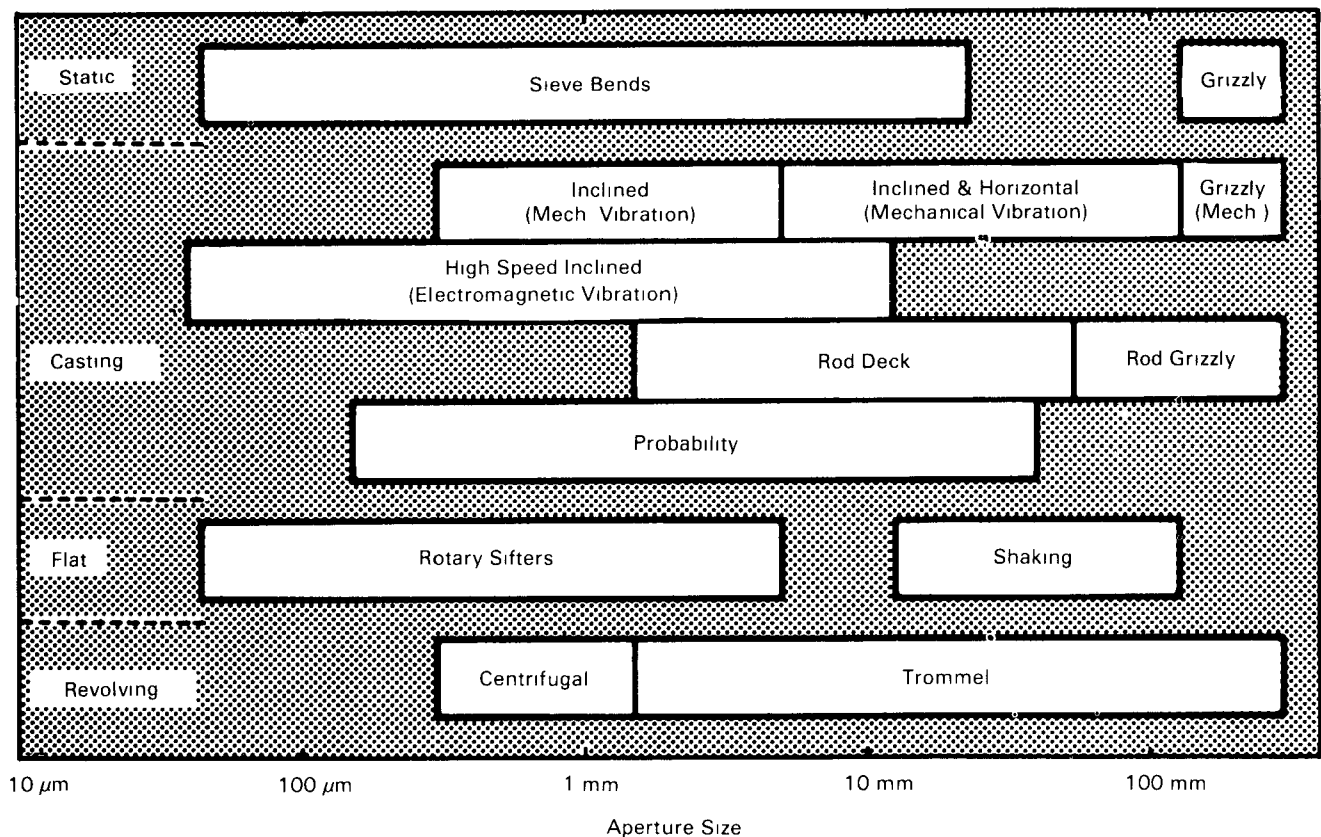
Classification is the separation of particles according to their settling rate in a fluid. Water is the fluid most commonly used in mineral processing [2,3,6,8,10,11,13,14,17-19].

Classifiers typically produce two streams—one containing the faster settling particles called sands (underflow or oversize) and another containing slow-settling particles called slimes or overflow.

Classifier types fall into three basic categories: (1) nonmechanical, (2) mechanical, and (3) hydraulic. Functionally, mechanical and nonmechanical classifiers are similar and differ only in the means of sand removal. In hydraulic types the character of separation is different because of the hindered settling induced by the hydraulic water.

Table 15 illustrates different classifier configurations. Mechanical classifiers are designated by M-S, nonmechanical classifiers by N-S, and hydraulic classifiers by M-F or N-F. All hydraulic classifiers are of the fluidized-bed type; some of them use

Figure 14. Typical separation sizes of the basic screen types. (Reprinted from [6]. Copyright © 1982. Reprinted by permission of John Wiley & Sons, Inc.)



mechanical means to remove sand. These are identified as M-F in Table 13. The table lists ranges of suitable operating conditions for each classifier.

Hydraulic Classifier – With the hydraulic classifier, water or air is introduced so that its direction of flow opposes that of the settling particles. The simplest form of a hydraulic separator is the settling-cone. Solid/liquid flows into the settling-cone like a fluid being poured into a funnel. The heavy, solid-laden flow exits the bottom, and the liquid flows radially over the lip of the cone.

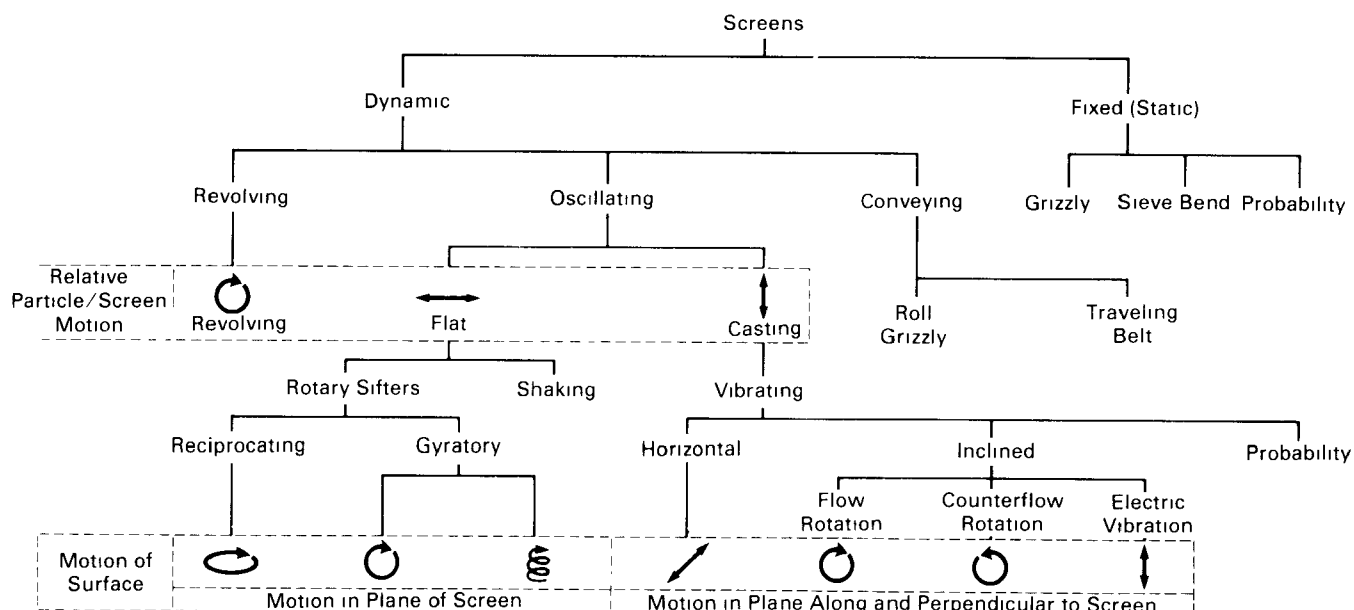
The more complex hydraulic classifiers are the Jet Sizer by Dorr-Oliver and the SuperSorter by Deister Concentrator Co. These multicompartiment, multiproduct classifiers operate on the basis of hindered settling. Each compartiment is served with low-pressure hydraulic water. The amount of hydraulic water is controlled so that in each succeeding compartiment the coarsest particles are maintained in hindered-settling condition, and the finer fractions pass along.

D-O Siphon Sizer is a single-compartment type built by Dorr-Oliver. Sands are discharged by siphons extending to the bottom of the hindered-settling zone. A hydrostatically actuated valve controls the siphon flow. Discharge for an intermediate fraction from the upper column can be obtained by additional siphons. Hydraulic water consumption is considerably lower than required for multicompartiment sizers.

Mechanical Classifiers – In mechanical classifiers, the slow-settling particles are carried away in a liquid overflow, and the particles with a higher settling velocity are deposited on the bottom of the equipment and dragged upwards against the flow of liquid by some mechanical means. The size and quality of separation depends on feed rate, speed of removal, degree of agitation, and height of the overflow weir. Mechanical classifiers are widely used in closed-circuit grinding operations and in the classification of products from ore-washing plants. Various mechanical classifiers are described below.

The *rake classifier* utilizes rakes which dip into the settled material and move it up the incline for a short distance. The rakes are then withdrawn and returned

Figure 15. The basic screen types and their classifications. (Reprinted from [6]. Copyright © 1982. Reprinted by permission of John Wiley & Sons, Inc.)



to the starting point, where the cycle is repeated; the settled material is thus slowly moved up the incline to the discharge.

Spiral classifiers use a continuously revolving spiral to move the sands up the slope. They can be operated at steeper slopes than the rake classifier, which results in drier product. Also, there is less agitation in the pool, which is important in separations of very fine material.

A *sedimenting centrifuge* consists of a bowl into which a suspension is fed and rotated at high speed. The liquid is removed through a skimming tube or over a weir while the solids that remain in the bowl are removed either intermittently or continuously. Centrifugal sedimentation is based on a density difference between solids and liquids; the particles are subjected to centrifugal forces which make them move radially through the liquid either outwards or inwards, depending on whether they are heavier or lighter than the liquid.

There are a variety of bowl designs and discharge mechanisms available for industrial centrifuges.

Drag classifiers are single endless belt or chain suspensions with cross flights running in an inclined trough. They have long been used for draining and classifying. They may be any of a variety of shapes and sizes.

The *countercurrent classifier* is an inclined, slowly rotating cylindrical drum; continuous spiral flights

attached to the interior of the drum form helical troughs. The direction of rotation is such that material in the troughs moves toward the higher end. Wash water introduced at the upper end drains from the lifting flights above the normal water level and progresses countercurrent to the material toward the overflow.

The countercurrent classifier is normally used for sand-slime separations, washing, and for closed construction restricting escape of heat and chemical fumes.

The *air classifier*, similar to the hydrocyclone (to be discussed in the next chapter on nonmechanical classifiers) uses air to produce coarse and fine fractions. The air classifier is used where solids must be kept dry, for example, in cement grinding.

Nonmechanical Classifiers – Nonmechanical classifiers rely on gravitational or centrifugal force to separate the coarse particles. The hydrocyclone, settling cone, and elutriator are three types that are commonly used.

A *hydrocyclone* is a widely used, small, inexpensive device that gives relatively efficient separation of fine particles in dilute suspension. The hydrocyclone is a continuous-operating classifying device, which utilizes centrifugal force to accelerate the settling rate of particles. It is one of the most important devices used in the minerals industry; there are over 50 hydrocyclone manufacturers in the world.

Table 13. The Major Types of Screens. (Reprinted from [6]. Copyright © 1982. Reprinted by permission of John Wiley & Sons, Inc.)

	Distinguishing Characteristics	Classifications	Description	Motion	Speed Amplitude	Applications	Advantages and Disadvantages
STATIONARY GRIZZLY	Heavy duty surface of fixed bars	Conventional	Heavy bars running in flow direction, sloped to allow gravity transport. Bars may spread along length to minimise blinding.	Stationary surface (Vibrating grizzlies also available - bar vibrating screens)		Scalping before crushers	Simple, robust. Probability form blinding resistant.
		Probability	Bars divergent in vertical plane.				
ROLL GRIZZLY	Surface of rotating rolls		Essentially a stationary screen surface, but non uniform shape of rolls conveys material.			Coarse separations before crushing. Primarily a conveyor.	Conveying action allows near horizontal operation in low head room situations.
SIEVE BENDS	Slurry feed, fixed bar surface	Straight or curved surface	Stationary parallel bars at right angles to slurry flow. Surface may be straight (with steep incline) or curved to 300°.	Stationary		Separations in range 2 mm to 45 µm, or those too coarse for hydrocyclone, or where density effects make classifier unsuitable. Dewatering.	Relatively high efficiency and capacity. Sharpness of cut less than true screen. Separation slightly affected by mineral density. Excessive dewatering can be a problem.
REVOLVING SCREENS	Screen surface rotating around cylinder axis	Trommel	Slightly inclined cylindrical screen. May have concentric surfaces.	Below critical speed (i.e. ball mill)	15-20 r.p.m.	Wet or dry separations 60 to 10 mm if dry, smaller if wet.	Simple, useful for scrubbing or rough size separations. High wear. Low surface utilisation.
		Centrifugal	Vertically mounted cylindrical screen centrifuges particles through screen.	Operates above critical speed. Also has vertical action of 800-1000 cycles/min.	60-80 r.p.m.	Wet or dry separations 12 mm to 400 µm. Dewatering.	High wear.
		Probability	Particles drop through surface formed by bars radiating out like spokes on a wheel.	Radiating bars rotate about vertical axis. Speed of rotation determines cut size.		Developed for separating coal < 6 mm.	Relatively high capacity with fine separations. Cut size easily changed and controlled by varying speed.
VIBRATING SCREENS	High speed motion, designed primarily to lift particles off surface	Inclined (Subclassified by vibrator mechanisms)	Inclined rectangular screening surface which allows material to flow with aid of vibrations.	Mechanical vibrations give circular motion at center, elsewhere it depends on vibrator. Electro magnetic vibrators may give linear vibration at center.	600-7000 r.p.m. Low < 25 mm	Wide applications, generally down to 200 µm in mineral industry, but down to 38 µm in chemical industry using the high speeds.	Relatively high efficiency and capacity but capacity generally inadequate below 200 µm.
		Horizontal	Horizontal rectangular screening surface. Linear vibration must have horizontal component to convey material along screen.	Linear motion, with vertical component to provide lift, and horizontal component for conveying.	600-3000 r.p.m. Low < 25 mm	Similar to inclined screens.	Similar to other vibrating screens, but can also be used where head room is restricted.
		Probability	Series of relatively small inclined screen surfaces separates by statistics rather than physical constraint.			Similar to inclined screens.	Generally superior to conventional vibrating screen. High capacity and efficiency for given space, low noise, low power. Low efficiency at low loading.
SHAKING SCREENS	Slow linear motion, essentially in plane of screen		Usually slightly inclined. May have several surfaces in series with different apertures.	Linear motion, essentially in plane of screen. Particles tend to remain in contact with screen surface.	30-800 r.p.m. 25-1000 mm	Down to 12 mm for coal preparation and non metallic minerals. Higher speeds may size down to 250 µm.	Low headroom and power requirements. May be used for conveying and sizing. Accurate for large sizes. High maintenance cost, low capacity.
ROTARY SIFTERS	Circular motion applied to screen surface	Reciprocating	Rectangular screen surface with slight (~5°) incline.	Circular motion is applied at feed end, and produces reciprocating motion at discharge end.	500-600 r.p.m. Low < 25 mm	Generally used for finer separations (12 mm to 45 µm, wet or dry) in non-metallurgical industries.	Suitable for finer separations, but with low capacity.
		Gyrating	Circular screen surface.	Circular motion over most of the screen surface.			
		Gyrating	Circular screen surface.	Screen moves with circular motion, but also has oscillating vertical component.			

Table 14.Types of Screening Operations and Equipment. (Reprinted from [6]. Copyright © 1982. Reprinted by permission of John Wiley & Sons, Inc.)

Operation and Description	Type of Screen
<i>Scalping:</i> Strictly, the removal of a small amount of oversize from a feed that is predominately fines. Typically the removal of oversize from a feed with, approximately, a maximum of 5% oversize, and a minimum of 50% halfsize.	Coarse, grizzly. Intermediate and fine: same as used for separations
<i>Separation, Coarse:</i> Making a size separation at 4 75 mm and larger	Vibrating screens, horizontal or inclined.
<i>Separation, Intermediate:</i> Making a size separation smaller than 4 75 mm and larger than 425 micron	Vibrating screens, high-speed, sifter, and centrifugal screens. Static sieves
<i>Separation, Fine:</i> Making a size separation smaller than 425 micron.	High-Speed, sifter, and centrifugal screens. Static sieves
<i>Dewatering:</i> Removal of free water from a solids-water mixture. Generally limited to 4 75 mm and larger.	Horizontal vibrating, inclined (about 10°), and centrifugal screens. Static sieves.
<i>Trash Removal.</i> Removal of extraneous matter from a processed material. Essentially a form of scalping operation. Screen type will depend on size range of processed material	Vibrating screens; horizontal or inclined. Sifter and centrifugal screens. Static sieves.
<i>Other Applications:</i> Desliming, conveying, media recovery, concentration	Vibrating screens, horizontal or inclined. Oscillating and centrifugal screens. Static sieves.

A typical hydrocyclone (Figure 16) consists of a conical vessel open at its apex, where underflow discharge occurs, joined to a cylindrical section, which has a tangential feed inlet. The top of the cylindrical section is closed, with a plate through which passes an axially mounted overflow pipe. The pipe is extended into the body of the cyclone by a short, removable section known as the vortex finder, which prevents feed from flowing directly into the overflow.

Because of a tangential inlet, the slurry entering the cone rotates at high velocity, causing heavier particles to move to the wall of the cyclone and discharge through the apex opening. The smaller or lighter particles move toward the vortex in the center, discharging through the overflow.

The *settling cone* is the simplest form of classifier. There are many different designs of cone. The machine essentially consists of a suspended circular tank, the base of which is in the shape of a truncated cone closed by a valve. Feed is introduced at the top. The sand settles in the cone, while the water and slimes overflow into a circular peripheral launder. As the sand accumulates in the cone, the weight of the whole machine increases. This opens the discharge valve. When the sand is discharged, the machine lightens, automatically closing the valve.

Elutriation is a process of sizing particles by means of an upward current of fluid, usually water or air. The process is the reverse of gravity sedimentation. Those particles having a terminal velocity less than that of the velocity of the fluid will overflow, while those particles having a terminal velocity greater than the fluid velocity will sink to the underflow.

6.3.2.2 Potential Applicable Situations

Classifiers can be considered for use in soil-washing schemes. A typical equipment arrangement is shown in block diagram form in Figure 13. In this figure a number of classifiers are used.

The front end uses a scrubber, which is a drum washer. A spiral classifier could also be used for this purpose. A hydrocyclone is used at an intermediate location in the scheme to separate the coarser fraction from the finer fraction. A centrifuge is used to remove the fines from the finer fraction. Each device is used to handle a particular size fraction in the process.

Other classifiers discussed in this subchapter can also be used; the application is determined by soil size fraction and solid concentration.

6.3.2.3 Advantages and Disadvantages

Advantages – The principal advantages of these classifiers are their high continuous processing capability and their extensive industrial processing track record. The mining industry relies on them as prime movers in ore refining and processing. Low cost per quantity of material being processed and equipment reliability are the major reasons for selecting the equipment.

Disadvantages – A drawback to classification is that soil with a lot of clay and sandy soil with humus materials are very difficult to process. In general, sandy soils low in clay and humus constituents with a high specific gravity are successfully processed with the classifiers.

Table 15. The Major Types of Classifiers. (Reprinted from [6]. Copyright ©. Reprinted by permission of John Wiley & Sons, Inc.)

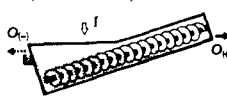
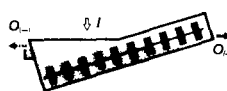
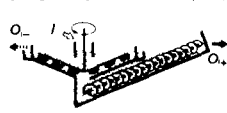
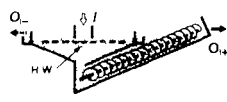
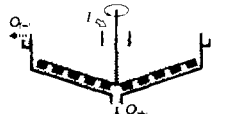
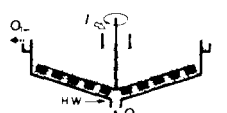

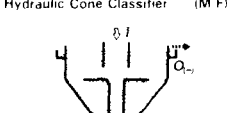
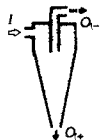

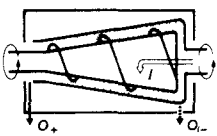
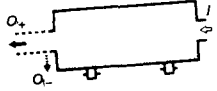
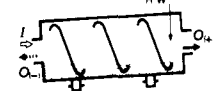
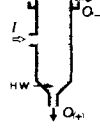
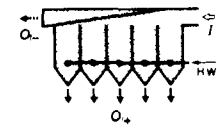
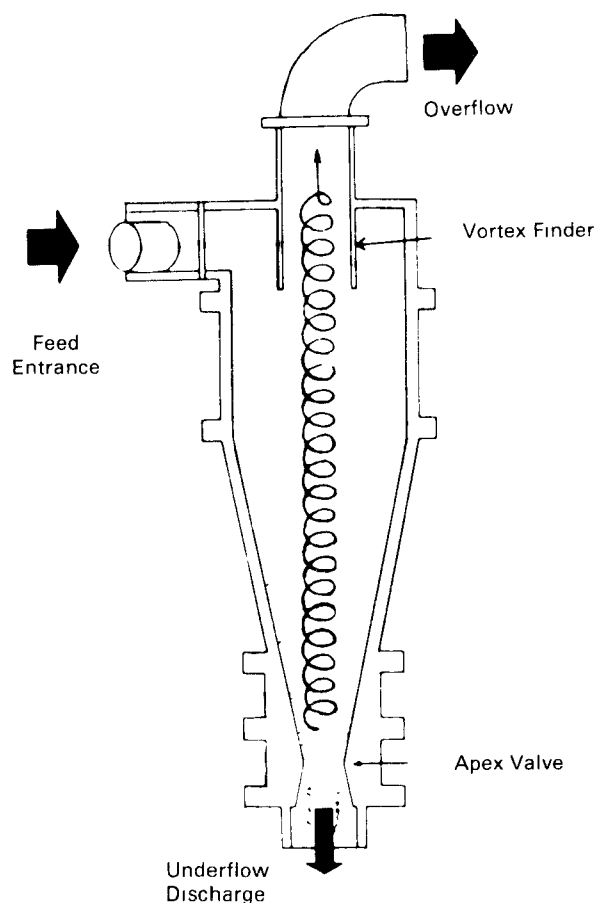
CLASSIFIER	(Type*)	DESCRIPTION	SIZE (m) Width Diameter Max Length	LIMITING SIZE (Max Feed Size)	FEED RATE (t/hr)	VOL % SOLIDS Feed Overflow Sands	POWER (kW)	SUITABILITY AND APPLICATIONS
	(M-S)	Classification occurs near deep end of sloping, elongated pool. Spiral rake or drag mechanism lifts sands from pool.	0.3 to 7.0 2.4 (spiral) 14	1 mm to 45 μ m (25 mm)	5 to 850	Not critical 2 to 20 45 to 65	0.4 to 110	Used for closed circuit grinding, washing and dewatering, desliming, particularly where clean dry sands are important. (Drag classifier sands not so clean). In closed circuit grinding discharge mechanism (spirals especially) may give enough lift to eliminate pump.
	(M-S)	Essentially a spiral classifier with paddles replacing the spiral.	0.8 to 2.6 0.6 to 1.1 4.6 to 11	(100 mm)	40 to 450		7.5 to 60	Used for rough separations such as removing trash, clay from sand. Also to remove or break down agglomerates.
	(M-S)	Extension of sloping tank classifiers, with settling occurring in large circular pool, which has rotating mechanism to scrape sands inwards (outwards in Bowl Desilter) to discharge rake or spiral.	0.5 to 6.0 1.2 to 15 12	150 μ m to 45 μ m (12 mm)	5 to 225	Not critical 0.4 to 8 50 to 60 (15 to 25 in Bowl Desilter)	Bowl 0.75 to 7.5 Rake 0.75 to 20	Used for closed circuit grinding (particularly regrind circuits) where clean sands are necessary. Larger pool allows finer separations. Bowl Desilter has larger pools (and capacities). Relatively expensive.
	(M-F)	Basically a hydraulic bowl classifier. Vibrating plate replaces rotating mechanism in pool. Hydraulic water passes through perforations in plate and fluidises sands.	1.2 to 3.7 1.2 to 4.3 12	1 mm to 100 μ m (12 mm)	5 to 225	Not critical 2 to 15 50 to 65	Vib 2.2 to 7.5 Rake 3.7 to 15	Gives very clean sands and has relatively low hydraulic water requirements (0.5 t/t sand). One of the most efficient single stage classifiers available for closed circuit grinding and washing. Relatively expensive.
	(M-S)	Effectively an overloaded thickener. Rotating rake feeds sands to central underflow.	- 3 to 45 -	150 μ m to 45 μ m (6 mm)	5 to 625	Not critical 0.4 to 8 15 to 25	0.75 to 11	Simple, but gives relatively inefficient separation. Used for primary dewatering where the separations involve large feed volumes, and sand drainage is not critical.
	(M-F)	Hydraulic form of overloaded thickener. Siphon Sizer (N-F) uses siphon to discharge sands instead of rotating rake.	- 1.0 to 40 -	1.4 mm to 45 μ m (25 mm)	1 to 150	Not critical 0.4 to 15 20 to 35	0.75 to 11	Two product device giving very clean sands. Requires relatively little hydraulic water (2 t/t sand). Used for washing, desliming and closed circuit grinding.
	(N-S)	Similar to cylindrical tank classifier, except tank is conical to eliminate need for rake.	- 0.6 to 3.7 -	600 μ m to 45 μ m (6 mm)	2 to 100	Not critical 5 to 30 35 to 60	None	Low cost (simple enough to be made locally) and simplicity can justify relatively inefficient separation. Used for desliming and primary dewatering. Solids build up can be a problem.
	(M-F)	Open cylindrical upper section with conical lower section containing slowly rotating mechanism.	- 0.6 to 1.6 -	400 μ m to 100 μ m (6 mm)	10 to 120	Not critical 2 to 15 30 to 50	3 to 7.5	Used primarily in closed circuit grinding to reclassify hydrocyclone underflow.

Table 15.(Continued)

CLASSIFIER	(Type*)	DESCRIPTION	SIZE (m) Width Diameter Max Length	LIMITING SIZE (Max Feed Size)	FEED Rate (t/hr)	VOL % SOLIDS Feed Overflow Sands	POWER (kW)	SUITABILITY AND APPLICATIONS
Hydrocyclone	(N S)							
		(Pumped) pressure feed generates centrifugal action to give high separating forces, and discharge	- 0.01 to 1.2 -	300 μ m to 5 μ m (1400 μ m to 45 μ m)	to 20 m ³ /min	4 to 35 2 to 15 30 to 50	35 to 400 kN/m ² pressure head	Small cheap device widely used for closed circuit grinding. Gives relatively efficient separations of fine particles in dilute suspensions.
Air Separator	(N S)							
		Similar shape to hydro cyclone, but higher included angle. Internal impeller induces recycle within classifier	- 0.5 to 7.5 -	2 mm to 38 μ m	to 2100		4 to 500	Used where solids must be kept dry, such as cement grinding. Air classifiers may be integrated into grinding mill structure.
Solid Bowl Centrifuge	(M S)							
		Power generates high settling forces. Slurry centrifuged against rotating bowl and removed by slower rotating helical screw conveyor within bowl	- 0.3 to 1.4 1.8	74 μ m to 1 μ m (6 mm)	0.04 to 2.5 m ³ /min	2 to 25 0.4 to 20 5 to 50	11 to 110	Relatively expensive but high capacity for a given floor space used for finer separations.
Scrubber	(M S)							
		Essentially a rotating drum mounted on slight incline	- 1.5 to 3.5 3 to 10	(450 mm)	to 700		1 to 55	Similar applications to log washer but lighter action. Tumbling (85% critical speed) provides attrition to remove clay from sand. Also removes trash.
Counter Current Classifier	(M-F)							
		One form based on scrubber another on spiral classifier. They have wash water added to flow essentially horizontally in opposite direction to sands which are conveyed and resuspended by some form of spiral	- 0.5 to 3.3 (spiral type) 12 (spiral type)	2 mm to 40 μ m	3 to 600	Not critical 2 to 15 50 to 65	0.2 to 19	Very clean sands product, but relatively low capacity for a given size.
Elutriator	(N F)							
		Basically a tube with hydraulic water fed near bottom to produce hindered settling. Sands withdrawn through valve at base. Column may be filled with network to even out flow	- 1.2 to 4.3 -	2.4 mm to 100 μ m (7.5 mm)	4 to 120	15 to 35 0.4 to 5 20 to 35	0.75 for valves	Simple and relatively efficient separation. Normally a two product device but may be operated in series to give a range of size fractions.
Pocket Classifier	(N F)							
		A series of classification pockets with decreasing quantities of hydraulic water in each producing a range of product sizes	0.5 to 6.0 - 12	2.4 mm to 100 μ m (10 mm)	4 to 120	15 to 35 0.4 to 5 20 to 35		Efficient separations but requires 3 t hydraulic water/t sand. Used to produce exceptionally clean sands fractioned into narrow size ranges.

*M Mechanical transport of sands to discharge
N Non mechanical (gravity or pressure) discharge of sand.
S Sedimentation classifier
F Fluidised bed classifier

Figure 16. Hydrocyclone. (Reprinted from [6]. Copyright © 1985. Reprinted by permission of Pergamon Press, Ltd.)



6.3.2.4 Information Needs

The characterization listed below must be considered in selecting a classifier type and implementing a classification process.

- Particle size distribution of the feed.
- Radionuclide distribution with particle size.
- Specific gravity and chemical analysis of the soil.
- Mineralogical composition.
- Characteristics of the soil
 - sand, humus, clay, or silt.
- Composition of the organics in each soil fraction.
- Moisture content.
- pH.

6.3.3 Flotation

6.3.3.1 Description and Development Status

Froth flotation is used extensively in mineral processing to concentrate constituents such as uranium from ores. Great strides have been made

both in the chemical aspects of flotation and in equipment development. Today flotation is used for almost all sulfide materials and is widely used for nonsulfide metallic minerals, industrial minerals, and coal. Flotation is the most economical method for separating particles in the size range of 0.1-0.01 mm.

Metallic ores are normally ground finer than 48 to 65 mesh for treatment in froth flotation, whereas coal and certain nonmetallic ores are generally treated by grinding to finer than the 10 to 28 mesh range. As a rule, coarser feed cannot be suitably mixed and suspended by a flotation machine. Fineness of grind is determined by the particle size at which the desired minerals are liberated from gangue (waste) particles. In flotation machines, the ore is suspended in water by means of mechanical or air agitation at a pulp density generally from 15 to 35 percent solids. The surfaces of suspended particles are treated with chemicals called promoters or collectors which render those particles air-avid and water-repellent. Through the use of modifying agents, undesired minerals are depressed or rendered non-flatable. With vigorous agitation and aeration in the presence of a frother—a chemical added to create bubbles—a layer of froth or foam forms at the top of the flotation machine. The air-avid minerals become attached to air bubbles and rise to the surface where they collect in the froth and are skimmed off [2,3,6,10, 11,13,14,17,20,21].

Flotation of sulfide compounds is well established. Sulfides are separated using alkyl xanthates or dithiophosphates. Oxide mineral forms can be floated from acid or basic solutions.

The pH level is established for each mineral oxide type. Oxides are separated with surfactants. Silicates and aluminosilicates accept ionic surfactants in the same way as oxides. Salt-type minerals respond to anionic surfactants.

Promoters or collectors are added with the ore to enhance flotation of the particles. The collector also serves as a water-repellent, which reduces the moisture content of the froth. Typical collectors for flotation of metallic sulfides and native metals are alkyl xanthates and dithiophosphates. These ionized collectors are adsorbed on a sulfide mineral surface, with bonding through the sulfur atoms.

In flotation, collectors of fluor spar, phosphate rock, iron ore, and other nonmetallics are likely to be crude or refined fatty acids and their soaps, petroleum sulfonates, and sulfonated fatty acids. Cationic collectors such as fatty amines and amine salts are widely used for flotation of quartz, potash, and silicate minerals.

Commonly used frothers are pine oil, cresylic acid, polypropylene glycol ether, and 5- to 8-carbon aliphatic alcohols such as methylisobutylcarbinol and methyl amyl alcohol. Quantities of frothers required are usually 0.01 to 0.2 lb/ton.

Depressants assist in selectivity (sharpness of separation) or to stop unwanted minerals from floating. A typical depressant is sodium or calcium cyanide to depress pyrite (FeS_2).

Alkalinity regulators such as lime, caustic soda, soda ash, and sulfuric acid are used to control or adjust pH, a very critical factor in many flotation separations.

The choice of reagent is based on past experience and trial and error, guided by a sketchy knowledge of surface chemistry. Over the past 40 years a good deal of research has gone into this problem, but a great deal more is needed.

Limited information is available in the literature on flotation cells. Some fundamental research into the physics of particle capture by bubbles is being pursued in several Eastern European countries, presumably in the conviction that a better understanding of flotation kinetics will lead to practical improvements in this technique [12].

Mechanical flotation devices are the most commonly used. Often one type of machine will be used for roughing and another for cleaning. These machines provide mechanical agitation and aeration by means of a rotating impeller on an upright shaft.

In addition, some cells utilize air from a blower to help aerate the pulp. In recent years, there have been dramatic increases in the size of individual flotation cells.

In a cell-type mechanical flotation machine, froth product discharge is obtained by overflow with or without the use of mechanical paddles.

In pneumatic flotation machines of both cell and tank types, mixing of air and pulp occurs in injection nozzles. In the flotation column, countercurrent flow is established in the lower section of the column. Although extensively tested, pneumatic flotation columns are not common in industry.

Dissolved-air flotation involves the dissolution of air (or other gas) into the liquid while under pressure, followed by precipitation. Electroflotation is another method to create ultrafine gas bubbles, but this technique uses electrolysis.

6.3.3.2 Potential Applicable Situations

Flotation cells can be considered for use in mill tailings to reduce the level of radioactivity. The

Palabora Mining Company in South Africa treats complex ore using flotation and physical separation techniques to recover copper, magnetite, uranium, and zirconium [22].

Canadians have used flotation cells to extract radium from uranium mill tailings [3] and uranium from Elliot Lake ore [8]. Research conducted at the U.S. Bureau of Mines shows that 95% of uranium can be extracted from sandstone ores containing 0.25% uranium oxide by means of flotation [8].

Of all the ores treated by flotation in the U.S., 66% were sulfides, 7% metal oxides and carbonates, 24% nonmetallic minerals, and 3% coal [11]. Although increasingly used for nonmetallic and oxidized minerals, flotation is primarily used to extract sulfides of copper, lead, and zinc from complex ore deposits.

6.3.3.3 Advantages and Disadvantages

Advantages – If the particle fraction containing the contaminants can be collected by the froth, then flotation is a very effective tool. High separation rates for fine particles can be achieved.

Disadvantages – If no suitable additive (promoter or collector) can be found, then flotation will not be effective. New additives may have to be developed to permit successful flotation separation for radiologically contaminated materials.

Flotation is a complex process, depending for effective separation on particle size, rate of feed, control of chemical additives, and handling of the refined product. The process is also expensive. Flotation uses small, compact equipment of lower capital cost but with higher operating costs than for gravity separation equipment.

6.3.3.4 Information Needs

The characteristics listed below must be considered in preparing to implement a flotation procedure.

- Particle size and shape distribution of the feed.
- Radionuclide distribution with particle size
- Characteristics of the soil – clay, humus, sand, or silt.
- Specific gravity and chemical analysis of the soil.
- Mineralogical analysis.
- Concentration ratio of solids to liquid forming the suspension.
- The nature of pretreatment.

6.3.4 Gravity Separation

6.3.4.1 Description and Development Status

Gravity methods of separation are used to treat a great variety of materials. With the advent of the froth-flotation process, which allows the selective treatment of low-grade complex ores, use of gravity separation declined. However, in recent years, many companies have been using gravity separation methods due to increasing costs of flotation reagents, the relative simplicity of gravity processes, and the fact that they produce comparatively little environmental pollution. One of the world's largest uranium processing plants, Palabora Mining Company in South Africa, recovers both uranium and baddeleyite using gravity separation techniques [22]. Modern gravity techniques have proved to be efficient for the concentration of minerals having particle sizes in the 50-100 micron range [6,8-12,14,17].

Gravity separation techniques exploit differences in material densities to bring about separation. Therefore, separation is influenced by particle size, density, shape, and weight.

All gravity separation devices keep particles slightly apart so that they are able to move relative to each other and thus separate into layers of dense and light minerals. Gravity separators or concentrators are classified by the means used to achieve this interparticle spacing. The type represented by jigs applies an essentially vertical oscillating motion to the solids-fluid stream. The shaking concentrators or shaking tables form the second group. These apply a horizontal shaking motion to the solids-fluid stream by vibrating the surface. Included in this type are the shaking table, the Bartles-Mozley concentrator, and the traditional miner's pan. Gravity flow concentrators such as sluices and troughs form the third type, in which interparticle space is maintained by the slurry flowing down an inclined surface. Jigs and gravity flow concentrators, which are mainly used in coal, beach sand, and iron ore processing, will not be discussed here. However, shaking concentrators (called tables) used in soil decontamination processes [23] will be addressed in this chapter.

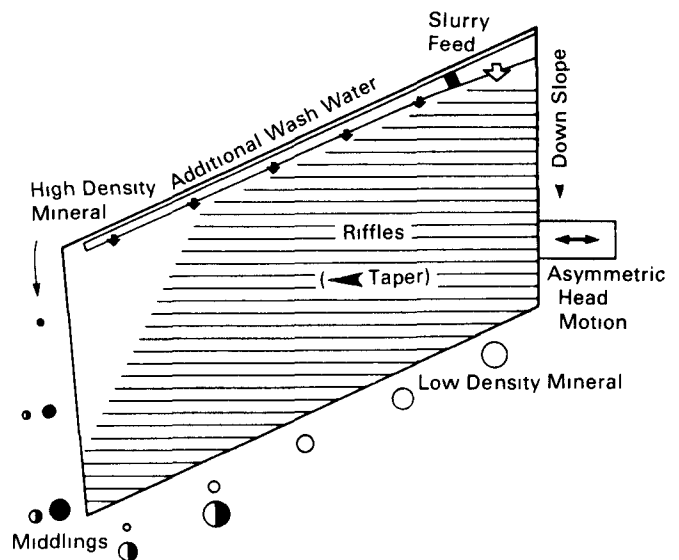
The shaking table is the most versatile of all gravity devices that in one pass can produce a high-grade concentrate over a wide range of particle sizes. The shaking table is a relatively old device that has slowly evolved. Generally, shaking tables treat materials finer than jigs are able to handle, but this is achieved at the expense of capacity; single deck tables have relatively low capacity for their cost and space requirements.

Shaking tables are very versatile units, and are used for a wide range of functions: from roughing to cleaning; from the treatment of sands to slimes; from

the separation of two heavy minerals to coal preparation.

A typical table is illustrated in Figure 17. Feed enters through a distribution box along part of the upper edge. The wash water and shaking action spread the feed out over the table. Product discharge occurs along the opposite edge and the end. The essentially rectangular table has an adjustable slope of about 0° - 6° from the feed edge down to the discharge edge. The surface is a suitably smooth material (e.g. rubber or fiberglass) and has an arrangement of riffles, which decrease in height along their length toward the discharge end. Different duties may require a different deck size or riffle pattern, and a range of decks are offered by most manufacturers.

Figure 17. Schematic of a shaking table, showing the distribution of products. (Reprinted from [6]. Copyright © 1982. Reprinted by permission of John Wiley & Sons, Inc.)



Modifications on the basic shaking table design include the Bartles-Mozley separator, the Holman slime table, and the Bartles crossbelt concentrator.

6.3.4.2 Potential Applicable Situations

In the soil decontamination processes installed at Heijmans Milieutechniek and HWZ Bodemsanering, both in Holland, tables are used in separating fine particles from extracting agents [23]. Concentration by gravity method is limited to those soils in which the contaminants are relatively coarse and capable of resisting breakage and sliming or are associated with other minerals that may themselves be separated by gravity differential. The concentrate thus obtained can be processed further by extraction. COG Mineral Corporation Mill in Utah uses a gravity separator as part of the uranium extraction process [14].

6.3.4.3 Advantages and Disadvantages

Advantages – Gravity separation is highly efficient and is a proven process for a wide range of applications. It gives a high-grade concentrate over a wide range of particle sizes and functions well with most soil types.

Disadvantages – A drawback is its low handling capacity: high throughput requires multiple decks. Gravity separation requires clean water, so that if water is recycled care must be taken to ensure there is no slime buildup.

6.3.4.4 Information Needs

The prerequisite information listed below must be considered in preparing to implement gravity separation procedures.

- Throughputs.
- Feed preparation (natural, sized, classified hydraulically, etc.).
- Feed density.
- Characteristics of the soil-sand, clay, humus, or silt.
- Particle size and shape distribution of the feed.
- Specific gravity and chemical analysis of the soil.

6.3.5 Support Technologies for Treatment of Liquid Recycle

Most mineral-separation processes require substantial quantities of water; the final concentrate has to be separated from a pulp in which the water/solids ratio may be high. Partial dewatering is performed at various stages in the treatment, so as to prepare the feed for subsequent processes. The separated water is purified and normally recycled. Dewatering is basically a solid-liquid separation technique and can broadly be classified into two types:

- sedimentation
- filtration

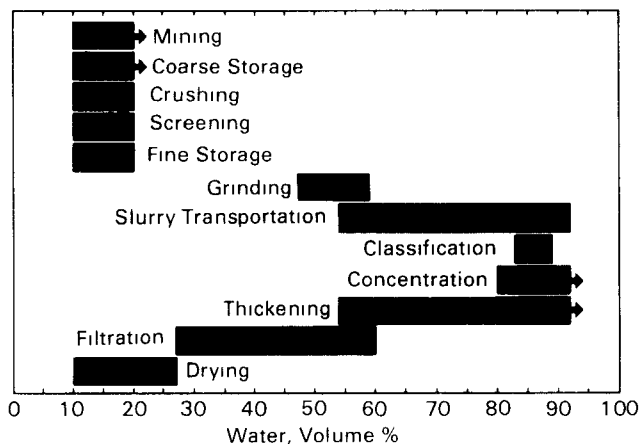
Dewatering is normally needed in any chemical and/or physical separation process and is a combination of several methods. The bulk of the water is first removed by sedimentation, which produces a thickened pulp with 55-60% solid loading. Filtration increases the solid loading to 80-90%.

With the exception of dry screening, the various technologies require the feed to be in the form of a pulp. Each of these technologies tolerate certain ranges in the water content beyond which they do not work efficiently. Figure 18 shows the limits of variation of the water content in feed pulp that can be tolerated

by screening, gravity concentration, classification, sedimentation (thickening), and filtration.

Also shown in Figure 18 are limits of water content for other mineral processing operations, such as

Figure 18. Limits of water content variation. (Reprinted from [6]. Copyright © 1982. Reprinted by permission of John Wiley & Sons, Inc.)



crushing, grinding, storage, drying, and slurry transportation. Even though these operations may not apply to a radioactive soil cleaning process, they are shown for clarity.

6.3.5.1 Description and Development Status

Sedimentation Technologies – Sedimentation technology can be classified into gravity sedimentation and centrifugal sedimentation [6,8,10,11,13,17,18,24].

Gravity sedimentation is the removal of suspended solid particles from a liquid by settling.

Rapid settling of solid particles in a liquid produces a clarified liquid, which can be decanted. A thickened slurry, which may require further dewatering by filtration remains. Very fine particles, of only a few microns diameter, settle extremely slowly by gravity alone.

Coagulants and flocculants are added, producing relatively large lumps, called flocs, which settle out more rapidly. There are several equipment designs available for sedimentation. These are:

- Deep cone thickeners
- Tank thickener
- High capacity thickeners
- Lamella thickeners

The most common type of sedimentation unit is the cylindrical continuous tank thickener with mechanical sludge-raking arms. Feed enters the thickener through a central feed well, and clarified liquor overflows around the periphery. Thickened sludge (the sludge blanket) collects in the conical base and

is raked by the slowly revolving mechanism to a central discharge point. One of the main disadvantages of these thickeners is the large floor area required.

With introduction of flocculant, the settling rates of suspension could be increased tenfold or more. High capacity thickeners take advantage of this by providing mechanical mixing of flocculant and slurry, and staged additions of flocculant. The high capacity thickeners are more expensive to operate but provide better performance and use less space.

The lamella thickener uses a nest of inclined plates, thus providing a large effective settling area in a compact space. Flocculants are added to aid the settling.

Deep cone thickeners are over 4-meter conical containers equipped with stirrers and overflow and underflow arrangement. High flocculant dosages are used to obtain high solid concentrations.

Selective flocculation is an important technique that uses a high-molecular-weight polymer, which selectively adsorbs only one of the constituents of a mixture. Selective flocculation is followed by removal of the flocs of one component. Selective flocculation has been applied to the treatment of clays, iron, phosphate, and potash ores.

Centrifugal sedimentation is appropriate for slurries with very fine particles, since gravity sedimentation may be very slow. Due to high centrifugal forces, separation of particles occurs quickly with high throughputs. The two types of centrifugal sedimentation designs are hydrocyclone and solid bowl centrifuges. Hydrocyclones are described in the chapter on classifiers.

The solid bowl centrifuge is a cylinder into which slurry is fed and rotated at high speed. The centrifugal action forces the heavier particles to the wall of the cylinder, while the liquid forms an inner layer and is removed. The solids are removed continuously or intermittently. There are several bowl designs available.

Newly developed centrifuges can separate particles as fine as 0.5 micron. Centrifuges have been engineered that integrate flocculations to ease solid removal. The newer centrifuges have abrasive-resistant coatings, require less power to operate, and are quieter than older versions.

Filtration – Filtration normally follows the thickening operation [6-8,10, 11,13,14,17-19,24] The filtration process can be classified into three types:

- Deep bed filtration
- Screening

- Cake filtration

Deep bed filtration uses a deep bed of granular media, usually sand, as a filter. Mainly used in water and wastewater treatment plants, it is inexpensive but cannot remove fine particles.

Screens are also used as dewatering media; they are described in the previous chapter.

Cake filtration is the most widely used dewatering technique in mineral processing. Cake filtration is the removal of solid particles from a fluid by means of a porous medium that retains the solids while allowing the fluid to pass. The porous medium used in industrial filtration is a relatively coarse material; therefore, clear filtrate is not obtained until the initial layers of cake have formed. Factors affecting the cake filtration operation are: the filtering surface, viscosity of the filtrate, resistance of the filter cake and filter media, and operating pressure or vacuum required to overcome the resistance.

Flocculants are sometimes added to aid filtration and prevent fine particles or slimes from blinding the filter media.

Cake filtration can be operated in two basic modes: constant pressure or constant rate. Constant pressure filtration maintains a constant pressure, but flow rates fall off as solid cake is formed and resistance increases. Most of the continuous filters operate on this principle, using vacuum to provide the pressure difference. Constant rate filtration requires gradually increasing pressure as the cake builds up and increases the resistance to flow.

Cake filtration systems utilize either pressure filters or vacuum filters. Pressure filters are normally operated in batch processing mode and vacuum filters generally in continuous mode.

Pressure filters are widely used in the chemical industries. The driving force for filtration is the fluid pressure generated by pumping. Since the filters work mainly in batch processing mode and are therefore labor intensive, they have seldom been used in mineral processing. New concepts such as continuous filter press are not really continuous operation systems but go through a series of automated cycles.

Another new development is the belt filter press (Manor tower press). Developed in Europe, it is a continuous pressure filter used in treatment of paper mill sludge, coal, and flocculated clay slurries [18].

All vacuum filtration techniques use a porous filter medium to support the filter deposits, beneath which pressure is reduced by connection to a vacuum system. The vacuum filtration can be operated in

batch or continuous mode. Batch vacuum filters are rarely used in commercial operation.

The most widely used continuous vacuum filters in mineral processing are drums, discs, and horizontal filters. Although different in design, all continuous vacuum filtration equipment is characterized by a filtration surface that moves by mechanical or pneumatic means from a point of slurry deposition under vacuum to a point of filter cake removal.

A typical drum filter essentially consists of a horizontal cylindrical drum that rotates while partially immersed in an open tank, into which slurry is fed and maintained in suspension by agitators. The drum shell itself is covered with a drainage grid and a filter medium. Vacuum is applied from the interior of the drum. As the drum revolves, the cake is raised above the liquid level, and wash water, if required, is sprayed on the surface.

Various methods are used for discharging the solids from the drum. The most common form is the use of a reversed blast of air and a scraper to remove the cake. Another form is the belt discharge, in which the filter medium leaves the drum and passes over external rollers before returning to the drum.

Disc filters operate in a similar fashion and consist of a number of discs partly immersed in a slurry and mounted along a hollow shaft, through which vacuum is applied. The disc is ribbed and supports the filter media.

The horizontal continuous vacuum filters are characterized by a horizontal filtering surface in the form of a belt, table, or series of pans in a circular or linear arrangement. Horizontal belt filters have been rapidly accepted in the uranium mining industries, because of their ability to filter heavy dense solids.

One new development in filtration is filter cake pressing, in which a squeezing action is applied to a previously formed filter cake to compress the cake and remove further moisture. Steam-assisted vacuum filtration is another new technique to reduce cake moisture [13].

Electrofiltration is a new technique used for separation of ultra fine particles (up to 10 microns). Here the slurry is placed in a direct current electric field; the negatively charged particles migrate toward the anode, forming a cake which is further dewatered by electroosmosis. In the cathode, the slurry is filtered through a filter cloth by vacuum filtration.

Membrane separation is a new technology that uses a semipermeable membrane to separate a solid/liquid system into its components. Physical, chemical, and electrical means can be applied to enhance the operation. Membrane separation is expensive and so

is not used in the mining industry. This technique is usually used to separate very fine particles (0.1-0.001 micron) from liquid. A manganese-impregnated acrylic fiber filter has been used to remove radium from a 3 M NaCl extractant solution and shows significant promise [20]. A review [25] of various membranes for uranium extraction concluded that there is a particularly promising membrane process called selective membrane mineral extraction (SMME). The SMME system has been shown to remove 98 percent of radium from water containing 1,500 pCi/l of the radionuclide. The membrane techniques can be used with chemical extraction technology to extract the radionuclide from the extractant.

6.3.5.2 Potential Applicable Situations

The selection of the particular technique depends on the throughput required, the particle size, and the density of the materials. Cylindrical tanks are normally used as thickeners but, because of the large area required and the low efficiency of tanks, centrifuges or high capacity thickeners are appropriate where there is a space limitation and high throughputs are required.

Pressure filters used in the chemical processing industry are rarely used in mining, as batch operations are expensive; however, pressure filters can remove fine particles.

Disc filters, and to a large extent drum filters, are the mainstay for most dewatering systems because of their ability to remove fine particles. Centrifugal filtration or electrofiltration may be used to remove very fine particles.

6.3.5.3 Advantages and Disadvantages [24]

Advantages – Gravity sedimentation is economical; it carries low maintenance and operating costs. The technique has a good long track record and is the simplest of the sedimentation methods.

Centrifuge sedimentation offers high efficiency, high throughput, and effective separation of fine particles.

One of the main advantages of the drum filters is the wide range of design (method of discharge, cloth design, etc.) and operating variation (drum speed, vacuum operation, submergence cycle, etc.) that permits treatment of a wide range of particles of diverse nature. Drum filter operations are clean, continuous, and automatic with minimal operating labor. Drum filters are also low in maintenance cost. Drum filters provide for effective washing of filter cloth and can also handle very thin filter cakes, resulting in increased filtration and draining rates with drier products.

One of the main advantages of disc filters is that they can handle large volumes of relatively free-filtering solids (typically 40-200 mesh range). It is possible to handle different slurries on one unit simultaneously by partitioning the filter tank and using one or separate automatic valves. The disc filter equipment provides for large filter areas on minimum floor space.

Another advantage of disc filters is the rapid medium replacement made possible by virtue of their design. In addition, the capital cost of disc filters per unit area is generally less than for drum filters.

The main advantage of horizontal filters is that large tonnage per unit area can be processed with rapid dewatering. Cakes ranging in thickness from 10 mm to 200 mm can be formed and washed. Horizontal filtering provides excellent washing with sharp wash liquid and filtrate separation. In this respect it is better than the drum filter. Horizontal filter equipment is very flexible in operation. Since in horizontal filtration the settling of solid assists the filtration, horizontal filters are ideal to handle quick settling slurries.

Disadvantages – Gravity separation is ineffective for fine particles. It involves a long settling time and requires a large floor area, especially when tank thicknesses are involved. If chemicals are used, operating costs will increase.

Disadvantages of centrifuge sedimentation include high capital cost, with a high maintenance cost that is higher than other sedimentation procedures. Equipment is noisy, and is subject to abrasive wear. Another disadvantage of centrifuge sedimentation is its high power requirements.

The main disadvantage of the drum filters is the high capital cost. Also, certain types of feed cannot be handled by drum filters, such as quick settling slurries. Use of blow-back air and a scraper knife to discharge the filter cake may produce wetter cakes and greater filter medium wear.

One of the main disadvantages of disc filters is that they are inflexible in operation. A good washing of the vertical cake surface is difficult, and because of limited cake drying time, wetter cakes are formed. Some designs result in excessive filtrate blow back, causing the cakes to be moist. Also, the discharge of thin cakes is difficult. The disc filter equipment has no means of separating different filtrates if the unit is used to filter more than one slurry simultaneously. The rate of medium wear will be high if scraper discharge is used.

The main disadvantage of horizontal filters is the heavy wear and tear of the flexible drainage belts, which results in loss of vacuum and poor drainage. The horizontal filter requires a large floor area. In the case of belt filters, only 45% of the belt area is effective. Horizontal filters are more expensive than drum filters, but this disadvantage is offset by the higher capacity per unit area, since horizontal filters can handle thicker cakes at higher speeds.

6.3.5.4 Information Needs

The prerequisite information listed below must be considered in implementing treatment procedures.

- Particle size and shape distribution of the feed.
- Radionuclide distribution with particle size.
- Specific gravity and chemical analysis of the soil.
- Characteristics of the soil – sand, humus, clay, or silt.
- Mineralogical analysis.
- The concentration ratio of solids to liquid forming the suspension.
- The nature of pretreatment.

6.4 Typical Costs of Physical Separation Technologies

The cost of the application of any of the physical separation technologies described in this section will depend upon several factors. Thus the costs cannot be reliably estimated for any technology and for any site at this stage, because most of the required prerequisite information is not available.

Among the cautions must also be included the fact that many, if not most, of the controlling factors will be site-specific. The cost for a technology at one site may be vastly different than for the same technology applied at another site.

Despite the limitations and cautions, some typical cost information is provided in Table 16 for the technologies described in this chapter. The costs shown do not include cost of transportation and disposal of concentrated fractions. The cost of returning "clean" treated material to a site is not included.

The purpose, capacity, equipment and operating costs in 1987 dollars, and factors affecting both cost and capacity are presented for the major types of physical separation equipment.

Table 16. Typical Costs of Major Physical Separation Equipment

These costs obtained from vendors are presented to give some typical costs. They are not intended to be applicable to any particular site. Cost of returning "clean" treated material to a site is not included.

Equipment	Purpose	Capacity	Equipment Cost in 1987 \$	Operating Cost in 1987 \$	Factors Affecting Cost and Capacity
Soil Prep. Package (grizzly crusher, screen, feeder)	To prepare soil for leaching	50 - 600 TPH	500K - 2500K	4 - 1/Ton	Soil type, site conditions, truck access, dust control
Screw Classifier	Preliminary separation of coarse and fines	10 - 950 TPH	9K - 167K	3 - 1/Ton	Soil type, availability of water radioactive shielding, corrosive resistance
Hydrocyclone	Intermediate Classification of sand and silt	50 - 500 GPM	1K - 5K	1 - 0.30/1000 Gal	Corrosion and abrasion resistance
Corrugated Plant Interceptor	Gravity separation of silt and fines	60 - 1000 GPM	4K - 74K	2 - 1/1000 Gal	Corrosion resistance, radioactive shielding, degree of separation
Clarifier	Gravity separation of fines	60-6000 GPM	40K - 520K	6 - 1/1000 Gas	Same as above
Drum Filter	Removal of all suspended solids	0.5 - 90 TPH	50 - 400K	80 - 2/Ton	Corrosion resistance, radioactive shielding, shelter
Centrifuge	Removal of unfilterable solids	10 - 600 GPM	60K - 850K	77 - 7/1000 Gal	Corrosion resistance, radioactive shielding, shelter
Flash Dryer	To dry settled or filtered solids	700 - 36K # water/hr	200K - 1800K	120 - 21/1000#	Corrosion resistance, radioactive shielding, multilevel construction, emissions control
Flotation Unit	For the selective separation of fines	30 - 1000 GPM	25K - 160K	15 - 3/1000 Gal	Corrosion resistance, radioactive shielding

6.5 References

- Borrowman, S.R., and P.S. Brooks. Radium Removal from Uranium Ores and Mill Tailings. U.S. Bureau of Mines Report 8099, 1975.
- Garnett, John, et al. Initial Testing of Pilot Plant Scale Equipment for Soil Decontamination. U.S. Dept. of Energy, RFP 3022, 1980.
- Raicevic, D. Decontamination of Elliot Lake Uranium Tailing. CIM Bulletin, 1970.
- G. Weismantle. Liquid Solids Separation and Filtration - Current Development. Chemical Engineering, Feb. 6, 1984.
- Roberts, E. J., and P. Stavenger, et. al. Solid/Solid Separation. Chemical Engineering Desk Book Issue, February 15, 1971.
- Kelly, E.G., and D.J. Spottiswood. Introduction to Mineral Processing. John Wiley, New York, 1982.
- Galkin, N.P. The Technology of the Treatment of Uranium Concentrates. Pergamon Press, New York, 1963.
- Organization for Economic Cooperation and Development. "Uranium Extraction Technology." OECD, Paris 1983.
- Clark, Don A. State of the Art: Uranium Mining, Milling, and Refining Industry. EPA-660-2-74-038 USEPA, Corvallis, Oregon, 1974.
- Merritt, R.C. The Extractive Metallurgy of Uranium. Colorado School of Mines Research Institute, 1971.
- Wills, B.A. Mineral Processing Technology. Pergamon Press, New York, 1985.
- O'Burt, Richard. Gravity Concentration Technology. Elsevier, New York, 1984.
- Wills, B.A., and R.W. Barley. Mineral Processing at a Cross Road - Problem and Prospects. Martinus Nijhoff Publishers, Boston, 1986.
- Mular, A.L., and R.B. Bhappu. Mineral Processing Plant Designs. American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, 1980.
- Mathews, Chris W. Screening. Chemical Engineering Desk Book Issue, February 15, 1971.
- Institute of Mechanical Engineers. Screening and Grading of Bulk Materials. Mechanical Engineering Publications Ltd., London, 1975.

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17. Perry, R., and C.H. Chilton. Chemical Engineer's Handbook. McGraw Hill, New York, 1973.
 18. Svarovsky, L. Advances in Liquid-Solid Separation. Chemical Engineering, July 1979.
 19. Poole, J.B., and D. Doyle. Solid-Liquid Separation. Chemical Publishing Co., New York, 1968.
 20. Ryan, R.K., and D.M. Levins. Extraction of Radium from Uranium Tailings. CIM Bulletin, October 1980.
 21. Ives, Kenneth J. The Scientific Basis of Flotation. Martinus Nijhoff Publishers, Boston, 1984.
 22. Burt, R.O. Gravity Concentration Technology. Elsevier, New York, 1984.
 23. Assink, S.W. Extraction Method for Soil Decontamination: A General Survey and Review of Operational Treatment Installation. *In*: Proceeding of 1984 International TNO Conference on Contaminated Soil. Martinus Nijhoff Publishers, Boston, 1985.
 24. Svarovsky, L. Solid-Liquid Separation. Butterworths, Boston, 1977.
 25. Kosarek, L. J. Uranium Extraction and In Situ Site Restoration via Membrane Technology. 1979 Mining Yearbook. 1979.

Chapter 7

Combined Physical Separation and Chemical Extraction Processes

7.1 Purpose and Mode of Operation

Employing physical separation techniques, it may be possible to decontaminate soil to low radiation levels by separating the highly contaminated particles on the basis of particle sizes. While the coarse soil particle fractions might still contain radiation above acceptable levels, removal of radioactive contaminants from them might allow return of the soil to the place of origin or placement in a nonhazardous waste landfill. While applying further physical separation techniques would not lower the radiation levels, chemical separation technologies applied to the separated coarse particles might bring the treated soil radiation to acceptable levels. This chapter discusses the various combined physical and chemical separation techniques that might be applied to decontaminate radioactive soils.

7.2 State of the Art

Three physical and chemical separation techniques will be discussed:

- soil washing and physical separation
- separation and chemical extraction
- separation, washing and extraction

Soil washing and physical separation has been used in two pilot plant tests to decontaminate plutonium contaminated soil [1] and to extract radium from uranium mill tailings [2].

Separation and chemical extraction have been used extensively in the mining industry, in particular for extracting uranium. Palabora Mines in South Africa uses gravity separation techniques followed by chemical extraction to separate uranium from complex copper ores [3-6].

Separation, washing and extraction have been used to decontaminate soils [7-10].

Table 17 shows the state of the art of the combined physical separation and chemical extraction technologies. All these technologies are in the pilot plant testing stage, and none have been field demonstrated with radioactive material. Major pilot plant testing and development work are needed prior

to application of these technologies to radiologically contaminated site remediation.

7.3 Technologies of Potential Interest

7.3.1 Soil Washing and Physical Separation

7.3.1.1 Description and Development Status

This process involves washing the soil with chemical solution, followed by separation of coarse and fine particles [1]. The type of solution used for washing will depend on the contaminant's chemical and physical composition.

The process water, which may lead to radioactive buildup in process streams, is treated--preferably by ion exchange--and the resulting decontaminated water is recycled.

In 1972 the Department of Energy initiated laboratory-scale studies of techniques for decontaminating soils [1]. Experiments were conducted to evaluate a variety of chemical and physical separation techniques. The techniques included chemical oxidation, calcination, flotation, desliming, heavy media separation, magnetic separation, wet and dry screening, and washing. Based on laboratory-scale studies, the washing and physical separation process was selected for pilot plant investigation. The pilot-plant process flow sheet is shown in Figure 19.

In the pilot-plant testing at Rocky Flats, the plutonium-contaminated soil was washed in a rotating drum washer using a pH 11 NaOH solution as a washing agent. A trommel screen was used to separate the coarse particles (+5 mesh), and a vibrating screen was used for further particle separation (+35 mesh). This was followed by use of a hydrocyclone and classification to separate +10 micron particles. Centrifugation and ultrafiltration were employed to separate the fine contaminants. The water was sent back for recycle without any purification.

The results of the pilot-plant testing show this process could have potential for success, but

Table 17. State of the Art of Combined Physical Separation and Chemical Extraction Technologies

Technology	Laboratory Testing	Bench Scale Testing	Pilot Plant Testing	Field Demonstration with Radioactive Material	Radiologically Contaminated Site Remediation	Remarks
<i>Combined Physical separation and chemical extraction</i>						
- Soil washing and physical separation		x	x			Pilot plant development and testing needed for radioactive materials
- Separation and chemical extraction			x			Various portions of the process have been developed for extraction of uranium from ores. Pilot plant testing and development needed for radioactive materials
- Separation, washing and extraction			x			Significant bench scale and pilot plant testing needed for radioactive material

additional pilot development work is needed before scale-up to production level. In pilot-plant test runs, soils contaminated 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 (Table 18). The coarse particle fraction ranged from 58% to 87%. The results of pilot-plant testing showed the fine soil particle fraction containing the concentrated contaminants to have much higher levels of radiation than the feed, ranging from 1440 pCi/g to 90,000 pCi/g. Feed rates ranged from 45 kg/hr to 120 kg/hr.

Recommendations based on the pilot-plant testing were that applying multistage washing and rinsing instead of single stage would be beneficial. Hydrocyclones and filtration techniques were recommended for removal of fine particles. Centrifuging of flocculated solution was not recommended, as the centrifuge action tends to break the flocs.

The Canadians used the froth flotation technique to separate radium from uranium mine tailings [2]. Results of their laboratory testing and bench-scale

Table 18. Soil Product Plutonium Level from Pilot Plant Operation[1]

Run ^a	Feed (pCi/g)	Product			
		Coarse Fraction (+ 35 Mesh)	Weight Fraction %	Fine Fraction (-35 Mesh)	Weight Fraction %
1	45	0.5	.. ^b	1440	
2	284	12	58	1485	42
3	7515	86	78	90,000	22
4	1305	340 ^c	87	10,800	13
5	675	89	58	5.850	42

^a Each run represents a different process.

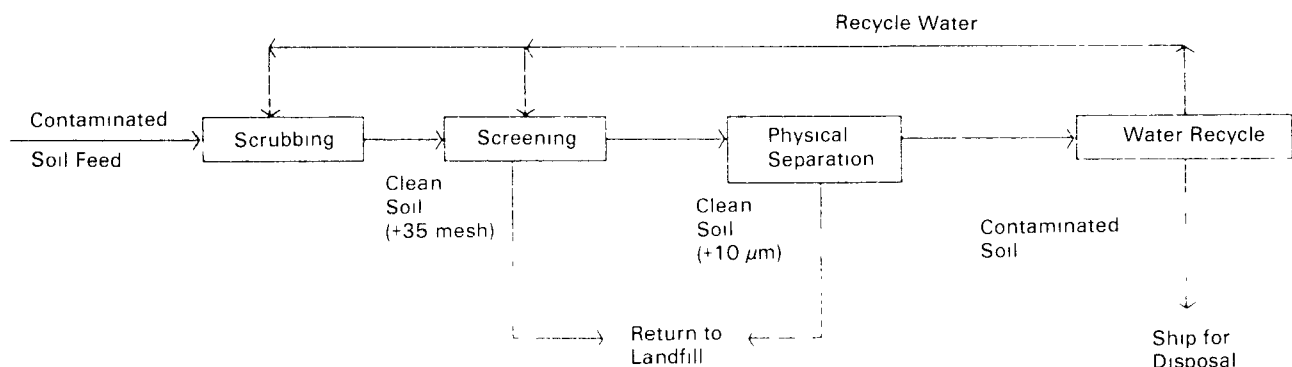
^b Not available.

^c Attributed to inadequate washing and scrubbing

testing at CANMET show that radium in uranium mill tailings can be reduced from 290-230 pCi/g to 50-60 pCi/g by flotation.

However, in the pilot-plant testing at Dennison Mill using the same process, the decontaminated tailings showed radium levels of 123-151 pCi/g. This was

Figure 19. Conceptual soil decontamination process flow sheet (Reprinted from [2].)



attributed to recycling the water. Whereas both the laboratory and bench-scale testing used fresh city water with no radium in it, the pilot-plant test water contained relatively high amounts of dissolved radium, ranging between 586 and 1179 pCi/g.

7.3.1.2 Potential Applicable Situations

The soil washing and physical separation process can be considered for use in situations where radioactive contaminants are closely associated with fine soil particles. Better success can be obtained with sandy soils; humus soils will be difficult to clean.

7.3.1.3 Advantages and Disadvantages

Advantages – The process is simple and relatively inexpensive and should require no major process development. It has achieved some degree of separation with clay soil in pilot-plant testing [1].

Disadvantages – The main disadvantage is that this process may not work for humus soil. Also, pilot-plant development and testing are needed. The process may work only for low level radiologically contaminated soils; this is yet to be determined by pilot-plant testing. The recycled water must be stripped of radioactive contaminants or the process will become inefficient.

7.3.1.4 Information Needs

The information listed below must be collected and considered before implementing soil scrubbing and physical separation procedures.

- Nature of the soil: sandy, clay, humus.
- Nature of the particle: size, shape, specific gravity, mineralogical and chemical properties, etc.
- Radionuclide distribution with particle size.
- Nature of the contaminant—chemical and physical properties.

7.3.2 Separation and Chemical Extraction

7.3.2.1 Description and Development Status

The soil would first be separated to fine and coarse particle fractions. The coarse particle fraction would be acid leached, the radioactive contaminants stripped by solvent extraction and separated by precipitation and/or ion exchange. The extractant would be cleaned and recycled. The fine particle fraction would be combined with extracted contaminants and sent to a secure disposal site. The clean coarse fraction would require appropriate disposal.

Processes using solvent extraction, ion exchange, and acid leaching, etc., have been used in extraction

of uranium from ores and radium from uranium mill tailings [6,11-13]. In mining, since the objective is to extract maximum quantities of the desired constituents (uranium and radium) from the ores and tailings, the leaching is applied to the feed as a whole, without separating into fine and coarse fractions. Although the process can be applied to the unseparated soil, this may not bring contaminant concentrations to the acceptable levels. Since the weight fraction of the coarse soil particle portion ranges from 60-80% [1], and since its contaminant radiation levels will be lower to start with, cleaning the coarse fraction could possibly clean a large percentage of the soil to acceptable standards.

There are several variations on the above process. Two-stage acid leaching instead of solvent extraction is one variation [14]. Another is to use ion exchange instead of solvent extraction, a technique used in several uranium extraction processes [6]. A third variation is to use a solvent to extract uranium and a salt solution to extract radium from acid leach residues [12].

The Canadians [14] have used leaching solution to extract thorium, radium, and uranium from uranium ore. Two-stage hydrochloric acid leaching was employed, which resulted in mill tailings with radium levels of 15 to 20 pCi/g.

In Europe, several solvent extraction techniques have been used to clean soil contaminated with cyanides, heavy metals, and organics [7]. In these processes, it is the fine fraction that receives the benefit of soil cleaning methods, since the contaminants are mainly associated with the fine particles. The estimated typical cost to clean soil in Europe is around \$100/ton [7]. This is exclusive of excavation and transportation costs, overheads, profits, and cost for safety measures [10].

Details of different chemical extraction techniques are discussed in Chapter 5 of this report. Physical separation techniques that can be used are discussed in Chapter 6.

7.3.2.2 Potential Applicable Situations

Separation and chemical extraction can be considered for use in sandy, clay, and humus soils. This type of process has been used, with limited success, to extract radium from uranium mill tailings in pilot plant testing. A large concentration of sulfide in the soil will have a marked effect on the radium extraction [12].

7.3.2.3 Advantages and Disadvantages

Advantages – An advantage of this process over other methods discussed in this chapter is that soils containing higher levels of radioactivity can be

treated. Also, various facets of the process have been developed for extracting uranium, and laboratory work is underway in Canada for extracting radium from uranium mill tailings. However, the development of various facets of a process does not mean the entire process will work.

Disadvantages – The main disadvantages of this process are that it is expensive and has high chemical usage. The chemical required will depend on the soil analysis. A problem may arise with high sulfur content in the soil interfering with radium extraction. Also, the process needs major development work prior to application in extracting radium from soil. In addition, the use of chemicals raises concerns of plant safety and environmental pollution. This approach may not be successful in extracting radium, thorium, and uranium in a single process.

7.3.2.4 Information Needs

The information listed below must be considered in implementing treatment procedures.

- Nature of the soil: sandy, clay, humus, silt.
- Physical and chemical properties of the soil.
- Nature of the particle: size, shape, specific gravity, mineralogical properties.
- Radionuclide distribution with particle size.
- Nature of the contaminant: chemical, physical, and mineralogical properties.
- Concentration ratio of solid to liquid forming the slurry.
- The nature of pretreatment.

7.3.3 Separation, Washing and Extraction

7.3.3.1 Description and Development Status

Following separation, contaminated soils conceivably can be scrubbed with a variety of washing fluids, followed by chemical extraction. The nature of the washing fluids and chemicals would depend on the contaminants and the characteristics of the soil. It is most effective to separate the soil into fine and coarse fractions and use the scrubbing system on the coarser soil fraction to reduce the throughput and chemical usage. The treated coarse soil might then be returned to the site. The finer soil fractions and contaminants could be sent to disposal. Depending on the soil grain size distribution, reduction in disposal volume of 60-80% may be possible.

The agents that can be applied to soil washing are:

- Surfactants that improve the solubility of the contaminants and the tendency for fine particles to separate from larger ones.
- Chelating additives used to chemically react with metals.

- Acid or alkaline solutions to mobilize and/or to improve solubility of the contaminant.

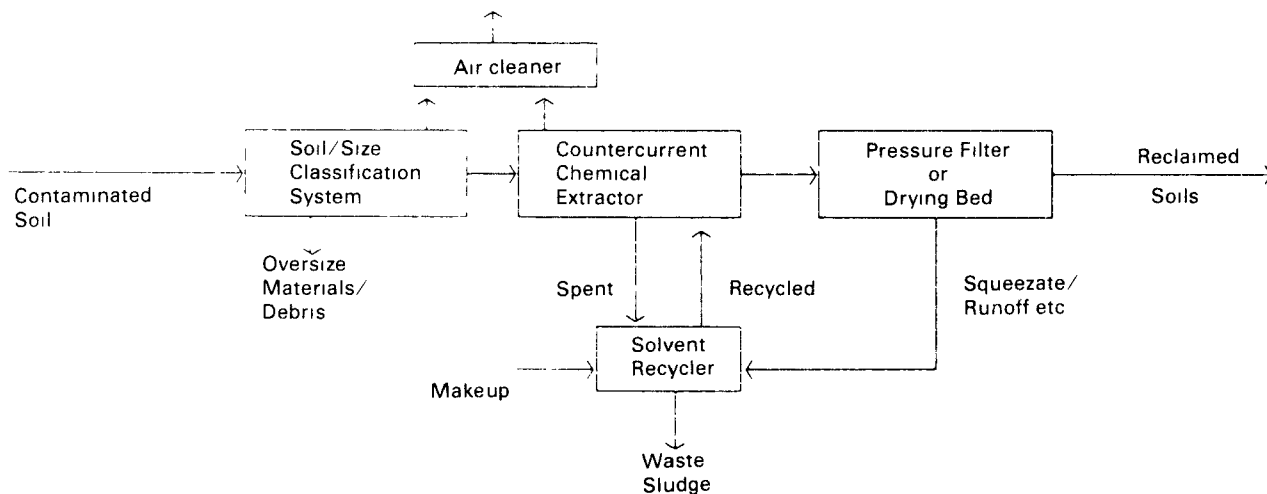
Washing solutions are basic aqueous solutions (caustic, lime, slaked lime, or industrial alkali-based washing compounds); acidic aqueous solutions (sulfuric, hydrochloric, nitric, citric, phosphoric, or carbonic acids); or solutions with surfactant or chelating agents. Hydrogen peroxide, sodium hypochlorite, and other oxidizing agents may also be used. A strong basic surfactant solution could be used for organic extraction, and strong acidic or chelating agent solutions can be used for metal extraction. Strong base or acid might be used in cases of high contaminant concentration, where the cost of chemicals is affordable and the wastewater can be treated for safe disposal. Surfactant and chelating agent soil cleaning are being developed to reduce chemical and equipment costs, make the soil reusable, and simplify wastewater treatment. The surfactant and chelating solutions have a moderate (almost neutral) pH, making equipment operation safer.

The EPA Soil Washing System, developed by the EPA Risk Reduction Engineering Laboratory at Edison, NJ, uses a scrubber extraction process to clean soil. Pilot studies were performed to select the equipment for the EPA soil washer. Three unit operations were developed and proved by testing:

- **Water Knife Concept** – A thin, flat, high-speed water jet breaks up clumps of soil and scrub contaminants from larger soil particles like stone and gravel. Testing showed that this concept is very effective.
- **Rotary Drum Screener** – A rotary drum was employed as a pretreatment to mix the soil with the extractant and separate the soil into two particle size categories (+2mm and -2mm).
- **Extraction and Separation Concept** – A four-stage counterflow extraction train was designed and built to treat the -2mm soil fraction separated by the drum screener. Each stage consists of a tank, stirrer, hydrocyclone, and circulating pump. The pump moves the soil from one stage to the adjacent stage. The hydrocyclone discharges the soil slurry in the next stage and returns the extractant. The extractant flows by gravity as a tank overflows in a stream from one tank to another, counter to the direction of the soil. Fresh extractant is added to the fourth stage, and spent extractant is removed from the first stage.

A mobile soil washing pilot-plant was built using the above features [15]. The pilot-plant scheme (Figure 20) was designed for water extraction of a broad

Figure 20. Simplified process flow diagram of the EPA soil washer. (Reprinted from [15].)



range of hazardous materials from spill-contaminated soils.

The system can (1) treat excavated contaminated soils, (2) return the treated soil to the site, (3) separate the extracted hazardous materials from the washing fluid for further processing and/or disposal, and (4) decontaminate process fluids before recirculation or final disposal. The washing fluid (water) may contain additives, such as acids, alkalies, detergents, and selected organics solvents to enhance soil decontamination. The nominal processing rate will be 3.2 cu m (4 cu yd) of contaminated soil per hour when the soil particles are primarily less than -2mm in size and up to 14.4 cu m (18 cu yd) per hour for soil of larger average particle size.

7.3.3.2 Potential Applicable Situations

The concept can be considered for use with granular soil. Clay and humus soil may be difficult to clean using countercurrent extraction. Pilot-plant testing is needed to determine the effectiveness of the process. The EPA Mobile Soil Washer was used to remove nonradioactive contaminants from soil. With equipment modifications and additions and significant bench-scale and pilot-plant testing, the unit can be considered for use to clean radiologically contaminated soils.

7.3.3.3 Advantages and Disadvantages

Advantages – It is possible that soils can be cleaned to acceptable limits. The same countercurrent decantation technology has been used in uranium

extraction. However, pilot plant testing is needed to determine the effectiveness of this process.

Disadvantages – The Soil Washing System needs further development to determine washing fluids that are effective in removing radioactive contaminants from soils.

The most suitable type of washing fluid must be determined using a bench-scale test for each soil. A process to clean the contaminated washing fluid for recycle must be established through pilot-plant testing. The process may not work for clay or humus soils. Significant bench-scale and pilot-plant testing is needed.

7.3.3.4 Information Needs

The soil and contaminant characteristics listed below must be considered in implementing treatment procedures.

- Nature of the soil: sandy, clay, humus.
- Nature of the particle: size, shape, specific gravity, mineralogical and chemical properties, etc.
- Radionuclide distribution with particle size.
- Nature of the contaminant: chemical and physical properties.

7.4 Typical Costs of Separation and Extraction Technologies

It must be noted that most of the cost controlling factors for cleaning soil using the separation and extraction technology will be site specific. In addition, the combined technology has not been demonstrated to clean radiologically contaminated sites. Since the

detailed process information is lacking, the cost for this technology cannot be reliably estimated.

However, the estimated typical cost for cleaning nonradioactive contaminated solid using separation and extraction technology ranges from \$45 - \$100/ton (1985 \$) [7], exclusive of excavation, transportation, and disposal costs for all fractions. These costs are not intended to be applicable to any particular site. Costs of returning "clean" treated material to a site are not included.

7.5 References

1. Garnett, John, et al. Initial Testing of Pilot Plant Scale Equipment for Soil Decontamination, US Dept. of Energy, RFP 3022, 1980.
2. Raicevic, D. Decontamination of Elliot Lake Uranium Tailing. CIM Bulletin, August 1970.
3. Wills, B.A. Mineral Processing Technology. Pergamon Press, New York, 1985.
4. Wills, B.A., and R.W. Barley. Mineral Processing at a Cross Road - Problem and Prospects. Martinus Nijhoff Publishers, Boston, 1986.
5. Merritt, R.C. The Extractive Metallurgy of Uranium. Colorado School of Mines Research Institute, 1971.
6. Clark, Don A. State of the Art: Uranium Mining, Milling, and Refining Industry. EPA-660-2-74-038 USEPA, Corvallis, Oregon, 1974.
7. Assink, S.W. Extraction Method for Soil Decontamination: A General Survey and Review of Operational Treatment Installation. In: Proceeding of 1984 International TNO Conference on Contaminated Soil. Martinus Nijhoff Publishers, Boston, 1985.
8. Schulz, Robert, and Joseph Milanowski. Mobile System for Extracting Spilled Hazardous Materials from Excavated Soils. In: Hazardous Materials Spill Conference, Milwaukee, Wisconsin, 1982.
9. Rulkens, W.H., and J.W. Assink, et. al. Extraction as a Method for Cleaning Contaminated Soil: Possibilities, Problems and Research. In: Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, DC, 1984.
10. Rulkens, W. H., and J. W. Assink, et. al. Development of an Installation for On-Site Treatment of Soil Contaminated with Organic Bromine Compounds. In: Conference on Management of Uncontrolled Hazardous Waste Sites, Washington DC, 1982.
11. Logsdaile, D.H. Solvent Extraction and Ion Exchange in the Nuclear Fuel Cycle. John Wiley & Sons, New York, 1985.
12. Ryan, R.K., and D.M. Levins. Extraction of Radium from Uranium Tailings. CIM Bulletin, October 1980.
13. Ives, Kenneth J. The Scientific Basis of Flotation. Martinus Nijhoff Publishers, Boston, 1984.
14. Perry, R., and C. H. Chilton. Chemical Engineer's Handbook. McGraw Hill, New York, 1973.
15. Traver, R. D., In-Situ Flushing and Soil Washing Technologies for Superfund Site. RCRA/Superfund Engineering, Technology Transfer Symposium, 1986.

Chapter 8

General Issues at Radiologically Contaminated Superfund Sites

8.1 Introduction

This chapter discusses some of the issues likely to be associated with remediating Superfund sites that contain radioactive materials. The discussion is not, by any means, comprehensive. These issues include:

- disposal siting;
- handling of concentrated residuals;
- site information needs;
- mixed wastes;
- public reaction and acceptance; and
- costs.

8.2 Disposal Siting

Every site remediation involving radioactive materials must include a final, environmentally safe disposal site for the radioactive materials. The total activity of the radionuclides will not be lessened by any remediation process, although the matrix in which they are included may be reduced in volume by some of the technologies discussed.

Site selection for disposing of radioactive materials is already a sensitive issue. As noted in the discussion of land encapsulation in Chapter 2, states are beginning to restrict the use of land within their borders for the disposal of commercial low-level waste from other states.

Any disposal site for radioactive waste must be selected or constructed such that it contains the radionuclides as long as their concentrations are unacceptable for release to the environment.

There are several guidance documents available from EPA that provide information that should be considered in selecting the location of a disposal site [1-4].

8.3 Handling of Concentrated Residuals

Chemical extraction and physical separation techniques applied to soil to remove radionuclides are intended to clean the soil and reduce the volume of contaminated materials. If that is done, there will be fractions in which the radionuclides will be much

more concentrated--i.e., the radioactivity per unit volume will be much higher. Handling and disposal of the concentrated materials will require precautions appropriate to the activity level. DOT and NRC regulations for containment and storage of radioactive materials provide guidance for this situation.

Final disposal may be even more difficult after volume reduction than it would be if the material were to be excavated, transported, and disposed of without treatment for volume reduction. In addition the "clean" fractions may contain traces of toxic chemicals used in the treatment process, along with some traces of the radioactive contaminants. Therefore, these fractions also may require environmentally safe disposal.

Any attempt to put "cleaner" soil off site is likely to meet with the same resistance as locating a disposal site for all the material in the first place. The goal would be to have a portion clean enough to be replaced at the site.

8.4 Site Information Needs

For many sites, available information is limited regarding the detailed physical, chemical, and mineralogical characteristics of the matrix materials associated with the radioactive contaminants. In some cases, even the nature of the radionuclides present does not appear to be known with certainty. More detailed information is essential if use of chemical extraction and/or physical separation techniques is considered.

8.5 Mixed Wastes

Sites that contain radioactive waste materials may also contain other types of hazardous waste. Some of the Superfund sites contain various types of hazardous wastes and the radioactive portion may pose a relatively minor threat by comparison. The presence of other hazardous materials may complicate dealing with the radioactive portion of the waste and vice-versa. This is an issue that is likely to arise at many Superfund sites and would impact the possible utility of some of the remediation technologies. The disposition of waste containing both

radiological and chemical constituents ("mixed wastes") poses unique problems that will have to be addressed early in the technology screening process.

8.6 Public Reaction and Acceptance

Public concerns with respect to Superfund sites may be magnified where radioactive wastes exist. Concerns can be expected regarding the contaminated site, moving the material (if necessary), any processing or treatment location, and final containment.

8.7 Costs

All methods with the exception of in situ techniques will involve excavation costs for the materials. Application of some of the technologies may result in a reduced volume of radiologically contaminated materials to be sent to a secure disposal suitable for such materials. The cost of such disposal would include transportation and land encapsulation. The "cleaner" fractions remaining after a treatment process is completed must be analyzed for residual contamination and evaluated for replacement at the point of origin or at a suitable alternative site. There is a cost associated with this placement.

Costs associated with a treatment technology can be divided into development and implementation costs. Development costs include several stages of laboratory tests, studies and process designs leading to pilot-scale testing, and final design. Additional development costs involve fabrication, shakedown, and final testing of a full-scale system under controlled and field conditions. These costs could range from under \$1 million for a small system applicable to one specific type of problem to many millions for a larger system with numerous subsystems, and applicable to numerous types of problems.

Implementation costs when a treatment option is chosen for a given site include mobilization and demobilization, and operating costs. The mobilization costs include all costs associated with performing site-specific laboratory and/or pilot-scale testing; selecting an operating site; preparing any permit application materials or other administrative documentation necessary for operations; interface with local, state, and federal officials for such permits; transportation, setup, and shakedown of the treatment system on the site (including any site modifications such as installation of water supply wells, power, road access, operating areas, buildings, and other such logistical site features); performing site-specific testing to determine if the full-scale system performs according to the laboratory and pilot-scale predictions; and any other pre-operating types of costs. Mobilization costs may range from a few tens of thousands of dollars for a simple, small site to

multiple millions at a site with a large, complex installation where complicated permitting issues have been involved.

After operations are complete, demobilization costs incurred include those associated with decontamination of the entire system and surrounding operating site, disassembly and transport of the system, final determination and documentation that the treatment site has met the ARARs and has been brought to a state protective of human health and the environment, preparation of operations documentation, and any other site-specific costs associated with the post-operation period. These costs can range from a few tens of thousands of dollars to a million dollars or more, depending upon the complexity of the installation and the degree of contamination.

Operating costs include all those labor and material costs needed to operate the treatment system at the site, sometimes on a 24 hour-per-day basis; to provide for site security and personnel safety; to maintain record-keeping including permit-related or mandatory administrative documentation for all site actions; and to maintain the system in good operating order. The costs per ton or per cubic yard must include all applicable operating costs. These operating costs per cubic yard are dependent upon the capacity of the treatment system and the percentage of the time that the system is operating as opposed to being in a maintenance mode.

Operating costs depend largely upon the cost of labor at the site. Special protective clothing and special handling of the contaminated materials (particularly the concentrated materials) could raise labor costs well above those that might be expected for a comparable crew size working at a nonradioactive Superfund site. Some costs may be reduced due to efficiencies in personnel monitoring and decontamination of workers and equipment compared to some of the lengthy procedures required for hazardous chemicals, since radiation is relatively easy to measure, especially compared to many chemicals.

Overall, the operating cost, if it is assumed to be similar to on-site incineration operations would probably range from several hundred dollars per cubic yard for a large, high-capacity system with a high percentage of operating time, to several thousand dollars per cubic yard for smaller capacity systems having numerous maintenance problems and a large crew.

The costs must include disposal costs for concentrated material and will be highly dependent on how far treatment must be taken to allow unrestricted disposal of the "cleaner" portion.

The costs of treatment for individual sites and groups of similar sites can be examined in further detail to determine the likely costs of such treatment and how those costs compare with the costs of transportation off site and land encapsulation.

8.8 References

1. U.S. Environmental Protection Agency. Combined NRC-EPA Siting Guidelines for Disposal of Commercial Mixed Low-Level Radioactive and Hazardous Waste, OSW-USEPA. March 13, 1987.
2. U.S. Environmental Protection Agency. Criteria for Location Acceptability and Existing Applicable Regulations – Phase I – Permit Writers' Guidance Manual for Hazardous Waste Land Storage and Disposal Facilities, USEPA. OSW-Final Draft, February 1985.
3. U.S. Environmental Protection Agency. Criteria for Identifying Areas of Vulnerable Hydrogeology under RCRA – Statutory Interpretive Guidance – Guidance Manual for Hazardous Waste Land Treatment, Storage, and Disposal Facilities, OSW-USEPA, Interim Final, July 1986.
4. U. S. Environmental Protection Agency. Standards for Cleanup of Land and Buildings Contaminated with Residual Radioactive Materials from Inactive Uranium Processing Sites. 40 CFR 192.12, 48 FR 602. January 5, 1983.

Chapter 9

Criteria for Further Studies

9.1 Introduction

Any choice of remediation technologies for radioactive wastes at Superfund sites would have to be site-specific. Since none of the chemical extraction and physical separation technologies has been used in a site remediation situation, their application must be approached cautiously. The same holds true for solidification or stabilization processes. Essentially, only land encapsulation has been used to remediate similar sites; ocean disposal has been used for low level radioactive wastes [1-3].

9.2 Alternative Assessment Studies

A complete site characterization would include mineral analysis, particle size distribution, radionuclide contaminant distribution on various size fractions, soil texture and permeability, moisture content, etc. A list of some important site and waste characteristics that may affect the applicability and effectiveness of various technologies is presented in Table 19 [4].

Since further developments and studies on alternative technologies for each Superfund site may be very expensive, it is important to study the patterns in waste characteristics at various sites and develop waste groups with similar major characteristics. Alternative assessment studies can be used to help select the alternative technologies to treat each waste group. Thus, a preliminary screening of technologies can be accomplished based primarily on the waste characteristics.

Based on these alternative assessment studies, one or more technologies, individually or in combination, can be selected for further investigation.

Physical separation and combined physical separation and chemical extraction techniques will not apply if radionuclides are uniformly distributed through all the soil size fractions. This, however, is unlikely. The highest concentration of radioactive materials appears to be contained in very fine particles [5,6].

Chemical extraction technologies may be applicable to tailings and contaminated soils but may not be applicable to building debris and contaminated

Table 19. Site and Waste Characteristics that Impact Remediation Technologies

Site Characteristics	
Site Volume	Depth of Bedrock
Site Area	Depth to Aquicludes
Site Configuration	Degree of Contamination
Disposal Methods	Cleanup Requirements
	Direction and Rate of Ground-water Flow
Climate	Receptors
- Precipitation	Drinking Water Wells
- Temperature	Surface Waters
- Evaporation	Ecological Areas
Soil Texture and Permeability	Existing Land Use
Soil Moisture	Depths of Ground Water or Plume
Slope	
Drainage	
Vegetation	
Waste Characteristics	
Quantity	Infectiousness
Chemical Composition	Solubility
Mineral Composition	Volatility
Acute Toxicity	Density
Persistence	Partition Coefficient
Biodegradability	Safe Levels in the Environment
Total Radioactivity	Compatibility with Other Chemicals
Radioisotopes and Concentration	Particle Size Distribution
Ignitability	Radioactivity Distribution with Particle Size
Reactivity/Corrosiveness	
Treatability	
Thermal Properties	

Source. [4]

equipment. Chemical extraction techniques may not clean soil and tailings that contain a large quantity of refractory minerals [7-9].

Discussed in this chapter are the various studies needed to evaluate the technologies for their applicability to site remediation.

9.3 Treatability Studies

When one or more remediation concepts are selected that appear applicable, plans may be made for bench-scale laboratory studies. Success there could lead to pilot-scale testing and eventually to full-

scale demonstration of site cleanup. This step-wise procedure can permit stopping or redirecting development of a remediation technology that appears unfruitful. Carefully developed work plans and quality assurance plans must precede each step.

More detailed information about the selected technologies would be developed at the bench-scale stage. Examples of bench-scale studies required include:

- For solidification or stabilization—selection and performance evaluation of solidifying agents compatible with the chemical composition of the specific waste group.
- For flotation—development of surfactants that enhance the removal of the contaminant in specific mineral form while suppressing the other minerals in the specific waste group.
- For chemical extraction with inorganic salts – identification of specific inorganic salts and determination of relevant process parameters to effectively extract the radionuclide contaminant from the specific waste group.

Based on the information developed in these studies, detailed remediation processes can be selected that may involve multiple technologies. Selection of any process must include consideration of whether appropriate disposal methods are available for both the concentrated fractions and the "clean" fractions. Preliminary cost information relative to each of these processes would be developed along with performance expectations. The criteria used to evaluate these processes so that some processes could be selected for further development could include:

- Amount of expected waste volume reduction;
- Radioactivity of the expected "clean" fractions;
- Applicability to other waste groups;
- Technological uncertainty;
- Potential risks to remediation personnel;
- Potential to construct mobile or transportable units;
- Generation of any toxic by-products or effluents;
- Potential to coremediate other hazardous chemicals in the specific waste group;
- Total cost of remediation; and
- Disposal site availability.

9.4 Pilot-Plant Studies

After all the criteria listed above are weighed appropriately, it is expected that no more than one or two processes may qualify for pilot-scale testing for a specific waste group.

The pilot testing would be used to develop better information on the performance of the process, assessment of technical problems, and costs. Testing must be carried out over a significant duration to obtain reliable data.

For field demonstration and full-scale site remediation, the criteria applied earlier could be used to select a remediation process.

9.5 References

1. U.S. Environmental Protection Agency. Technical Resource Documents on Hazardous Waste Land Disposal. SW860 and SW870 Series. Office of Solid Waste, Washington DC. 1979-1987.
2. U.S. Environmental Protection Agency. Minimum Technology Guidance on Double Liner Systems. Draft. Office of Solid Waste. May 1985.
3. Council on Environmental Quality. Ocean Dumping - A National Policy. A Report to the President. U.S. Government Printing Office. 1970.
4. U.S. Environmental Protection Agency. Guidance on the Preparation of Feasibility Studies. Municipal Environmental Research Laboratory, Cincinnati, Ohio Office of Emergency and Remedial Response, Washington, D.C. 1983.
5. Olsson, R.K. Geological Analysis of and Source of the Radium Contamination at the Montclair, West Orange, and Glen Ridge Radium Contaminated Sites. Department of Geological Sciences, Rutgers University, New Brunswick, New Jersey, 1986.
6. Borrowman, S.R., and P.T. Brooks. Radium Removal from Uranium Ores and Mill Tailings. U.S. Bureau of Mines Report 8099, 1975.
7. Ryan, R.K., and D.M. Levins. Extraction of Radium from Uranium Tailings. *CIM Bulletin*, October, 1980, pp. 126-133.
8. Yagnik, S.K., M.H.I. Hurst, and S. Seely. An Investigation of Radium Extraction from Uranium Mill Tailings. *Hydrometallurgy*, 7:61-75, 1981.
9. Ryon, A.D., F.J. Hurst, and F.G. Seely. Nitric Acid Leaching of Radium and Other Significant Radionuclides from Uranium Ores and Tailings. ORNL/TM-5944, Oak Ridge National Laboratories, Oak Ridge, Tennessee, 1977.

Chapter 10

Conclusions

This report provides a technical review of the technologies that may be useful in removing radionuclides from radiologically contaminated Superfund sites. As a result of this review, the following conclusions have emerged:

- Remediation may include soil ventilation and shielding around homes to protect people from radon and gamma radiation exposure.
- Ocean disposal could potentially be a technically viable method.

10.1 Technological Approaches

- Alteration or remediation of the radioactive decay process, thus changing the fundamental hazard, is not possible.
- Remediation, to date, has only involved removing contaminated material and containing it in above-ground land encapsulation, drums, or temporary storage sites. This approach has substantial technical backup.
- Alternative treatment technologies that may warrant further study include solidification, vitrification, chemical extraction, physical separation, and combinations of physical separation and chemical extraction. Even if these treatment technologies were effective, some form of final disposal would always be needed.
- Various remediation technologies may have potential to reduce the volume of the contaminated waste with an associated increase in concentration of the radioactive material.
- Remediation technologies generally result in the disturbance of contaminated material. The additional risk to human health and the environment must be weighed against leaving the contaminated materials on-site in a contained state, if that is an option.
- Physical separation and/or chemical extraction technologies can potentially concentrate the contamination, thereby reducing the volume and weight of the waste material for final disposal.

10.2 Disposal

- All nonresidual waste must be disposed at a final site that is designed to meet security and longevity criteria appropriate for the concentration of radioactivity that is present.
- Capping could be a more suitable method than areal removal of radon for controlling radon emissions from large sources.

10.3 On-Site Treatment

- Solidification and vitrification technologies do not reduce the amount of the contaminated material. However, they may immobilize the contamination in the waste material thereby increasing the effectiveness and safety of the conventional remediation (e.g., land encapsulation). Solidification may actually increase the volume by the addition of the solidifying materials.

10.4 Chemical Extraction Technology

- Several chemical extraction technologies have been studied in the laboratory by various investigators. These include the use of salt solutions, mineral acids, and various complexing agents to extract the radioactive contaminants from the soil. Several of these experiments had relatively high extraction efficiencies. For example, up to 97 percent radium and 99 percent thorium were removed using nitric acid and up to 92 percent of radium was removed from uranium mill tailings using EDTA.

- Chemical extraction technologies potentially applicable for treating radioactive wastes at Superfund sites are being researched and investigated. Significant development work at bench and pilot scale would be required before these technologies could be utilized at full scale.

10.5 Physical Separation and Reduction

- Physical separation technologies can only be useful for those waste materials in which the radioactive contamination resides in a certain particle size fraction. This information about the waste materials at the 20 Superfund sites is not presently available in sufficient detail. Extensive soil characterization is required at these Superfund sites to better establish the applicability of the physical separation technologies.
- The physical separation technologies are at a mature stage of development. A significant selection and variety of hardware are available in the uranium mining industry. If detailed soil characteristics at the radiologically contaminated Superfund sites are developed, it could be possible to design specific systems for further bench-scale and pilot-scale testing and evaluation.

10.6 Combined Physical Separation and Chemical Extraction

- At a specific site, using a combination of physical separation and chemical extraction technologies is likely to be more effective than using either type of technology separately.

10.7 General Issues

- It is important to note that in some cases there may be two categories of residual contamination: process wastes and soils contaminated with isolated radionuclides or groups of radionuclides. While removal of the radioactive fractions of soils contaminated only with single radionuclides such as uranium or plutonium might result in "clean" fractions acceptable for unrestricted disposal, removal of the radioactivity from a soil also contaminated with process wastes may not. In the second case the nonradioactive fractions of the residues could result in an unacceptable product. Therefore, before considering any separation technique, it is necessary that acceptable limits for both the radiological contaminants and the non-radiological contaminants be defined. In some

cases, multiple treatments or combined technologies could be required to achieve environmental goals.

- Every site remediation involving radioactive materials must involve a final, environmentally safe disposal site for the radioactive materials.
- Even if it proves feasible at a particular site to lower the concentration of radionuclides in the soil by physical separation and/or chemical extraction to some acceptable level, the "clean" fractions are likely to contain traces of radionuclides. Therefore, adequate attention must be given to whether the "clean" fractions may be returned to the original site or an unrestricted location or must be sent to a disposal site.
- When developing technologies for cleanup at a site, it is essential that a step-wise procedure be used. This should begin with assessment studies and bench-scale testing, followed by pilot-scale testing. Only if these are successful should full-scale demonstrations be attempted. Carefully developed work plans and quality assurance plans should precede each step.

10.8 Site Characteristics

- Twenty Superfund sites have radiologically contaminated soil spread over 9500 acres. Of these sites, five are DOE sites (3 FUSRAP and 2 SFMP). [Data presented here are accurate as of December 1987.]
- Any choice of remediation technologies for radioactive waste at Superfund sites would have to be site specific. Extensive site soil characterization studies, such as complete mineral analysis, particle size distribution, radionuclide-contaminated distribution, soil texture, and permeability, would be required prior to development and application of most of the technologies, land encapsulation being an exception.

Appendix A

Applicable Laws, Regulations, and Guidance

This appendix briefly presents some of the laws, regulations, and guidance that are part of the framework within which technologies may be selected for remediation of Superfund sites. This report does not attempt nor is it intended to provide a complete or detailed analysis of how various laws, regulations, and guidance apply in general or at a specific Superfund site, nor is it intended to set or interpret policy for the selection or use of technologies to clean up any Superfund or other hazardous waste site.

Superfund sites are remediated under the provisions of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA). Several sections of CERCLA and SARA are pertinent to the intent of this document.

EPA undertakes remedial investigation and feasibility studies (RI/FS) at National Priorities List (NPL) sites where there is a release of a hazardous substance or pollutant or contaminant, or threat of release, to identify those releases and their nature, along with planning and investigations necessary to direct response actions. Radiologically contaminated sites have qualified for the NPL.

Section 311 of CERCLA, commonly referred to as the Superfund Innovative Technology Evaluation (SITE) program, provides for demonstrations of alternative technologies in the cleanup of sites on the NPL. Radiologically contaminated sites and treatment technologies, such as those described in this document, may qualify for demonstration under this program. The SITE program generally requires that a technology developer bear the cost of demonstrating his technology, while EPA bears the cost of its evaluation. Proof of concept laboratory results must be supplied by the technology developer before EPA can consider funding a demonstration under this program.

SARA Section 118(m) (not an amendment to CERCLA) states that it is the sense of Congress that fully demonstrated remediation methods, such as off-site transport and disposal, are not necessarily required at sites on the NPL because of the presence

of radon. This section states that innovative or alternative methods that protect human health in a more cost effective manner may be used.

SARA Section 121 (Cleanup Standards) states a strong statutory preference for remedies that are highly reliable and provide long-term protection. In addition to the requirement for remedies to be both protective of human health and the environment and cost-effective, additional remedy selection considerations in 121(b) include:

- A preference for remedial actions that employ treatment that permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants as its principal element.
- Offsite transport and disposal without treatment is the least favored alternative where practicable treatment technologies are available.
- The need to assess the use of permanent solutions and alternative treatment technologies or resource recovery technologies and use them to the maximum extent practicable.

Section 121(d)(2)(A) of SARA incorporates into law the CERCLA Compliance Policy, which specifies that Superfund remedial actions meet any Federal Standard requirements, criteria, or limitations that are legally applicable or relevant and appropriate requirements (ARARs) under any Federal or state environmental law.

CERCLA Section 104(a)(3) limits Federal response authority for releases of naturally occurring substances in locations where they are naturally found. However, this section does not apply for many of the radiologically contaminated Superfund sites.

The Low-Level Radioactive Waste Policy Amendments Act of 1985 (LLRWPA) requires states and compacts to develop siting plans for low-level radioactive waste (LLW) disposal facilities by January 1, 1988. These disposal facilities may receive commercial mixed low-level radioactive and hazardous waste (Mixed LLW), which is regulated by

the U.S. Nuclear Regulatory Commission (NRC) under the Atomic Energy Act (AEA) as amended, and by the EPA under the Resource Conservation and Recovery Act of 1976 (RCRA), as amended. NRC has promulgated LLW regulations and EPA has issued guidance that pertains to the siting requirements for disposal facilities for Mixed LLW.

Section 5(e)(1)(B) of the LLRWPA requires states and compacts to develop siting plans for LLW disposal facilities by January 1, 1988. In addition to other information, these siting plans must identify, to the extent practicable, the process for (1) screening for broad siting areas, (2) identifying and evaluating specific candidate sites, and (3) characterizing the preferred site(s). It is anticipated that this process will be based primarily on the site suitability requirements that apply to LLW disposal. If facilities also receive Mixed LLW, their siting requirements will reflect additional requirements that apply to disposal of hazardous waste as defined by RCRA.

Combined NRC-EPA Siting Guidelines for Disposal of Commercial Mixed Low-Level Radioactive and Hazardous Waste (see Addendum) provide guidance to facilitate development of siting plans for disposal facilities that may receive Mixed LLW.

Joint NRC-EPA Guidance as a Conceptual Design Approach for Commercial Mixed Low-Level Radioactive and Hazardous Waste Disposal Facilities (see Addendum) presents a conceptual design approach that meets the regulatory requirements of both agencies for the safe disposal of Mixed LLW. Other designs, or variations on the proposed design concept, may also be acceptable under the requirements of both agencies and will be reviewed on a case-by-case basis as received.

Standards developed under Section 275 of the Atomic Energy Act and Section 206 of the Uranium Mill Tailings Radiation Control Act of 1978 may be applicable or relevant and appropriate on a site specific basis to the cleanup of radiologically contaminated Superfund sites. In January 1983, the EPA promulgated 40 CFR 192, Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings under authority of these Acts. The pertinent standards are contained in 40 CFR 192.12, 192.32, and 192.41, and deal with the acceptable levels of radioactivity in residual materials and radiation emission levels from them, and with disposal requirements. The disposal requirements include a design life of at least 200 years and preferably 1,000 years where reasonably achievable.

The Department of Energy (Office of Nuclear Energy) operates four remedial action projects for radiologically contaminated sites that parallel EPA's Superfund program. Remedial actions have been

completed or are in advanced stages at some of these sites. These DOE projects are as follows:

1. Formerly Utilized Sites Remedial Action Project (FUSRAP) under authority of the Department of Energy Organization Act of 1977.
2. The Uranium Mill Tailings Remedial Action Project (UMTRAP) under authority of Public Law 95-604, the Uranium Mill Tailings Control Act of 1978.
3. The Grand Junction Remedial Action Project (GJRAP) under Public Law 92-314 (1972) amended by Public Law 95-236 (1978).
4. The Surplus Facilities Management Program (SFMP) under authority of the Department of Energy Organization Act of 1977.

These projects are described in Appendix B.

In addition, DOE's Office of Defense Waste and Transportation Management (DWTM) is responsible for safely managing defense waste as generated, transporting it, and storing it, and is also responsible for developing and implementing the technology needed for long-term management and eventual disposal of the waste.

One of the options for radioactive waste disposal is ocean disposal. Ocean disposal is controlled by regulations under the Marine Protection, Research, and Sanctuaries Act of 1972, as amended. The regulations are contained in 40 CFR Parts 220 through 229 and are currently being revised. Perhaps the most pertinent are found in 40 CFR 227, Criteria for the Evaluation of Permit Applications for Ocean Dumping of Materials. A unique provision of the Act is that a permit may not be issued by EPA for ocean disposal of radioactive materials without the approval of both Houses of Congress. The Act prohibits ocean disposal of high level wastes; only low level wastes are eligible to be considered for a permit.

Although this document has been specifically directed at the remediation of Superfund sites, it may have applicability to permitted sites that require corrective actions under RCRA as amended by the Hazardous and Solid Waste Amendments of 1984 (HSWA). A RCRA site can be placed on the CERCLA NPL if the operator is bankrupt, unwilling to carry out corrective action, or has lost his authorization to operate (see Preamble to 40 CFR Part 300, June 10, 1986).

Addendum 1 – Combined NRC-EPA Siting Guidelines for Disposal of Commercial Mixed Low-Level Radioactive and Hazardous Wastes

Introduction

The Low-Level Radioactive Waste Policy Amendments Act of 1985 (LLRWPA) requires states and compacts to develop siting plans for low-level radioactive waste (LLW) disposal facilities by January 1, 1988. These disposal facilities may receive commercial mixed low-level radioactive and hazardous waste (Mixed LLW), which is regulated by the U. S. Nuclear Regulatory Commission (NRC) the Atomic Energy Act (AEA), as amended, and by the U. S. Environmental Protection Agency (EPA) under the Resource Conservation and Recovery Act (RCRA), as amended. Mixed LLW is defined as waste that satisfies the definition of LLW in the LLRWPA and contains hazardous waste that either is listed in Subpart D of 40 CFR Part 261 or causes the LLW to exhibit any of the hazardous waste characteristics identified in Subpart C of 40 CFR Part 261. To assist in applying that definition, NRC and EPA recently developed joint guidance entitled "Guidance on the Definition and Identification of Commercial Mixed Low-Level Radioactive and Hazardous Waste and Answers to Anticipated Questions" (Jan. 8, 1987). NRC has promulgated LLW regulations and EPA has promulgated hazardous waste regulations that pertain to the siting requirements for disposal facilities for Mixed LLW. Because of uncertainty about the precise content of EPA's future location standards, states and compacts may have questions regarding the site selection process. This document provides combined NRC-EPA siting guidelines, to be used before EPA's new location standards are promulgated, to facilitate development of siting plans for disposal facilities that may receive Mixed LLW.

Section 5(e)(1)(B) of the LLRWPA requires states and compacts to develop siting plans for LLW disposal facilities by January 1, 1988. In addition to other information, these siting plans must identify, to the extent practicable the process for (1) screening for broad siting areas, (2) identifying and evaluating specific candidate sites, and (3) characterizing the preferred site(s). It is anticipated that this process will be based primarily on the site suitability requirements that apply to LLW disposal. If facilities also receive Mixed LLW, their siting requirements will reflect additional requirements that apply to disposal of hazardous waste as defined by RCRA.

In 1982, NRC promulgated regulations which contain minimum site suitability requirements for LLW land disposal facilities in 10 CFR 61.50. EPA has also promulgated minimum location standards for hazardous waste treatment, storage and disposal

facilities in 40 CFR 264.18. Considerations affecting siting are also found in 40 CFR 270.3, 270.14(b) and (c). Although both NRC and EPA have incorporated siting requirements in existing regulations for LLW and hazardous waste disposal, respectively, the 1984 Hazardous and Solid Waste Amendments (HSWA) to RCRA require EPA to publish guidance identifying areas of vulnerable hydrogeology. In July 1986, EPA published this guidance in "Criteria for Identifying Areas of Vulnerable Hydrogeology under the Resource Conservation and Recovery Act – Statutory Interpretative Guidance, July 1986, Interim Final (PB-86-224953)." The 1984 HSWA also requires (in Section 3004(o)(7)) that EPA specify criteria for the acceptable location of new and existing hazardous waste treatment, storage, and disposal facilities. EPA anticipates proposing these location standards in September 1987 and promulgating them in final form by September 1988.

EPA's scheduled date for promulgating its final location standards is nine months after the LLRWPA January 1, 1988, milestone for non-sited states and compacts to develop siting plans. Therefore, states and compacts may require some assistance in their efforts to develop siting plans for LLW disposal facilities that may receive Mixed LLW. The two agencies are issuing these combined guidelines to promote the development of siting plans by states and compacts. Both NRC and EPA consider that the absence of EPA's final comprehensive location standards for hazardous waste disposal facilities is an adequate basis for states and compacts to delay development of siting plans for LLW disposal.

States and compacts should proceed at this time to develop siting plans in accordance with the existing NRC and EPA requirements. The following combined NRC-EPA guidelines are provided for use by the states and compacts, and are based on existing NRC regulations in 10 CFR Part 61 and EPA regulations in 40 CFR Parts 264 and 270. As EPA continues its development of location standards, both agencies will strive to keep states and compacts informed about the status of the developing siting requirements.

Combined NRC-EPA Siting Guidelines

Site suitability requirements for land disposal of LLW are provided in 10 CFR Section 61.50. These requirements constitute minimum technical requirements for geologic, hydrologic, and demographic characteristics of LLW disposal sites. Several of these requirements identify favorable site characteristic for near-surface disposal facilities for LLW. The majority of the site suitability requirements, however, identify potentially adverse site characteristics that must not be present at LLW disposal sites. The site suitability requirements in 10 CFR Part 61 are intended to function collectively with the requirements for facility design and operation, site

closure, waste classification and segregation, waste form and packaging, and institutional controls to assure isolation of LLW for the duration of the radiological hazard. The NRC Technical Position entitled "Site Suitability, Selection, and Characterization" (NUREG-0902) provides detailed guidance on implementing the site suitability requirements in 10 CFR Part 61.

EPA has also promulgated certain minimum location standards for hazardous waste treatment, storage, and disposal facilities. These standards are provided in 40 CFR Section 264.18. As previously noted, the hazardous waste regulations also include other location considerations as well as applicable provisions of other Federal statutes. For example, Subpart F of 40 CFR Part 264 requires establishment of ground-water monitoring programs capable of detecting contamination from land disposal units. While not a siting criterion per se this requirement can preclude siting in locations that cannot be adequately monitored or characterized. A further description of location-related standards and applicable provisions of other Federal statutes can be found in the "Permit Writers" Guidance Manual for Hazardous Waste Land Storage and Disposal Facilities: Phase I Criteria for Location Acceptability and Existing Applicable Regulations" (Final Draft - February 1985). This guidance manual describes five criteria for determining location acceptability; ability to characterize, exclusion of high hazard and unstable terrain, ability to monitor, exclusion of protected lands, and identification of areas of vulnerable hydrogeology. The first four of these criteria have a basis in the regulations and are fully described in the manual. The fifth criterion, vulnerable hydrogeology, is defined in the RCRA interpretive guidance manual mentioned above (Criteria for Identifying Areas of Vulnerable Hydrogeology under the Resource Conservation and Recovery Act-Statutory Interpretive Guidance, July 1986, Interim Final (PB-86-224953)).

However, since HSWA also added other requirements in addition to location standards to prevent or mitigate ground-water contamination, EPA recognizes that vulnerable hydrogeology must be considered in conjunction with design and operating practices. Vulnerability should not be the sole determining factor in RCRA siting decisions. Rather, this criterion provides a trigger for more detailed evaluation of sites that are identified as having potentially vulnerable hydrogeology. The extent of necessary site review and evaluation is related directly to the extent to which a location "fails" or "passes" the vulnerability criterion. Sites that are determined to be extremely vulnerable will require much closer examination than sites that are deemed non-vulnerable. The results of this more detailed review may then provide a basis for eventual permit conditions or modifications in design or operating practices.

By combining the above technical requirements, standards, and guidance of both agencies, NRC and EPA have formulated the eleven guidelines listed below. The use of terms in the guidelines is consistent with their regulatory definition in 10 CFR Part 61 and 40 CFR Parts 260 and 264. The combined set of location guidelines is intended by the agencies to apply only as guidance to states and compacts developing siting plans for LLW disposal facilities that may receive Mixed LLW. These combined guidelines are not intended to displace existing standards and guidance. In addition, the independent guidance of both agencies should be considered in any application of the combined siting guidelines.

The combined siting guidelines for a commercial Mixed LLW disposal facility are as follows:

1. Primary emphasis in disposal site suitability should be given to isolation of wastes and to disposal site features that ensure that the long-term performance objectives of 10 CFR Part 61, Subpart C are met.
2. The disposal site shall be capable of being characterized, modeled, analyzed, and monitored. At a minimum, site characterization must be able to (a) delineate ground-water flow paths, (b) estimate ground-water flow velocities, and (c) determine geotechnical properties sufficiently to support facility design. At a minimum for site ground-water monitoring disposal site operators must be able to (a) assess the rate and direction of ground-water flow in the uppermost aquifer, (b) determine background ground-water quality, and (c) promptly detect ground-water contamination.
3. The disposal site must be generally well-drained (with respect to surface water) and free of areas of flooding or frequent ponding.
4. The disposal site shall not be in the 100-year floodplain.
5. The site must be located so that upstream drainage areas are minimized to decrease the amount of runoff that could erode or inundate waste disposal units.
6. Disposal sites may not be located on lands specified in 10 CFR Section 61.50(a)(5), including wetlands (Clean Water Act) and coastal high hazard areas (Coastal Zone Management Act). Location of facilities on the following lands must be consistent with requirements of applicable Federal statutes: archeological and historic places (National Historic Places Act); endangered or threatened habitats (Endangered Species Act); national parks, monuments, and scenic rivers (Wild and Scenic Rivers Act); wilderness areas (Wilderness Protection

Act); and wildlife refuges (National Wildlife Refuge System Administration Act).

7. The disposal site should provide a stable foundation for engineered containment structures.

8. Disposal sites must not be located in areas where:

(a) tectonic processes such as faulting, folding, seismic activity, or vulcanism may occur with such frequency and extent to affect significantly the ability of the disposal facility to satisfy the performance objectives specified in Subpart C of 10 CFR Part 61, or may preclude defensible modeling and prediction of long-term impacts; in particular, sites must be located more than 200 feet from a fault that has been active during the Holocene Epoch;

(b) surface geologic processes such as mass wasting, erosion, slumping, landsliding, or weathering occur with such frequency and extent to affect significantly the ability of the disposal facility to meet the performance objectives in Subpart C of 10 CFR Part 61, or may preclude defensible modeling and prediction of long-term impacts;

(c) natural resources exist that, if exploited, would result in failure to meet the performance objectives in Subpart C of 10 CFR Part 61;

(d) projected population growth and future developments within the region or state where the facility is to be located are likely to affect the ability of the disposal facility to meet the performance objectives in Subpart C of 10 CFR Part 61; and

(e) nearby facilities or activities could adversely impact the disposal facility's ability to satisfy the performance objectives in Subpart C of 10 CFR Part 61 or could significantly mask an environmental monitoring program.

9. The hydrogeologic unit beneath the site shall not discharge ground water to the land surface within the disposal site boundaries.

10. The water table must be sufficiently below the disposal facility to prevent ground-water intrusion into the waste, with the exception outlined under 10 CFR Section 61.50(a)(7).

11. In general, areas with highly vulnerable hydrogeology deserve special attention in the siting process. Hydrogeology is considered vulnerable when ground-water travel time along any 100-foot flow path from the edge of the engineered containment structure is less than approximately 100 years (Criteria for Identifying Areas of Vulnerable Hydrogeology Under RCRA—Statutory Interpretive Guidance, July 1986, Interim Final (PB-86-224953)). Disposal sites located in areas of vulnerable hydrogeology may require extensive, site-specific investigations which could lead to and provide bases for restrictions or modifications to design or operating practices. However, a finding that a site is located in an area of vulnerable hydrogeology alone, based on the EPA criteria, is not considered sufficient to prohibit siting under RCRA.

Addendum II – Joint NRC-EPA Guidance on a Conceptual Design Approach for Commercial Mixed Low-Level Radioactive and Hazardous Waste Disposal Facilities

Introduction

The Low-Level Radioactive Waste Policy Amendments Act of 1985 (LLRWPA) requires that the three operating low-level radioactive waste (LLW) disposal facilities remain available through 1992. By that time, all states and compact regions are required to assume complete responsibility for LLW disposal. Both existing and new disposal facilities may receive commercial mixed low-level radioactive and hazardous waste (Mixed LLW), which is regulated by the U.S. Nuclear Regulatory Commission (NRC) under the Atomic Energy Act (AEA), and by the U.S. Environmental Protection Agency (EPA) under the Resource Conservation and Recovery Act (RCRA). Mixed LLW is defined as waste that satisfies the definition of LLW in the LLRWPA and contains hazardous waste that either (1) is listed as a hazardous waste in Subpart D of 40 CFR Part 261 or (2) causes the LLW to exhibit any of the hazardous waste characteristics identified in Subpart C of 40 CFR Part 261. To assist in applying this definition, NRC and EPA issued joint guidance entitled "Guidance on the Definition and Identification of Commercial Mixed Low-Level Radioactive Waste and Answers to Anticipated Questions" on January 8, 1987.

This jointly developed NRC-EPA guidance document presents a conceptual design approach that meets the regulatory requirements of both agencies for the safe disposal of Mixed LLW. Other designs, or variation of the proposed design concept may also be acceptable under the requirements of both agencies and will be reviewed on a case-by-case basis as received.

EPA regulations in 40 CFR Part 264, Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities, identify the design and operating requirements for owners and operators that dispose of hazardous waste in landfills [264.300 to 264.317]. These regulations involve requirements for the installation of two or more liners and a leachate collection and removal system (LCRS) above and between the liners to promote human health and the environment. Exceptions to the double liner and leachate collection system requirements are allowed, if alternative design and operating practices, together with location characteristics, are demonstrated to EPA Regional Administrator to be equally effective in preventing the migration of any hazardous constituent into the ground water or surface water.

NRC regulations in 10 CFR Part 61, Licensing Requirements for Land Disposal Radioactive Waste, indicate that long-term stability of the waste and the disposal site require minimization of access of water to the waste [61.7(b)(2)] and that the disposal site must be designed to minimize, to the extent practicable, the contact of water with waste during storage, the contact of standing water with waste during disposal, and the contact of percolating standing water with wastes after disposal [61.51(a)(6)]. The primary objective of the above NRC regulations is to preclude the possibility of the development of a "bath-tub" effect in which the waste could become immersed in liquid (e.g., from infiltration of surface water runoff) within a disposal unit below grade with a low-permeability bottom surface.

The guidance on a conceptual design approach that is offered in the subsequent paragraphs is intended to present basic design concepts that are acceptable in addressing the regulations of both the NRC and EPA with respect to requirements for liners, leachate collection systems and efforts to minimize the contact of liquid with the waste. It should be recognized that the guidance is being provided at the conceptual level and that the design and details that are complementary to specific site conditions need to be engineered by potential waste facility owners and operators. The application of the guidance in this document will not affect the requirements for licensees of waste disposal facilities to comply with all applicable NRC and EPA regulations.

Conceptual Design

Sketches and a brief discussion of the design considerations for an above grade disposal unit are provided. This design concept has been developed primarily to demonstrate the integration of EPA's regulatory requirements for two or more liners and a leachate collection system above and between liners and the regulations of the NRC that require the contact of water with the waste be minimized. In addition, the design concept fulfills the need under both agencies' regulations to assure long-term stability and minimize active maintenance after site closure.

In this approach, the Mixed LLW would be placed above the original ground surface in a tumulus that would be blended into the disposal site topography. Schematic details of some of the principal design features of an above grade Mixed LLW disposal unit are provided in the sketches accompanying this guidance document. Figure A1 depicts the three dimensional overall view of a concept Mixed LLW disposal unit; Figure A2 provides details of the perimeter berm, liners, and leachate collection system; Figure A3 presents a cross-sectional view

of the covered portion of the disposal unit; and Figure A4 describes the final cover system.

In the overall view of the Mixed LLW disposal facility, the double liners leachate collection and removal system are installed before the emplacement of the Mixed LLW; and the cover system is added at closure. The leak detection tank and leachate

collection tank are encircled by a berm that controls surface water runoff from precipitation that would fall directly on the waste facility site. The drainage pipes in the upper primary collection system would collect any leachate that could possibly develop above the top flexible membrane liner and below the emplaced waste. Any leachate collected would drain through pipes to the primary leachate collection tank where

Figure A1. Mixed waste disposal facility.

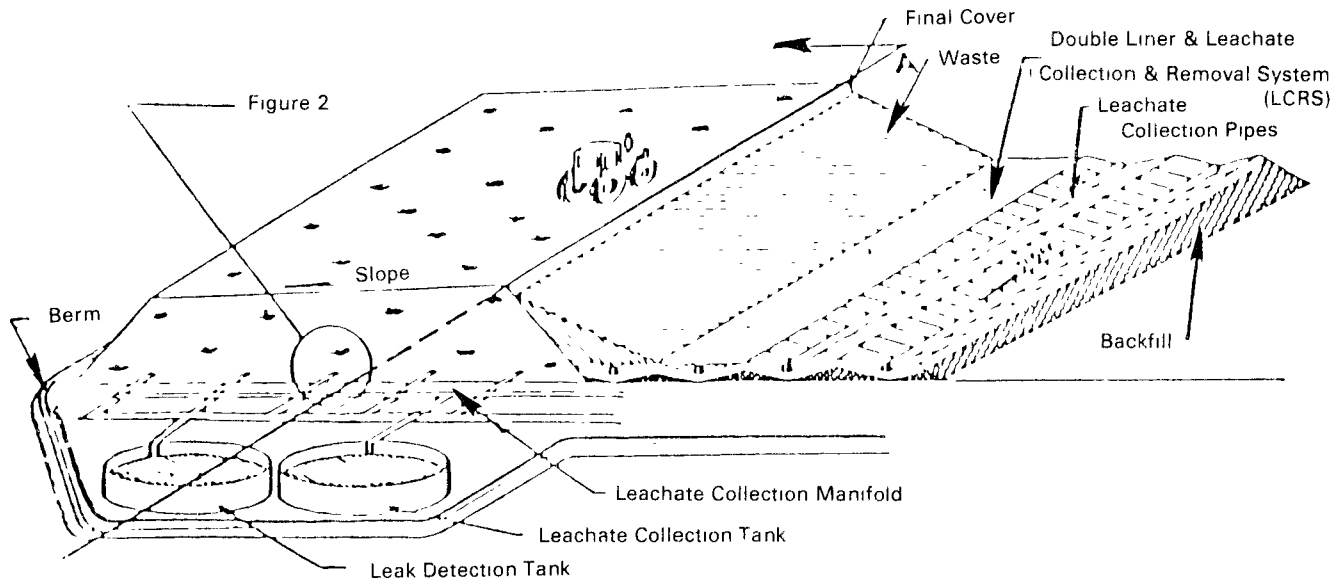
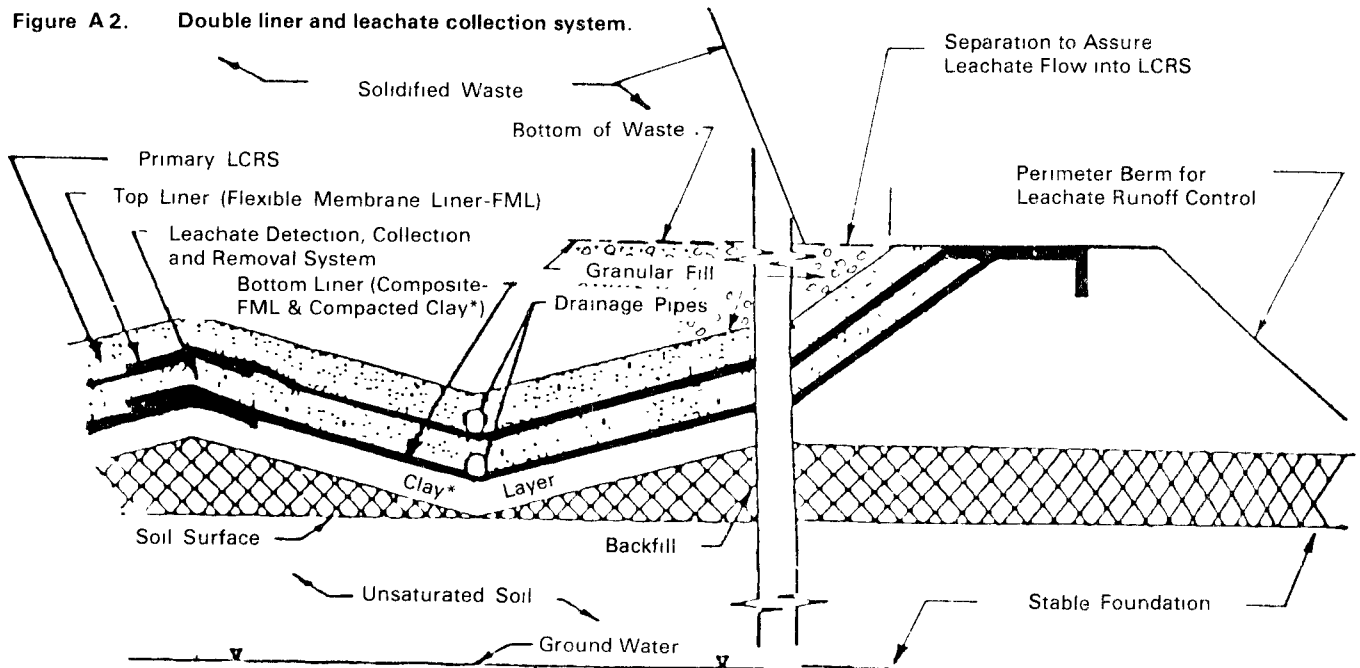


Figure A2. Double liner and leachate collection system.



*The compacted clay layer is to be a minimum 3 feet in thickness and have a hydraulic conductivity less than 1×10^{-7} cm/sec

the leachate would be tested and treated, if required. Any leachate collected by the lower leachate collection and removal system would drain to the leak detection tank. The development of significant amounts of leachate from the solidified waste after closure is not anticipated. This is because the closure requirements provide that the cover must be designed and constructed 1) to provide long-term minimization of water infiltration into the closed disposal facility, 2) to function with minimum maintenance, 3) to promote drainage and minimize erosion, and 4) to have a permeability less than or equal to the permeability of any bottom liner system. It is anticipated that the area shown on Figure A3 between the slope of the final cover and the run-on control berm, where the tanks are located, would be regraded and the tanks removed at the end of the post-closure care period (normally 30 years) when leachate development and collection is no longer a problem.

Figure A2 provides the general details required by EPA regulations for the double liner and leachate collection and removal system. The perimeter berm for leachate runoff control would assure that all leachate is collected below the waste and safely contained and transported through the drainage layers and pipes to the tanks located outside the final cover slope. NRC's regulation requiring minimizing contact of the waste with water are fulfilled by requiring the waste to be placed above the level of the highest water table fluctuation and above the drainage layers where leachate would collect. The bottom elevation of the solidified Mixed LLW would be required in all

instances to be at elevations above the top of the perimeter berm.

In Figures A3 and A4, the design concepts for the final cover over the solidified waste zone and the perimeter berm are presented. The actual zone for placement of solidified Mixed LLW may consist of different options, depending on the licensee's selection. Options that would be acceptable include use of stable high integrity waste containers (HICs) that have the spaces between containers filled with a cohesionless, low compressible fill material or placement of the waste in an engineered structure, such as a reinforced concrete vault. A cover system over the waste that would be acceptable to the EPA and NRC is shown in Figure A4. The cover system would consist of (1) an outer rock or vegetative layer to minimize erosion and provide for long-term stability, (2) a filter and drainage layer that transmits infiltrating water off of the underlying low permeability layers, (3) an impervious flexible membrane liner overlying a compacted low permeability clay layer, and (4) a filter and drainage layer beneath the compacted clay layer. If the solidified waste zone does not consist of an engineered vault structure with a top roof, an additional compacted clay layer should be placed immediately above the emplaced waste to direct any water infiltration away from the waste zone. Mixed LLW that contains Class C waste as designated by NRC's regulations would need to provide sufficient thickness of cover materials or an engineered intruder barrier to ensure the required protection against inadvertent intrusion.

Figure A3. Cross-sectional view A-A (vertical scale exaggerated).

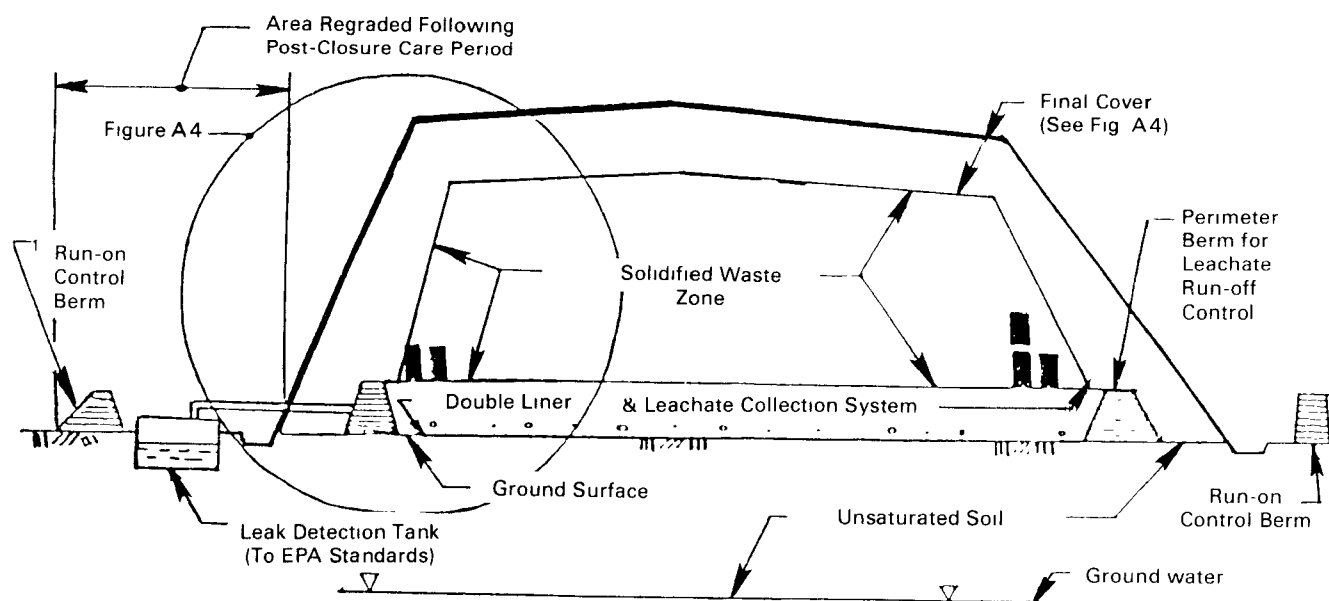
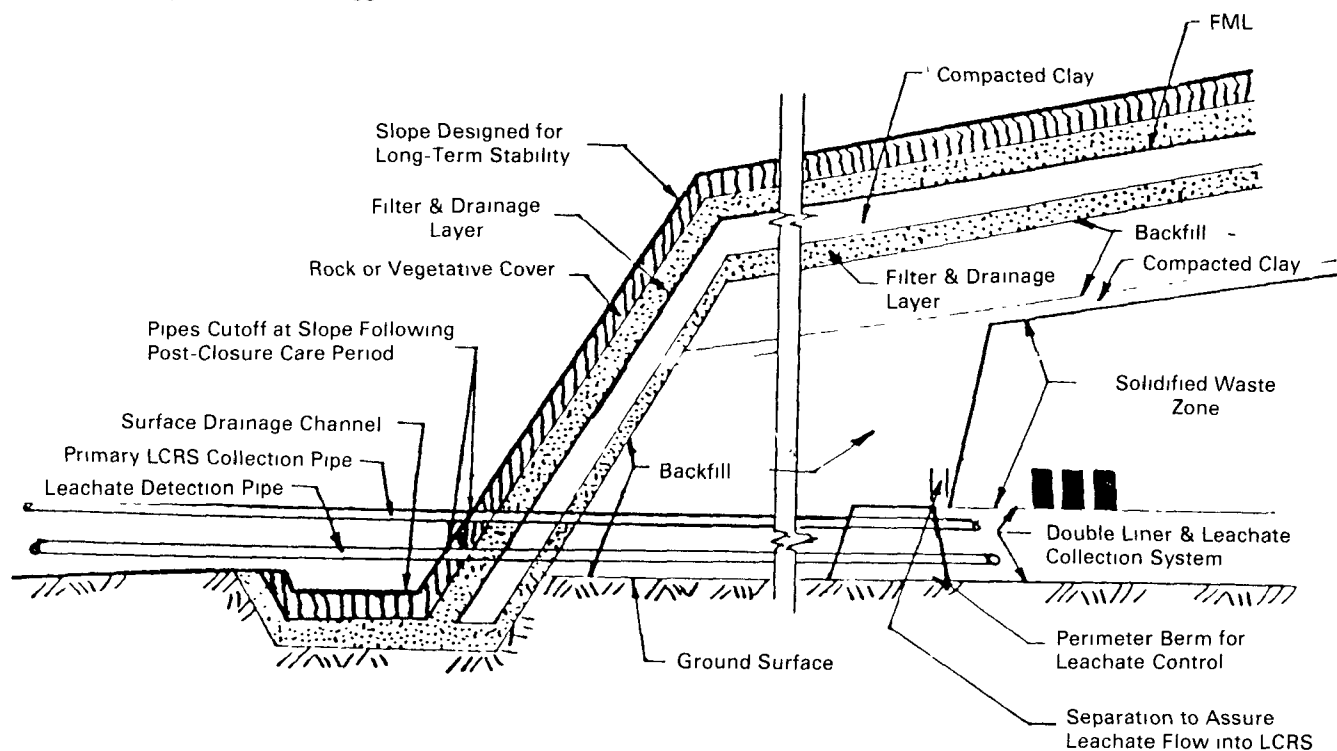


Figure A4. Waste cover system
(vertical scale exaggerated).



Variations on the above described design approach may include placement of the Mixed LLW in an engineered reinforced concrete vault, a steel fiber polymer-impregnated concrete vault, or double-lined high integrity containers that are hermetically sealed. If proposed by license applicants, these variations would be reviewed by both the EPA and NRC on a case-by-case basis to evaluate their acceptability and conformance with established federal regulations.

For questions related to NRC regulations and design requirements, contact:

Dr. Sher Bahadur, Project Manager
Division of Low-Level Waste Management and
Decommissioning
Mail Stop 623-SS
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Facility specific questions, permitting requirements, variances and other related concerns should be addressed to either the EPA regional office or state agency authorized to administer the mixed waste program as appropriate. For general questions related to EPA regulations and design requirements, contact:

Mr. Kenneth Skahn, Senior Engineer
Waste Management Division
Mail Stop WH-565E
U.S. Environmental Protection Agency
401 M Street, SW
Washington, DC 20460

Appendix B

Characteristics of Man-Made Radiologically Contaminated Sites

Introduction

The type of remediation that may be reasonably applied to sites contaminated with radioactive wastes depends to a great extent upon the physical, chemical, and mineralogical characteristics of the matrix (e.g., soil) material. Other important factors are the site location (e.g., proximity to a population center), the volume to be remediated, the radioactive elements, the level of radioactivity, and the presence of other hazardous substances.

This appendix briefly describes the sites on the Superfund NPL that contain radioactive materials. In addition, information is presented on the DOE's Formerly Utilized Sites Remedial Action Project (FUSRAP), its Uranium Mill Tailings Remedial Action Project (UMTRAP), Grand Junction Remedial Action Project (GJRAP) and Surplus Facilities Management Program (SFMP). The sites and remediation experiences in DOE's projects are very similar to those of the Superfund program. In fact a few of the DOE sites are on the NPL. Site information presented in this Appendix is accurate as of December 1987.

Radiologically Contaminated Superfund Sites

The information presented here has been compiled from the various written status reports and investigation reports obtained principally from the EPA Regional personnel who have the responsibility for the described sites. The descriptions are limited to the 20 sites currently listed on or proposed for the NPL that are known to contain man-made radioactive waste materials. These sites are listed in Table B1, which is followed by the site descriptions.

A distinction exists between man-made radioactive wastes and naturally occurring and accelerator produced radioactive material (NARM), which has been technologically concentrated or otherwise altered in such a way that the potential for human exposure has been increased. The uranium and thorium series are hallmarks of naturally occurring radioactive materials. The majority of the listed Superfund sites with radionuclide contamination are presumed to be contaminated by elements in these

series. The listed sites may not be the only Superfund sites that are radiologically contaminated. In fact, it may be expected that, as other Superfund sites are more fully characterized, the list will expand. On the other hand, there are a few Superfund sites containing radioactivity of natural origin in measurable amounts from the bedrock in the vicinity.

Two of the 20 sites described are landfills containing solid waste, hazardous waste, and radioactive waste. Ten of the sites are primarily tailings from ore processing. Four sites include radiologically contaminated building materials. At least five of the sites have been used as sources of fill material on properties in their vicinities.

Contaminated site areas total more than 9,500 acres and individually range from about one acre to 6,550 acres. The individual sites range from less than 50 cubic yards to more than 16 million cubic yards. The largest volume sites (those containing more than one million cubic yards) are uranium mill tailings sites. There are five sites in New Jersey, four in Illinois, four in Colorado, and two in New Mexico. The remaining sites are located in Massachusetts, Pennsylvania, Kentucky, Missouri, and Utah.

1. Radioactive Waste Superfund Site – Description

Name and Location:

Shpack/ALI (adjacent landfills), Norton/Attleboro, Massachusetts

EPA Contact Region I:

Robert Shatten, FTS 835-3679

Status:

NPL Final, Rank 672

Final site response assessment report, 11/21/85, prepared by NUS Corp. for performance of remedial activities. Monitoring program included water samples from 10 observation wells and soil

Table B1. Radioactive Waste Superfund Sites

	Site Name	City/County	State/EPA Region
1.	Shpack/ALI (Adjacent Landfills)	Norton/Attleboro	MA/I
2.	Maywood Chemical Co./Sears Property	Maywood/Bergen Co.	NJ/II
3.	U.S. Radium Corp.	Orange, Essex Co.	NJ/II
4.	W. R. Grace & Co. (Wayne Plant)	Wayne/Passaic Co.	NJ/II
5.	Montclair, West Orange, and Glen Ridge Radium Sites	Essex Co.	NJ/II
6.	Lodi Municipal Well	Lodi, Bergen Co.	NJ/II
7.	Lansdowne Property	Lansdowne	PA/III
8.	Maxey Flats Nuclear Disposal Site	Fleming City/Hillsboro	KY/IV
9.	West Chicago Sewage Treatment Plant	West Chicago	IL/V
10.	Reed-Keppler Park	West Chicago	IL/V
11.	Kerr-McGee Off-Site Properties	West Chicago	IL/V
12.	Kerr-McGee Kress Creek/West Branch of Dupage River	West Chicago	IL/V
13.	The Homestake Mining Co. Uranium Mill	Cibola Co.	NM/VI
14.	United Nuclear Corp.	Church Rock	NM/VI
15.	Weldon Spring Quarry	St. Charles City	MO/VII
16.	Monticello Radioactivity-Contaminated Properties	Monticello San Juan, Co.	UT/VIII
17.	Denver Radium Superfund Sites	Denver	CO/VIII
18.	Lincoln Park	Canon City	CO/VIII
19.	U.S. DOE Rocky Flats Plant	Golden	CO/VIII
20.	Uravan Uranium Project	Montrose City/Uravan	CO/VIII

samples analyzed for priority pollutants and gross alpha, beta, and gamma radioactivity.

No Remedial Investigation/Feasibility Study (RI/FS) available yet.

Radiation Data:

Ra-226, U-238, U-235, U-234 above natural background levels but uneven distribution in surface and subsurface soil. K-40, Th-228, Th-230 present. Rn-222, 240 pCi/l in ground water. Some measured values in soil: Ra-226, 1571 pCi/g; U-238, 16,460 pCi/g; U-235, 200 pCi/g; U-234, 4,200 pCi/g.

Matrix Characteristics:

Wetland or swamp area; sand, gravel, silt, and clay, organic deposits. Nonradioactive contaminants: 1,2-dichloroethylene, trichloroethylene, tetrachloroethylene, chromium, cadmium, nickel.

Source:

Unknown, possibly manufacture of luminescent dials and former operation of nuclear submarine contractor.

Approximate Area and Volume:

Shpack about 8 acres; ALI about 23 acres; 100 tons.

Environmental Impact:

10,000 residents relying on well water within 1-mi radius. 270 residents live within 3-mi radius. About 35 private wells within 3 mile radius of the site serve approximately 130 people. ORNL 1982 survey revealed no migration of radionuclides into ground water; no hydraulic gradient (vertical or horizontal) in underlying aquifers. Rn-222 at 328 pCi/l in ground water in 1980 study by private consultant considered suspect. Airborne radionuclide contamination no apparent threat to public. Based on existing data as of 11/85, no indication of immediate public health threat.

Source of Information:

Final Site Response Assessment Report D583-1-5-22, Revision 2; prepared by NUS Corp., 11/21/85.

2. Radioactive Waste Superfund Site – Description

Name and Location:

Maywood Chemical Co./Sears Property,
Maywood, Rochelle Park, New Jersey

EPA Contact Region II:

Pasquale Envangelista, FTS 264-2649

Status:

NPL Final, Rank 157.

Site was identified under FUSRAP, and DOE was designated to perform remedial action related to radioactive residues. Residential properties in Maywood, Rochelle Park, and parts of Lodi, NJ were remediated. Soil from old disposal areas was removed. Temporary storage facility called the Maywood Interim Storage Site (MISS) developed. DOE conducting continuous monitoring at MISS and detailed characterizations of properties related to the Maywood site.

Radiation Data:

Elevated gamma radiation; gross alpha in water, 18.4 pCi/l. Surface soil Th-232, 70 pCi/g; Ra-226, 10 pCi/g; U-238, 77 pCi/g. Subsurface soil Th-232, 180 pCi/g; Ra-226, 37 pCi/g; U-238, <232 pCi/g. Stream sediment Th-232, 93 pCi/g; Ra-226, 9 pCi/g; U-238 <57 pCi/g. Rn-222, 0.9-300 pCi/l in ground water.

Matrix Characteristics:

Tailings, soil, clay-like tailings; used as fill material in several residential and commercial properties; stream sediment; water; air. Nonradioactive contaminants in soil and tailings: arsenic, chromium, nickel, lead, cadmium, beryllium, pesticides, methyl chloride, xylene, toluene, ethyl benzene, acetone, MEK.

Source:

Maywood Chemical Works; extraction of thorium.

Approximate Area and Volume:

42 acres (entire location), area of contamination not known; 270,000 cu yd.

Environmental Impact:

36,000 residents within 4-mi radius. Radon gas found by NRC at levels higher than background in

one residence. Elevated gamma radiation levels on adjacent properties.

Source of Information:

"Characterization Report for Sears Property, Maywood, New Jersey," DOE/OR/20722-140, Oak Ridge National Laboratory, May 1987. "Engineering Evaluation of Disposal Alternatives for Radioactive Waste from Remedial Actions in and around Maywood, New Jersey," DOE/OR/20722-79, Oak Ridge National Laboratory, March 1986.

EPA NPL Site Status Sheet

3. Radioactive Waste Superfund Site – Description

Name and Location:

U.S. Radium Corp., Orange, Essex Co. New Jersey

EPA Contact Region II:

Douglas Johnson, FTS 264-1870

Status:

NPL Final, Rank 423.

Limited site characterization done at U.S. Radium and satellite properties by EPA and NJDEP. Final work plan for RI/FS prepared in July 1987. Field investigation to begin in Fall 1987.

Radiation Data:

New Jersey Department of Environmental Protection (NJDEP) has found radon and decay products in air in elevated concentrations and gamma radiation levels around property significantly above background levels. U-238, U-234, Th-230 and Ra-226 present in soil and concrete and Rn-222 in air.

Surface Soil:

Ra-226 3.2-670 pCi/g
U -238 minor

Subsurface Soil (2-4.5 ft):

Ra - 226 2090-3290 pCi/g
U - 238 90-12000 pCi/g

Matrix Characteristics:

Building materials, grounds, soil, surface, and ground water.

Source:

Former radium ore processing plant, lab and manufacturing facility, and radium cottage industry.

Approximate Area and Volume:

One acre; estimated 10,000 cu yd of tailing waste on-site.

Environmental Impact:

32,000 residents within 1/2-mi radius. NJDEP has found radon and decay products in air in excessive concentrations; gamma radiation levels around property greater than normal. Satellite properties where radium dial painting and lab work done may also be contaminated.

Source of Information:

EPA NPL Site status sheet. EPA Office of Radiation Programs. "Final Work Plan for Remedial Investigation and Feasibility Study, U.S. Radium Corporation-site, City of Orange, Essex County, New Jersey," Camp Dresser & McKee Inc., for USEPA April 1987.

4. Radioactive Waste Superfund Site – Description

Name and Location:

W. R. Grace & Co. (Wayne Plant), Wayne, New Jersey

EPA Contact Region II:

Carole Peterson, FTS 264-6190

Status:

NPL Final, Rank 214

Site was partially remediated in 1986 by DOE. Private residences along Sheffield Brook, where thorium tailings were carried by surface runoff cleaned in 1986. Excavations continued in July/August 1987. Completion of excavation is contingent upon locating a final disposal facility. Temporary storage of thorium tailings will be at Wayne Interim Storage Site (WISS) awaiting a permanent disposal site in NJ. Most of the off-site material has been removed.

Radiation Data:

Total U, 2.7 pCi/g; Th-232, 3.78 pCi/g; Ra-226, 5.1 pCi/g; Ra-228, 6.9 pCi/g; gamma radiation and Rn-222 in 1985 were less than in 1984 findings, due to remedial activities at the site.

Matrix Characteristics:

Sand and gravel; tailings from processing monazite ores; tailings buried on-site; surface and ground water; air.

Source:

Thorium ore (monazite) extraction plant on-site.

Approximate Area and Volume:

6.5 acres; 120,000 cu yd.

Environmental Impact:

51,000 residents within 3-mi radius. Extensive soil contamination. The potential for further contamination by runoff has been abated somewhat by work done to date at site.

Source of Information:

"Wayne Interim Storage Site Annual Site Environmental Report Calendar Year 1985," DOE/OR/20722-103, Oak Ridge Operations Office. August 1986.

5. Radioactive Waste Superfund Site – Description

Name and Location:

Montclair/West Orange Radium Site and Glen Ridge Radium Site, Essex County, New Jersey

EPA Contact Region II:

Robert McKnight, FTS 264-1870

Status:

NPL Final, Rank 178

EPA released a draft Remedial Investigation and Feasibility Study (RI/FS) report 9/85. New Jersey Department of Environmental Protection (NJDEP) began remediation of nine residential properties by excavating contaminated soil 6/85. EPA RI/FS report considered remedial cleanup and disposal alternatives. Due to the extent of radium contamination, EPA has been conducting additional field studies. As of 3/87, EPA has been unable to solve the soil disposal problem and is

developing a supplemental RI/FS to focus on continuing protective action while final remedy is developed.

Radiation Data:

Rn-222 gas in homes, 0.5-440 pCi/l before remediation; radium in soil above background in 40% of properties; Ra-226, U-234 present. Gamma radiation levels as high as 1300 μ R/hr.

Subsurface concentration:

Ra 1 - 5386 pCi/g (maximum)
Th 1 - 4620 pCi/g(maximum)
U 1 - 248 pCi/g(maximum)

Matrix Characteristics:

Ash and cinders in discrete pockets; also apparently mixed with soil (silt, sand, and gravel) or used alone as fill.

Source:

Alleged to be former radium-processing facility nearby.

Approximate Area and Volume:

127 acres; 350,000 cu yd total in three separate areas; over 750 properties involved.

Environmental Impact:

Approximately 750 properties in three areas. 76,000 residents within 3-mi radius. EPA, Centers for Disease Control (CDC), Agency for Toxic Substances and Disease Registry (ATSDR) have determined the long-term impact on health of residents.

Source of Information:

Superfund Program Fact Sheet 5/86; update 11/86 and 3/87.

"Radon Contamination in Montclair and Glen Ridge New Jersey Investigation and Emergency Response," by J.V. Czapor and K. Gigliello, and J. Eng.

"Feasibility study for Montclair/West Orange, Glen Ridge, New Jersey Radium Sites", Draft Final Report, USEPA, 1985.

6. Radioactive Waste Superfund Site – Description

Name and Location:

Lodi Municipal Well, Lodi, Bergen County New Jersey

EPA Contact Region II:

Richard Wice, FTS 264-1870

Status:

NPL proposed.
Well closed 12/83.

RI/FS Work Plan being prepared. Field activities scheduled to begin Fall 1987. RI/FS will determine whether the source of contamination may be attributed to either a man-made contaminant or a naturally occurring source.

Radiation Data:

One well out of nine contaminated with gross alpha radiation from U-238 decay.

Matrix Characteristics:

Ground water; VOCs present in most of nine wells.

Source:

Possibly nearby thorium-processing facility, or may be natural source.

Approximate Area and Volume:

One well radiologically contaminated; 2.35 sq mi.

Environmental Impact:

One well closed due to radiological contamination. Other eight are shut down due to volatile organic contamination. Lodi using alternate water supply.

Source of Information:

EPA NPL status sheet.

7. Radioactive Waste Superfund Site – Description

Name and Location:

Lansdowne Property, 105-107 E. Stratford Ave., Lansdowne, Pennsylvania

EPA Contact Region III:

Vic Janosik, FTS 597-8996

Status:

NPL Final, Rank 703.

Based on a radiological assessment of the property and a remedial action plan prepared by Argonne National Laboratory in 1985, EPA has decided to dismantle the duplex residence and dispose of contaminated materials at a licensed burial site (Hanford, WA).

Radiation Data:

Elevated gamma radiation levels. Soil, sewer lines, building materials contaminated with Ra-226, Th-230, Ac-227, and Pa-231. Rn at 0.021 - 0.309 working level (WL). Concentration in soil: Ra-226, 797 pCi/g; TH-230, 30 pCi/g.

Matrix Characteristics:

Soil, concrete, other building materials, sewer line waste.

Source:

Basement operation for radium purification and packaging by former occupant.

Approximate Area and Volume:

52,000 sq ft of land; 2,000 cu yd contaminated soil, extending to 8 ft depth.

Environmental Impact:

Severe contamination of building and surrounding grounds. One family in area. ATSDR issued (3/85) health advisory warning that radiation levels in the structure were unsafe.

Source of Information:

Radiological Assessment Report and Remedial Action Plans for the Lansdowne Property, prepared by Argonne National Laboratory.

8. Radioactive Waste Superfund Site – Description

Name and Location:

Maxey Flats Nuclear Disposal Site, Fleming City, Hillsboro, Kentucky

EPA Contact Region IV:

Harold Taylor, FTS 257-2234

Status:

NPL Final, Rank 612 RI/FS work plan completed 6/30/86 with focus on risk assessment and evaluation of alternative remediation, based on containment of waste. Consent order entered into 3/87 by EPA and site steering committee to perform RI/FS per work plan.

Radiation Data:

Transuranic nuclides in the environment; elevated concentrations of tritium, cobalt and strontium. Site contains 2.4 million Ci of radioactivity including 430 kg of special nuclear material and 64 kg of plutonium. Gamma radiation 10-32 μ R/hr; 30,000 pCi/cu m activity level.

Matrix Characteristics:

Low-level radioactive waste burial facility; leachate, soil, air; flora, fauna. Nonradioactive contaminants: benzene, naphthalene, d-n-oxyphthalate, 1,4-dioxane, dichlorodifluoromethane, 1,1-dichloroethene, pentanol, ethylenediaminetetracetic acid, 2-methylpropionic acid, 2-methylbutanoic acid, 3-methylbutanoic acid, valeric acid, isobutyric acid, 2-methylbutyric acid, 3-methylbutyric acid, pentanoic acid, 2-methylpentanoic acid, 3-methylpentanoic acid, C₆-branched acids, phenol, hexanoic acid, 2-methylhexanoic acid, cresol (isomers), 2-ethylhexanoic acid, C₈-branched acid, benzoic acid, octanoic acid, phenylacetic acid, phenylpropionic acid, phenylhexanoic acid, toluic acid, p-dioxane, methyl isobutyl ketone, toluene, xylene (isomers), cyclohexanol, dibutyl ketone, fenchone, triethyl phosphate, naphthalene, tributyl phosphate, a-terpineol.

Source:

Disposal site for various low-level radioactive waste sources.

Approximate Area and Volume:

280 acres (total site), 25 acres (contaminated), 178,000 cu yd.

Environmental Impact:

One hundred residents live within 1-mi radius. Leachate escaping through bedrock fractures into underlying sandstone and trenches. Leachate from a number of trenches contains soluble plutonium. Evidence of migration of tritium from

trench water to wells has been established but not in high enough levels to pose a public health hazard. Local residents are on public water supply system, however.

Source of Information:

RI/FS Work Plan (6/86).

9. Radioactive Waste Superfund Site – Description

Name and Location:

West Chicago Sewage Treatment Plant, West Chicago, Illinois

EPA Contact Region V:

Neil Meldgin, FTS 886-4726

Status:

NPL proposed. The Remedial Investigation Report has been completed. Samples were analyzed for metals, radon, thoron and thorium. Values were presented for As, Ba, Cd, Cr, Fe, Pb, Hg, and Se.

Radiation Data:

The nominal concentration of Th-232 in the soil was 4900 pCi/g; Th-232, 0.03 pCi/l; Th-230, 0.4 pCi/l; and Ra-226, 0.03 pCi/l were measured in the ground water; gamma radiation, 2000-3000 µR/hr.

Matrix Characteristics:

Soil; till; gravel; ground water; monazite ore.

Approximate Area and Volume:

25 acres (includes plant site and Reed-Keppler Park and not just contaminated area); 40,000 cu yd.

Source:

The Rare Earths Facility, an ore processing facility that had been used to process thorium and rare earth ores containing radioactive thorium, uranium, and radium.

Environmental Impact:

There are several routes of potential risks to the environment and public health, including direct external radiation exposure; inhalation exposure; and ingestion of contaminated soils, ground water, and surface water. The contaminated media at the site are wastes from the Rare Earths

Facility. The primary radionuclide present is thorium-232.

Source of Information:

Remedial Investigation Report, Kerr-McGee Radiation-sites, West Chicago, Illinois, September, 1986 CH2M Hill.

10. Radioactive Waste Superfund Site – Description

Name and Location:

Reed-Keppler Park, West Chicago, Illinois

EPA Contact Region V:

Neil Meldgin, FTS 886-4726

Status:

NPL proposed. The Remedial Investigation Report has been completed. Samples were analyzed for 23 metals, Th-232, U-238, Ra-228, and Ra-226 in the soil; and gross alpha, Th-232, and Ra-226 in the ground water. Radiation Data The concentrations of radioactivity in the ground water samples were: Th-232, 23 pCi/l and Ra-226, 7.6 pCi/l. In the soil sample, Th-232 up to 11,000 pCi/g. Gamma exposure levels up to 16,000 µR/hr.

Matrix Characteristics:

Till, gravel, ground water, and air.

Approximate Area and Volume:

It is estimated that 20,000 cu yd of thorium-contaminated material is located within the Park in 11,000 sq yd area.

Source:

The Rare Earths Facility, an ore processing facility that had been used to process thorium and rare earth ores containing radioactive thorium, uranium, and radium.

Environmental Impact:

There are several routes of potential risks to the environment and public health including direct external radiation exposure; inhalation exposure; and ingestion of contaminated soils, ground water, and surface water. The contaminated media at the site are wastes from the Rare Earths Facility. The primary radionuclide present is thorium-232.

Source of Information:

Remedial Investigation Report, Kerr-McGee Radiation-sites, West Chicago, Illinois, September, 1986 CH2M Hill.

11. Radioactive Waste Superfund Site – Description

Name and Location:

Kerr-McGee Off-Site Properties, West Chicago, Illinois

EPA Contact Region V:

Neil Meldgin, FTS 886-4726

Status:

NPL proposed. The Remedial Investigation Report has been completed. Mitigation procedures were carried out at 116 locations.

Radiation Data:

Contamination in excess of 2000-3000 $\mu\text{R/hr}$ was noted prior to the mitigative measures. Th-232 up to 16,000 pCi/g in soil was measured.

Matrix Characteristics:

Till, gravel, fill, tailings.

Approximate Area and Volume:

The area consists of 117 residential lots of various sizes. Approximately 61,000 cu yd.

Source:

The Rare Earths Facility, an ore-processing facility that had been used to process thorium and rare earth ores containing radioactive thorium, uranium, and radium.

Environmental Impact:

There are several routes of potential risks to the environment and public health including direct external radiation exposure; inhalation exposure; and ingestion of contaminated soils, ground water, and surface water. The contaminated media at the site consists of wastes from the Rare Earths Facility. The primary radionuclide present is thorium-232.

Source of Information:

Remedial Investigation Report, Kerr-McGee Radiation-sites, West Chicago, Illinois, September, 1986 CH2M Hill.

12. Radioactive Waste Superfund Site – Description

Name and Location:

Kress Creek and the West Branch of the DuPage River, West Chicago, Illinois

EPA Contact Region V:

Neil Meldgin, FTS 886-4726

Status:

The Nuclear Regulatory Commission (NRC) issued an order to Kerr-McGee to prepare a cleanup plan for Kress Creek and affected portions of the West Branch of the DuPage River. The NRC's Atomic Safety Licensing Board upheld Kerr-McGee's challenge. The NRC staff has appealed this decision. Should the appeal fail, EPA must consider using Superfund to remedy the creek and river contamination.

Radiation Data:

About 1.5 mi of creek and river are contaminated in the streams and along the banks. Peak total thorium concentrations are 555 pCi/g at a depth of 60 cm (2 ft). Thorium has been identified as deep as 170 cm (6 ft). Peak gamma levels are 250 $\mu\text{R/hr}$ along the bank.

Matrix Characteristics:

Sediment, soil, tailings.

Approximate Area and Volume:

Undetermined but substantial. Affected area is about 1.5 miles of creek and river bed and the adjacent banks.

Source:

The Rare Earths Facility, an ore processing facility that had been used to process thorium and rare earth ores containing radioactive thorium, uranium, and radium.

Environmental Impact:

There are several routes for potential risks to the environment and public health, including direct external radiation exposure; inhalation exposure;

and ingestion of contaminated soils, ground water, and surface water. The contaminated media at the site consists of wastes from the Rare Earths Facility. The primary radionuclide present is Th-232.

Source of Information:

Comprehensive Radiological Survey of Kress Creek, West Chicago Area, Illinois, February 1984, Oak Ridge Associated Universities.

13. Radioactive Waste Superfund Site – Description

Name and Location:

The Homestake Mining Co. Uranium Mill, Cibola County, New Mexico, about 5.5 miles north of Milan.

EPA Contact Region VI:

Ursula Lennox, FTS 255-6735

Status:

NPL Final, Rank 528. Homestake and EPA signed an Administrative Order in June 1987 for implementation of a workplan for a radon RI/FS developed by New Mexico's contractor, Geomet. A 15 month RI testing program will be started by Homestake in November 1987. Naturally occurring dispersed tailings, ground water contamination, and tailings piles may be considered as to how they act as sources.

Radiation Data:

Rn-222 in the air, 0.03 WL; radium in the mill tailings, 60-100 pCi/g; uranium in the water, 720 ppb. One year monitoring study of indoor and outdoor radon concentrations. Outdoor radon concentrations ranged from 0.05 pCi/l (background) to 2.6 pCi/l.

Matrix Characteristics:

Soil, tailings, ground water, and air.

Approximate Area and Volume:

245 acres at 6,600 foot elevation; 16,500,000 cu yd.

Source:

Potential sources are:

Homestake Mining Company uranium mill tailings, Anaconda mill tailings, Ambrosia Lake mining

area, and areas of near-surface uranium mineralization.

Environmental Impact:

About two hundred people depend upon the shallow aquifer as a water supply. An alternate water supply is in place, and aquifer restoration by Homestake has been somewhat successful. Radon levels indoors and outdoors in several subdivisions near the mill may be above background.

Source of Information:

Geomet Report Number IE-1739, March 20, 1987. "WORK PLAN FOR HOMESTAKE MINING COMPANY STUDY AREA NEAR MILAN, NEW MEXICO," RI/FS for E.I.D., R.P.B., State of New Mexico.

14. Radioactive Waste Superfund Site – Description

Name and Location:

United Nuclear Corp., Church Rock, New Mexico. The site is 15 miles northeast of Gallup, New Mexico.

EPA Contact Region VI:

Alan Tavenner, FTS 255-6735

Status:

NPL Final, Rank 651 Remedial Investigation begun January, 1985. United Nuclear is developing a reclamation plan. The RI/FS is scheduled for completion Spring, 1988

Radiation Data:

Measurements of ground water showed levels as high as 12.6 pCi/l for Ra-226 and Ra-228 and 8.15 pCi/l for uranium. Th was measured at 40,000 pCi/l and Ra at 45 pCi/l. Data are shown for As, Cr, Se, Cd, Pb, N, and SO₄.

Radioactive Contaminants	Tailings Pile (pCi/g)	Pond (pCi/l)
U-238	29	3.9 x 10 ³ pCi/l
Th-230	290	9.3 x 10 ⁴ pCi/l
Ra-226	290	1.3 x 10 ² pCi/l
Rn-222	no data	no data

Matrix Characteristics:

Tailings, ground water. Nonradioactive contaminants:

	<i>Pond (mg/l)</i>
arsenic	1.22
barium	0.29
cadmium	0.11
lead	1.56
mercury	0.5 x 10 ⁻³
molybdenum	2.30
selenium	0.53
vanadium	46.94
zinc	7.22

Approximate Area and Volume:

The mill tailings pond covers 170 acres and is 15-20 ft thick; 4,700,000 cu yd.

Source:

The source of the radiation is a uranium mill site, largely from the tailings ponds.

Environmental Impact:

Several people use the shallow alluvial aquifers in the area. A break in the tailings dam in 1979 sent 93 million gallons of tailings fluid into the Rio Puerco. The upper Gallup aquifer is contaminated in the vicinity of the tailings pond. The alluvial aquifer is also contaminated.

Source of Information:

Site Status Summary, May, 1987 and Technical Memorandum, Phase I Field Study, RI/FS, United Nuclear, Church Rock, N. Mexico, October 4, 1985, CH2M Hill.

15. Radioactive Waste Superfund Site – Description**Name and Location:**

Weldon Spring Quarry, St. Charles City, Missouri

EPA Contact Region VII:

Katie Biggs, FTS 757-2823

Status:

NPL Final. Under an agreement with EPA (4/87), DOE will clean up quarry and all nearby contaminated properties and develop an Environmental Impact Statement incorporating all the requirements of a RI/FS.

Radiation Data:

According to results of monitoring by DOE and the U.S. Geological Survey (USGS), radioactive materials have been released to surface water, ground water, and air. Thorium, uranium, and radium residues have been placed in quarry.

Matrix Characteristics:

Drums, process equipment, building rubble, debris, raffinate sludges and soils which range from gravelly to clay-like and organically rich. Soils and sludges are variably contaminated with TNT, DNT, and other organics.

Source:

Uranium and thorium ore processing. Previously US Army Ordnance works.

Approximate Area and Volume:

220 acre complex; quarry is 9 acres; 780,000 cu yd radioactive material; 51,000 cu yd radioactive residues were deposited in quarry along with other wastes.

Environmental Impact:

Potential contamination of alluvial aquifer 0.5 mi from quarry, serving 58,000 people. Uranium and radium have been detected in off-site monitoring wells, with radium concentrations exceeding drinking water standards.

Source of Information:

Status report from EPA Region VII.

16. Radioactive Waste Superfund Site – Description**Name and Location:**

Monticello Radioactivity-Contaminated Properties, Monticello, Utah (San Juan County)

EPA Contact Region VIII:

Lam Nguyen, FTS 564-1519

Status:

NPL Final, Rank 502. DOE has assumed responsibility for most of the remedial action. EPA is negotiating Memorandum of Agreement (MOA) with DOE to better define respective roles in clean-up activities. DOE has authorized clean-up of 15 properties and is studying several more

for inclusion in program. EPA conducted a planned removal action of two of the most contaminated structures in Monticello during 1983-1984.

Radiation Data:

Widely dispersed radioactive tailings; U-238, -234, -226, Th-230, Rn-222, Ra-226.

Exposure Rates:

Ra-226	1-23,000 pCi/g
U-238	1-24,000 pCi/g
U	18,000 pCi/g

Matrix Characteristics:

Tailings from vanadium and uranium ore processing; radioactive tailings widely dispersed throughout town as fill material and as aggregate for mortar and concrete. Vanadium 1-16,532 ppm.

Source:

Uranium and Vanadium ore processing in Monticello plant from 1942 to 1960. Some tailings may have been brought in from another mill in Dry Valley.

Approximate Area and Volume:

152 potentially contaminated properties; 182,000 cu yd.

Environmental Impact:

1500 residents within 1/2-mi radius. 152 potentially contaminated properties. Widely dispersed contamination, apparently mostly in near-surface soils.

Source of Information:

4/87 Fact Sheet. EPA Office of Radiation Programs

17. Radioactive Waste Superfund Site – Description

Name and Location:

Denver Radium Superfund Sites, Denver, Colorado

EPA Contact Region VIII:

Marilyn Null, FTS 564-1698

Status:

NPL Final, Rank 269. Feasibility Studies have been completed for ten fund-lead operable units and for four fund-lead operable unit ROD's are pending. Remedial Design is underway at four operable units. Negotiations with Potentially Responsible Parties are underway at the enforcement-lead operable unit.

Radiation Data:

U-234, -238, Th-230, Ra-226, Rn-222 present. Maximum gamma radiation concentrations at properties included in the site ranged from 57 μ R/hr to 2,547 μ R/hr, maximum radium concentrations ranged from 79 pCi/g to 5,093 pCi/g, and maximum radon decay progeny levels of 0.30 WL (grab) have been measured on the site.

Matrix Characteristics:

Asphalt, soil, pond bottom sediment, building debris and contents, ground water, and airborne particulates.

Source:

Former Denver National Radium Institute and other processors involved in radium processing through World War I and early 1920s, generating large quantities of radioactive residues.

Approximate Area and Volume:

Approximate volume 106,000 cu yd, covering a total of about 40 acres in 44 locations within a 4-mi radius of downtown Denver.

Environmental Impact:

Potential risk to human health, including direct exposure, inhalation of radon, ingestion of radionuclides and contaminated media.

Source of Information:

Final Feasibility Study, Denver Radium site, Operable Unit X, 6/87; Final Feasibility Study & Responsiveness, Denver Radium Site, Operable Units IV/V, Vols. I & II, 9/86; Remedial Alternative Selection and Community Relations Responsiveness Summary, Operable Unit VII, 3/86. Remedial Investigation Report April 1986.

18. Radioactive Waste Superfund Site – Description

Name and Location:

Lincoln Park, Canon City, Colorado

EPA Contact Region VIII:

Gene Taylor, FTS 564-1519

Status:

NPL Final, Rank 621. RI/FS submitted to EPA by the State for review 3/86. Memorandum of Agreement between State and EPA 4/86, the State of Colorado has lead responsibility for negotiations development and implementation of a remedy.

Radiation Data:

Groundwater quality studies per 1987 USGS report included Ra-226 between 0.05 and 1.6 pCi/l, and U-234 and -238 between 0.4 and 5,700 µg/l.

Matrix Characteristics:

Contaminated ground water derived from unlined tailings ponds. Nonradioactive contaminants: molybdenum and selenium.

Source:

Uranium mill (Cotter Corporation).

Approximate Area and Volume:

900 acres; 1,900,000 tons.

Environmental Impact:

386 residents within 3-mi radius. Contaminated ground water in the vicinity and down gradient. No permitted drinking water wells in the area. Company's monitoring data indicate a plume of contaminants, including molybdenum, uranium, and selenium extending from mill and affecting private wells that were serving 200 people.

Source of Information:

4/87 Fact Sheet. "Ground-water Flow and Quality Near Canon City, Colorado." US Geological Survey, WRI Report 87-4014, 1987. EPA Office of Radiation Programs.

19. Radioactive Waste Superfund Site – Description

Name and Location:

U.S. DOE Rocky Flats Plant, Golden, Colorado

EPA Contact Region VIII:

James Littlejohn, FTS 564-1519

Status:

NPL proposed. Compliance agreement entered into by DOE, EPA, and Colorado Dept. of Health 7/86, defining respective roles and responsibilities. DOE is responsible for remedial actions. RI/FS work plans completed 2/87; results due 7/87. DOE has done some remedial work such as capping and removing plutonium-contaminated soil.

Radiation Data:

Plutonium and tritium releases.

Matrix Characteristics:

Soil and sediment; wastewater impoundments.

Source:

Production of nuclear weapons triggers; plutonium recovery; americium research.

Approximate Area and Volume:

6,550 acres total area; 91 sites; over 1,000 waste streams.

Environmental Impact:

Plutonium and tritium have contaminated soils and sediments in surface water. Ground water has been contaminated with nitrate. Approximately 80,000 people live within 3 mi of the facility.

Source of Information:

4/87 Fact Sheet; 7/85 NPL Fact Sheet.

20. Radioactive Waste Superfund Site – Description

Name and Location:

Uravan Uranium Project, Montrose City, Uravan, Colorado

EPA Contact Region VIII:

Holly Fliniaux, FTS 564-1519

Status:

NPL Final Rank 275. State of Colorado negotiating remedy with responsible parties. EPA and State have entered into MOA 4/86, designating State to pursue effective remedy. The State of Colorado has negotiated an agreement with Responsible Parties, and the agreement has been approved by U.S. District Court. EPA submitted comments to State on remedial action plan 12/86.

Radiation Data:

Radionuclides and Rn-222, U-234, U-238; Th-230; Ra-226.

Th	16,000	-	165,000	pCi/l
U	1,500	-	16,000	pCi/l
Ra	66	-	676	pCi/l

Matrix Characteristics:

Ground water and air, raffinate, tailings, surface water. Selenium, nickel, ammonia, sulfates.

Source:

Uranium and vanadium recovery plant; milling operations; little activity at present; owned and operated by Union Carbide Corporation.

Approximate Area and Volume:

900 acres; 2,000,000 tons removed/10,000,000 tons stabilized.

Environmental Impact:

Town in remote area. 125 residents within 3-mi radius. All residents moved December 1986; no permanent residents. Ground water and air contaminated with process waste, including uranium. Discharge and disposal of large volume of process wastes releasing radiation.

Source of Information:

4/87 Fact Sheet

Department of Energy Remediation Programs

The DOE has four major site remediation projects involving radioactive materials. They are the Uranium Mill Tailings Remedial Action Project (UMTRAP), the Formerly Utilized Sites Remedial Action Project

(FUSRAP), the Grand Junction Remedial Action Project (GJRAP), and the Surplus Facilities Management Program (SFMP).

Formerly Utilized Sites Remedial Action Project (FUSRAP)

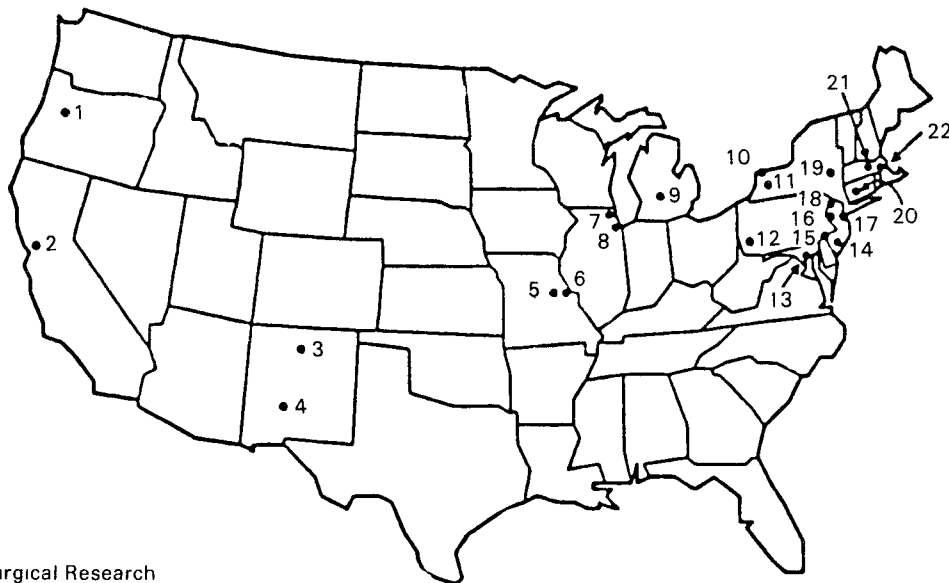
The U.S. Army Corps of Engineers, Manhattan Engineer District (MED) and its successor, the U.S. Atomic Energy Commission (AEC) conducted programs during the 1940s and 1950s involving research, development, processing, and storage of radioactive ores and their processing residues. Virtually all of this work was performed for the Federal government by private contractors at sites that were either federally, privately, or institutionally owned. Many of these sites and nearby properties were contaminated with radionuclides at low concentrations and mostly of natural origin.

When the contracts for MED/AEC activities were terminated, the sites were decontaminated according to then-current health and safety criteria and released for unrestricted use. However, as research on the effects of low-level radiation progressed, radiological criteria and guidelines for returning sites to unrestricted use became more stringent. In 1974, the AEC initiated a program to identify former MED/AEC sites and to determine their radiological status based on a review of historical records. In 1977 the AEC changed to the US DOE which subsequently initiated FUSRAP [1,3]. Figure B1 shows the locations of the FUSRAP sites [2].

The most seriously contaminated sites, located in New Jersey and New York, were involved in storing, sampling, and processing very rich pitchblende ores. As of June 1987, a total of 29 sites in 12 states were designated for remedial action [J. Wagnor, DOE, Personal Communication, July 2, 1987]. Preliminary estimates are that 29 authorized sites may contain a total volume of 1.1 million cu yd of low-level contaminated dirt, sediment, and rubble. Of these, remediation has been completed to the satisfaction of the DOE at seven sites [A. Wallo, DOE, Personal Communication, July 2, 1987]. The disposition of these seven sites as per DOE is as follows:

- Radiologically contaminated materials from Kellex Research (Jersey City, NJ), Bayo Canyon, and Acid Pueblo Canyon (Los Alamos, N.M.) were excavated and removed to an authorized disposal facility.
- Radiologically contaminated material from Middlesex Landfill (Middlesex, NJ) was excavated and stored at an interim storage site (above grade with a leachate collection system).

Figure B1. FUSRAP sites as of 1982. (Reprinted from [2].)



- | | | |
|---|---|--|
| 1 Albany Metallurgical Research Center, Albany, OR | 7 University of Chicago, Chicago, IL (Completed) | 13 W R Grace & Company, Curtis Bay, MD |
| 2 University of California, Berkeley, CA (Completed) | 8 National Guard Armory, Chicago, IL | 14 Middlesex Landfill, Middlesex, NJ |
| 3 Acid/Pueblo Canyon, Los Alamos, NM (Completed) | 9 General Motors, Adrian, MI | 15 Middlesex Sampling Plant, Middlesex, NJ |
| 4 Chupadera Mesa, White Sands Missile Range, NM (Completed) | 10 Niagara Falls Storage Site, (Vicinity Prop), Lewiston, NY | 16 Du Pont & Company, Deepwater, NJ |
| 5 Hazelwood (Latty Avenue), MO | 11 Ashland Oil Co #1, Tonawanda, NY | 17 Maywood, NJ |
| 6 St Louis Airport Storage Site, (Vicinity Prop), St Louis, MO | 12 Seaway Industrial Park, Tonawanda, NY | 18 Wayne/Pequannock, NJ |
| 7 St Louis Airport Storage Site, St. Louis, MO | 13 Linde Air Products, Tonawanda, NY | 19 Colonie, NY |
| 8 Mallinckrodt, Inc , St. Louis, MO | 14 Ashland Oil Co #2, Tonawanda, NY | 20 Seymour Speciality Wire, Seymour, CT |
| | 15 Universal Cyclops, Allquippa, PA | 21 Shpack Landfill, Norton, MA |
| | | 22 Ventron, Beverly, MA |

- Radiologically contaminated laboratory buildings at the University of California (Berkeley, CA) and the University of Chicago (Chicago, IL) were surface cleaned (washed, scraped, chipped).
- Investigation showed that the seventh site, Chupadera Mesa (White Sands, NM), required no cleanup.

The remaining twenty-two sites are undergoing remediation or are awaiting remediation. Three of the twenty-two are also Superfund sites:

1. Shpack Landfill, Norton/Attleboro, MA.
2. Maywood Chemical Company, Maywood, NJ.
3. W. R. Grace & Company, Wayne, NJ.

Remediation at vicinity properties consisted of land disposal or burial in a land encapsulation approved for radioactive waste. In some cases site buildings were decontaminated and returned to use, and in other cases they were demolished and the rubble stored or buried.

Removal and containment of contaminated materials has been the strategy used thus far at FUSRAP sites. None of the other techniques described in this report has been attempted in full-scale remediation.

Uranium Mill Tailings Remedial Action Project (UMTRAP)

The use of uranium for weapons research and production resulted in the generation of huge quantities of uranium mill tailings, the waste material remaining after uranium is extracted from the uranium ore. The Atomic Energy Act of 1954 authorized the AEC to license the receipt or transfer of ores that contained 0.05% or more of uranium and/or thorium. However, the AEC exempted any unrefined and unprocessed ore and processed uranium mill tailings, which were assumed to contain less than the required percentage of uranium and thorium. Due to this exemption, the uranium industry was not required to isolate or even to retain control of uranium tailings.

Although most of the uranium has been removed from the tailings, the radium remains and is a source, through radioactive decay, of radon gas. Also,

radionuclides and other trace elements present in the tailings can be leached from the pile and contaminate the ground water [2].

In 1978, Congress passed Public Law 95-604, the Uranium Mill Tailings Radiation Control Act of 1978, based on the finding that uranium mill tailings located at mill sites posed a potential health hazard to the public. Title I of the Act instructed the DOE to perform remedial actions at the designated sites, which contained a total of approximately 25 million cu yd of tailings. The program to carry out these actions is the Uranium Mill Tailings Remedial Action Project (UMTRAP).

The remediation also includes cleanup of those contaminated properties outside the designated boundaries of the processing sites that became contaminated through the use of tailings for fill and/or construction. Approximately 8000 of these "vicinity" properties have been identified for surveying to confirm the presence of tailings and contamination levels requiring remedial action [2,4].

Of the 24 UMTRAP sites, one is in Pennsylvania (Canonsburg) and 23 in the western United States (Figure B2). The sites range in size from 10 acres to over 500 acres and include tailings piles, evaporation ponds, windblown contaminated areas, and former mill buildings and associated structures. Depths of tailings piles range from a few feet to over 275 feet in Durango, Colorado. Many of the sites have exposed tailings. Some sites are covered with a foot or so of soil or sparse vegetation.

Some of the UMTRAP sites, such as Grand Junction and Rifle, Colorado, are adjacent to river systems. Many, such as Canonsburg, PA; Gunnison, CO; and Shiprock, NM, are near small rivers or creeks, and many sites have shallow water tables [5].

Remedial action began at the first site in 1983, and cleanup of all sites is scheduled for completion in 1993 [6]. For tailings piles, remediation consists principally of stabilization through the use of liners and covers to prevent migration and limit radon emanation. This approach is consistent with EPA regulation 40 CFR 192. For vicinity properties, remediation consists principally of excavation and disposal of contaminated material to tailings piles, cleaning of buildings, and, where necessary, destruction of buildings and removal of the rubble.

Grand Junction Remedial Action Project

Between the years 1952 and 1966, several hundred thousand tons of tailings were removed from the Climax Uranium Company's mill tailings pile in Grand Junction, Colorado and used locally as fill and construction material. In 1966, when the Colorado Department of Health and the U.S. Public Health

Service discovered this fact, the practice was stopped, and investigations were begun to determine the potential radiological health effects of tailings use in residential and commercial or civic construction. In 1972, the U.S. Surgeon General issued guidelines for determining the need for corrective action at those locations where increased levels of radiation were measured as a result of the presence of tailings. The U.S. Congress passed PL 92-314 in 1972, authorizing Federal appropriations to assist the State of Colorado in conducting a remedial action project at Grand Junction. The objective was to perform corrective action at sites where radiation exposures exceeded the Surgeon General's guidelines. The project is a State-operated activity, with DOE providing 75 percent of the funding and the State, 25 percent [7].

In order to obtain the benefits of the project, a property owner had first to apply to the Colorado Department of Health for a determination of eligibility. The criteria for eligibility (the Surgeon General's guidelines) were based on annual average exposures to external gamma radiation, or inhalation of airborne radon daughter products resulting directly from uranium mill tailings used in the construction of a building. Of these two modes of exposure, the inhalation of airborne radon daughters is by far the more important in terms of numbers of locations exceeding the criteria and in terms of potential population exposure [8].

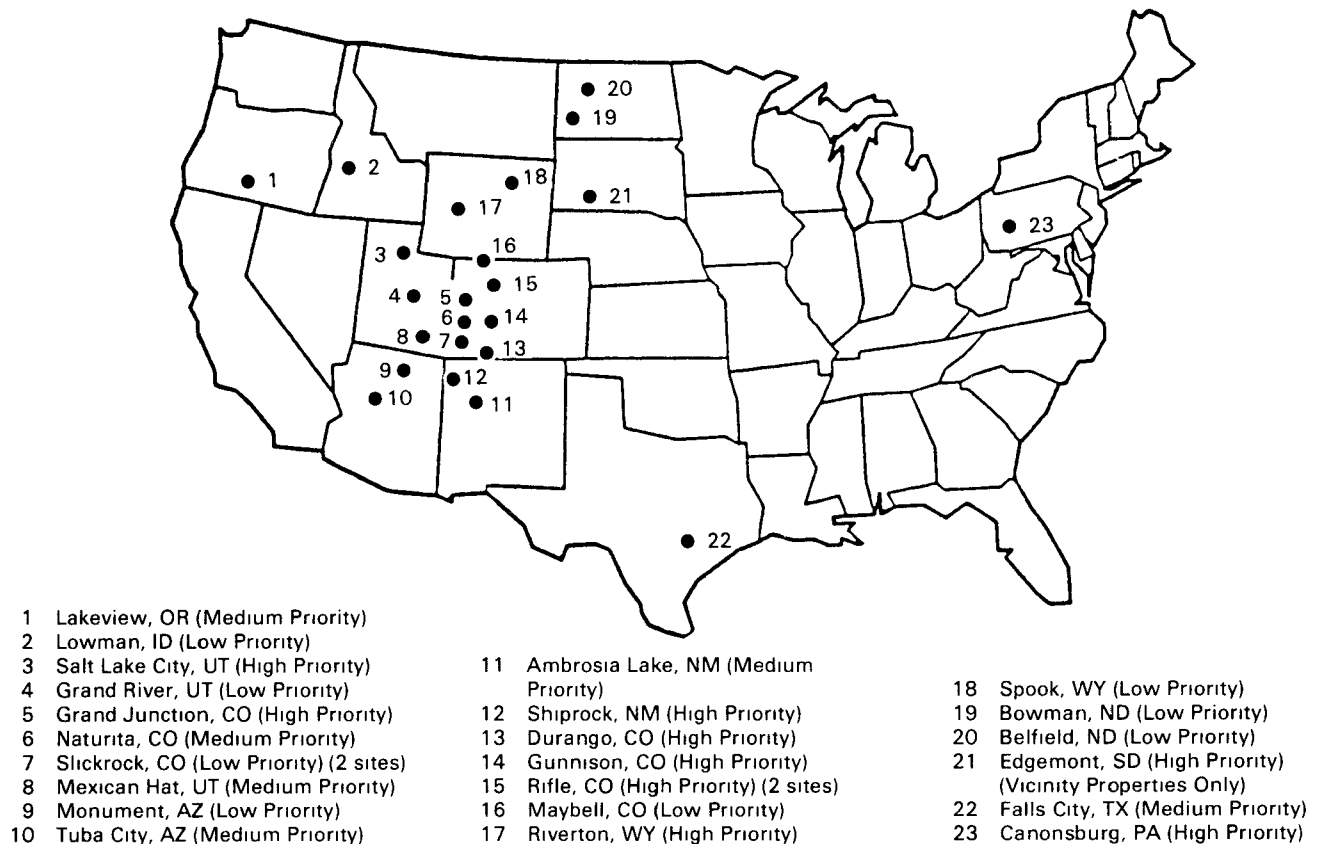
The cleanup project began in 1973. The assessment project had identified 740 structures that would require some form of remedial action to meet the Surgeon General's guidelines. Schools and the more highly contaminated dwellings were given first priority. The project was to have been completed by the end of fiscal year 1987.

Whenever possible, the contaminated sites have been cleaned up by excavation and removal of tailings. Remediation has been confined to the area of the structure and out to a distance of ten feet surrounding it. In many cases, the structure has been shored up and material actually excavated from beneath it. The original tailings site was used to store the tailings from the cleanups. That site, in turn, will be cleaned up under UMTRAP [T. Brazley, DOE, Personal Communication, July 23, 1987].

Where removal of the tailings is not possible, the structures have been remediated by applying sealants or increasing ventilation and filtration to reduce radon gas in the structures to acceptable levels [7].

Starting in about 1975, the Colorado Department of Health, DOE, and the USEPA conducted a survey of approximately 40,000 properties. The survey identified about 6,000 vicinity properties as "core sites," which were contaminated to some degree. Some of the

Figure B2. Locations of UMTRAP sites. (Reprinted from [2].)



properties remediated under the Grand Junction Remedial Action project are included in UMTRAP, e.g., where remediation is necessary beyond ten feet from the structure. The list has been narrowed to about 3,800 properties requiring remediation. About 2,000 have been recommended by ORNL for inclusion in the UMTRAP cleanup. This remedial project has been initiated.

A second part of the UMTRAP effort is remediation (which may include relocation) of the original tailings pile from which all of the problem tailings originated. The actual fate of the tailings pile has not yet been decided.

Surplus Facilities Management Program (SFMP)

The overall objective of the SFMP is to provide the program direction, planning, and resources for the DOE surplus facilities to (1) maintain surplus facilities in a safe condition pending decommissioning, (2) maximize the options for future use of real property, and (3) dispose of all radioactive facilities and waste in accordance with accepted practices. Other objectives include (1) providing research and development funding for property and equipment decommissioning techniques and technology transfer, and (2) conducting cooperative information

exchanges on decommissioning activities with other countries and international organizations.

The current inventory of surplus facilities in the program was established by review of facilities in 1977 and by subsequent addition of some facilities from defunct programs. Thirty-five projects at 17 sites are included in the civilian portion of the SFMP. The sites were prioritized based on (1) the assessment of potential for exposure to the public and workers at the site, (2) contractual commitments, (3) reducing the cost of continuing surveillance and maintenance, and (4) making the property available for alternative or unrestricted use.

Decommissioning has been conducted at the Special Power Excursion Reactor Test Area in Idaho, at Argonne National Laboratory-East in Illinois, vicinity properties at Monticello, Utah, and buildings at the Santa Susana Field Laboratory, in California. Entombment projects have been completed at the Bonus Facility in Puerto Rico, the Hallam Facility in Nebraska, and the Piqua Facility in Ohio. Major activities continue at the Idaho National Engineering Laboratory in Idaho, the Mound Laboratory in Ohio, Santa Susana in California, Monticello in Utah, and ANL-East in Illinois [9]. The Shippingport Station Decommissioning Project will place the station in a

long-term radiologically safe condition by dismantling and removing the radioactive portions of the plant. One of the purposes of the Project is to demonstrate to the nuclear industry the practical and affordable dismantlement of a large nuclear power plant. Actual physical decommissioning activities were initiated in September 1985.

Other near term activities include initiating work at the Weldon Spring Site. This site was first used by the Department of the Army as an ordnance works and, later, by a DOE predecessor agency as a uranium feed materials plant. The site is contaminated with thorium, uranium, and decay products. Near-term activities include further characterizing the contamination on the site, initiating conceptual engineering studies, establishing a project office at the Weldon Spring site, and completing the NEPA documentation.

Both the Weldon Spring and Monticello sites are also Superfund sites. The Surplus Facilities Management Program is scheduled for completion in the early 2000's.

Summary of Remediation Methods Used to Date

Most of the remedial technologies to date have consisted of excavation and/or removal of contaminated materials from plant sites and from property owned by others in the vicinity of those properties. In some cases, the contaminated material has been temporarily stored in above-ground, covered piles. In others, the material has been permanently placed in secure land encapsulations.

No extraction or solidification technology has been applied to any of these sites. Some laboratory experimentation on radionuclide extraction from tailings and soils have been conducted, as described in Chapters 5, 6, and 7.

References

1. U.S. Department of Energy. Pathways Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites. ORO-832, Revised, 1983.
2. U.S. Department of Energy, Office of Remedial Action and Waste Technology Program Summary, DOE/NE-0075. November 1986.
3. U.S. Department of Energy. Methods for Assessing Environmental Impacts of RAP Property Cleanup/Interim Storage Remedial Action. ANL/EIS-16, Argonne National Laboratory, 1982.
4. Stassi P.J., M.A. Jackson, and A.O. Clark. Remedial Action at Vicinity Properties. Proceedings of the Symposium on Waste Management, Tucson, AZ. March 24-28, 1985.
5. Meyer, H.R., D. Skinner, J. Coffman, and J. Arthur. Environmental Protection in the UMTRA Project. Proceedings of the Fifth DOE Environmental Protection Information Meeting, Albuquerque, NM., November 6-8, 1984.
6. Matthews, M.L. UMTRA Project: Implementation of Design. Geotechnical and Geohydrological Aspects of Waste Management. Proceedings of the Fifth Annual Symposium, Fort Collins, CO. February 5-7, 1986.
7. U.S. Department of Energy, Program Summary - Nuclear Waste Management, Fuel Cycle Programs. DOE/NE-0039. Assistant Secretary for Nuclear Energy, Washington, D.C., July 1982.
8. U.S. Department of Energy, Grand Junction Remedial Action Program - Analysis of Currently Approved and Proposed Procedures for Establishing Eligibility for Remedial Action. DOE/EV10162-T1. Assistant Secretary for Environment, Washington, D.C., December 1980.
9. U.S. Department of Energy. Office of Defense Waste and Transportation Management. 1987 Program Summary Document. April 1987.

Bibliography

Disposal

Capping

Lutton, R. J., P. G. Malone, R. B. Meade, and D. M. Patrick. Parameters for Characterizing Sites for Disposal of Low-Level Radioactive Waste. NUREG/CR-2700, U.S. Army Engineer Waterways Experiment Station. May 1982.

Mitchell, J. K. Fundamentals of Soil Behavior. John Wiley & Sons, Inc., New York. 1976.

Parry, G. D. R., R. M. Bell, and A. K. Jones. Degraded and Contaminated Land Reuse Covering Systems. In: Proceedings, National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington DC. 1982.

Rishel, H. L., T. M. Boston, and C. J. Schmidt. Costs of Remedial Response Actions at Hazardous Waste Sites. EPA-600/2-82-035. Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1981.

Schomaker, N. B. and R. F. Murdock. Selection and Placement of Soil Cover Material in a Sanitary Landfill. Open file report UD- 03-68-20. U.S. Public Health Service, Cincinnati, Ohio. 1969.

Schroeder, P. R., J. M. Morgan, T. M. Walski, and A. C. Gibson. The Hydrologic Evaluation of Landfill Performance (HELP) Model; Vol. I, User's Guide for Version I. EPA/530-SW-84-009. Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1984.

Spangler, M. G. and R. L. Handy. Soil Engineering. 4th Edition. Harper and Row, New York. 1982.

Spigolon, S. J., and M. F. Kelley. Geotechnical Quality Assurance of Construction of Disposal Facilities. EPA/600/2-84-04 Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1984.

Terzaghi, K., and R. B. Peck. Soil Mechanics in Engineering Practice. 2nd Edition. John Wiley & Sons, Inc., New York. 1967.

Warner, R. C., and N. Peters. Construction Quality Assurance for Hazardous Waste Landfills with Emphasis on Cover Systems. University of Kentucky. Unpublished. March 5, 1987.

Vertical Barriers

Boyes, R. G. H. Structural and Cut-off Diaphragm Walls. Applied Science Publishers Ltd., London, England. 1975.

D'Appolonia, D. J. Soil-Bentonite Slurry Trench Cutoffs. Journal Geotechnical Eng. Div., ASCE. 106(4). 1980.

Guertin, J. D., and W. H. McTigue. Ground water Control Systems for Urban Tunneling; Volume 1. FHWA/RD-81/073, Federal Highway Administration, Washington DC. 1982.

Jefferis, S. A. Bentonite-Cement Slurries for Hydraulic Cutoffs. In: Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering. Stockholm, Sweden. 1981.

May, J., H. R. J. Larson, P. G. Malone, and V. A. Boa, Jr. Evaluation of Chemical Grout Injection Techniques for Hazardous Waste Containment. In: 11th Annual Research Symposium on Land Disposal of Hazardous Wastes. EPA-600/9-85-013. 1985.

U.S. Environmental Protection Agency. Lining of Waste Impoundment and Disposal Facilities. EPA SW-870. Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1983.

Xanthakos, P. P. Slurry Walls. McGraw-Hill Book Company, New York. 1979.

Land Encapsulation

U.S. Environmental Protection Agency. Evaluating Cover Systems for Solid and Hazardous Waste. SW-867, Office of Solid Waste, Washington DC. September 1982.

U.S. Environmental Protection Agency. Hydrologic Simulation of Solid Waste Disposal Sites. SW-868,

Office of Solid Waste, Washington DC. September 1982.

U.S. Environmental Protection Agency. Landfill and Surface Impoundment Performance Evaluation. SW-869, Office of Solid Waste, Washington DC. April 1983.

U.S. Environmental Protection Agency. Linings of Waste Impoundment and Disposal Facilities. SW-870, Office of Solid Waste, Washington DC. September 1983.

U.S. Environmental Protection Agency. Land Disposal of Hazardous Waste: Proceedings of the 4th Annual Research Symposium. EPA-600/9-78-016, Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1978.

U.S. Environmental Protection Agency. Disposal of Hazardous Waste: Proceedings of the 6th Annual Research Symposium. EPA-600/9-80-010, Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1980.

U.S. Environmental Protection Agency. Land Disposal: Hazardous Waste, Proceedings of the 7th Annual Research Symposium. EPA-600/9-81-002b, Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1981.

U.S. Environmental Protection Agency. Land Disposal of Hazardous Waste: Proceedings of the 8th Annual Research Symposium. EPA-600/9-82-002, Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1982.

U.S. Environmental Protection Agency. Land Disposal of Hazardous Waste: Proceedings of the 9th Annual Research Symposium. EPA-600/9-83-018, Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1983.

U.S. Environmental Protection Agency. Land Disposal of Hazardous Waste: Proceedings of the 10th Annual Research Symposium. EPA-600/2-84-007, Municipal Environmental Research Laboratory, Cincinnati, Ohio. 1984.

U.S. Environmental Protection Agency. Land Disposal of Hazardous Waste: Proceedings of the 11th Annual Research Symposium. EPA-600/9-85-013, Hazardous Waste Engineering Research Laboratory. Cincinnati, Ohio, 1985.

U.S. Environmental Protection Agency. Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste: Proceedings of the 12th Annual Research Symposium. EPA-600/9-

86-022, Hazardous Waste Engineering Research Laboratory. Cincinnati, Ohio, 1986.

Underground Mine Disposal

Belter, W. G. Deep Disposal Systems for Radioactive Wastes. In: Proceedings of Underground Waste Management and Environmental Implications Symposium. The American Association of Petroleum Geologists, Tulsa, Oklahoma. 1972.

Bennett, R. D., W. O. Miller, J. B. Warriner, P. G. Malone, and C. C. McAneny. Alternative Methods for Disposal of Low-Level Radioactive Wastes, Vol. 1. NUREG/CR-3774, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. 1984.

Brunton, G. D., and W. C. McClain. Geological Criteria for Radioactive Waste Repositories. Office of Waste Isolation, Union Carbide Corporation, Nuclear Division, Ridge, Tennessee. 1977.

Cooley, C. R. Radioactive Waste Storage and Isolation Programs in the United States of America. In: Proceedings of First International Symposium on Storage in Excavated Rock Caverns (Rockstore 77), Stockholm, Sweden. Pergamon Press, Inc., New York. 1978.

Deju, R. A. Feasibility of Storing Radioactive Wastes in Columbia River Basalts. In: Proceedings of First International Symposium on Storage in Excavated Rock Caverns (Rockstore 77), Stockholm, Sweden. Pergamon Press, Inc., New York. 1978.

Gnirk, P. F., and W. C. McClain. An Overview of Geologic Disposal of Radioactive Wastes. In: Proceedings of International Symposium on Subsurface Space (Rockstore 80), Stockholm, Sweden. Vol. 2, Pergamon Press, Inc., New York. 1981.

Hooper, M. W., J. N. Geeselman, and T. E. Noel. Mined Cavities in Salt - A Land Disposal Alternative. In: Proceedings of National Conference on Management of Uncontrolled Hazardous Waste Sites. Hazardous Materials Control Research Institute, Silver Spring, Maryland. 1984.

Johnson, G. Underground Disposal of Herfa-Neurode. In: Proceedings of the NATO CCMS Symposium on Hazardous Waste Disposal, Washington DC. Plenum Press, New York. 1983.

Kown, B. T. Cost Assessment for the Emplacement of Hazardous Materials in a Salt Mine. EPA-600/3-77-215, U. S. Environmental Protection Agency, Cincinnati, Ohio. 1977.

Thomas, W. A. Legal Aspects of Using Subsurface Space. In: Proceedings of International Symposium

on Subsurface Space (Rockstore 80), Stockholm, Sweden, Vol. 3. Pergamon Press, Inc., New York. 1981.

Ocean Disposal

Champ, M. A., and P. K. Park. Ocean Dumping of Sewage Sludge: A Global Review. *Sea Technology* 22, 1981.

Cole, H. A. Pollution of the Sea and Its Effects. *Proceedings Royal Society of London, B*, 205. 1979.

Dayal, R., A. Okubo, I. W. Duedall, and A. Ramamoorthy. Radionuclide Redistribution Mechanisms at the 2800-m Atlantic Nuclear Waste Disposal Site. *Deep Sea Research* 26A, 1979.

Dyer, R. S. Sea Disposal of Nuclear Waste: A Brief History. In: *Nuclear Waste Management*, Pergamon Press, New York. 1980.

Interagency Committee on Ocean Pollution Research, Development and Monitoring. The National Marine Pollution Program Plan: Federal Plan for Ocean Pollution Research, Development and Monitoring for Fiscal Years 1981-1985. NOAA, Environmental Research Laboratories, Boulder, Colorado. 1981.

Ketchum, B. H., D. R. Kester, and P. K. Park (eds.) *In: Dumping of Industrial Wastes. Proceedings of the First International Ocean Dumping Symposium*, University of Rhode Island. Plenum Press, New York. 1981.

National Advisory Committee on Oceans and Atmosphere. The Role of the Ocean in a Waste Management Strategy: A Special Report to the President and the Congress. 1981.

National Research Council. *Disposal in the Marine Environment – An Oceanographic Assessment*. Washington DC. 1976.

Reed, A. W. *Ocean Waste Disposal Practices*. Noyes Publications, Park Ridge, New Jersey. 1975.

On-Site Treatment

Stabilization or Solidification

Bartos, M. J., and M. R. Palermo. Physical and Engineering Properties of Hazardous Industrial Wastes and Sludges. EPA-600/2-77-139, U. S. Environmental Protection Agency, Cincinnati, Ohio. 1977.

Cullinane, M. J., L. W. Jones, and P. G. Malone. *Handbook for Stabilization/Solidification of Hazardous Waste*. EPA/540/2-86/001, Hazardous Waste

Engineering Research Laboratory, Cincinnati, Ohio. 1986.

U.S. Environmental Protection Agency. *Guide to Disposal of Chemically Stabilized and Solidified Waste*. SW-872, Office of Solid Waste and Emergency Response, Washington DC. 1982.

U.S. Environmental Protection Agency. *Feasibility of In Situ Solidification/Stabilization of Landfilled Hazardous Wastes*. EPA-600/2-83-088. 1983.

Vitrification

Oma, K. H., et. al. In Situ Vitrification of Transuranic Wastes: Systems Evaluation and Applications Assessment. PNL-4800, Pacific Northwest Laboratory, Richland, Washington. 1983.

Radon Removal

Bruno, R. C. Sources of Indoor Radon in Houses: A Review. *Journal Air Pollution Control Association*, 33(2). 1983.

Nazaroff, W. W., M. L. Boegle, C. D. Hollowell, and G. D. Roseme. The Use of Mechanical Ventilation with Heat Recovery for Controlling Radon and Radon Daughter Concentration in Houses. *Atmospheric Environment*, 19(1). 1985

Sachs, H. M., and T. L. Hernandez. Residential Radon Control by Subslab Ventilation. Presented at 77th Annual Meeting of the Air Pollution Control Association, San Francisco, CA. June 1984.

Scott, A. G. A Review of Potential Low-Cost Mitigation Measures for Soil-Generated Radon. Report No. 1401/1334, American ATCON. April 1985.

Tappan, J. T. Mitigation Methods for Natural Radioactivity Associated with Energy Efficient Structures. Presented at National Conference on Environmental Engineering, Boulder, CO. July 1983.

U.S. Environmental Protection Agency and U. S. Department of Health and Human Services. *A Citizen's Guide to Radon – What It Is and What to Do About It*. OPA-86-004. EPA Office of Air and Radiation, and DHHS Centers for Disease Control, Washington DC. 1986.

U.S. Environmental Protection Agency. *The Effects of Home Ventilation Systems on Indoor Radon-Radon Daughter Levels*. EPA-520/5-77-011, Office of Radiation Programs, Eastern Environmental Radiation Facility, Montgomery, Alabama. 1978.

U.S. Environmental Protection Agency. *Interim Protocols for Screening and Follow-up Radon and*

Radon Decay Product Measurements. Office of Radiation Programs, Washington DC. 1987.

Chemical Extraction

Abel, K.H. Techniques for chemical analysis of radionuclides in fly ash: An evaluation. Battelle Pacific Northwest Labs, Final Report.

Allard, B.H., H. Kipatsi, and B. Torstenfelt. Sorption of long-lived radionuclides in clay and rock. Part 2. Kaernbraenslesaeckerhet, Stockholm, April 1978.

Beak Consultants Ltd (sponsor). Assessment of the long-term suitability of present and proposed methods for the management of uranium mill tailings. Atomic Energy Control Board, Ottawa.

Beard, H.R., I.L. Nichols, and D.C. Seidel. Absorption of radium and thorium from Wyoming and Utah uranium mill tailings solutions. Bureau of Mines, Salt Lake City Research Center Report, 1979.

Beard, H.R., H.B. Salisbury, and M.B. Shirts. Absorption of radium and thorium from New Mexico uranium mill tailing solutions. Bureau of Mines, Salt Lake City Research Center Report of Investigations, 1980.

Bryant, D.N., D.B. Cohen, and R.W. Durham. Leachability of radioactive constituents from uranium mine tailings. Environmental Protection Service Report. Ottawa, April 1979.

Chin, N.W., J.R. Dean, and C.W. Sill. Techniques of sample attack used in soil and mineral analysis. Phase 1. Atomic Energy Control Board, Ottawa.

Cline, J.E. Development of new and improved data reduction techniques for radiometric assay of bulk uranium ore samples. Science Applications, Inc., Dept Energy Final Report, Washington DC, September 1977.

Cokal, E.J., D.R. Dreesen, and J.M. Williams. Chemical characterization and hazard assessment of uranium mill tailings. Los Alamos Nat Lab. Dept Energy Report, Washington DC, 1981.

Conference of Radiation Program Directors, Inc. Natural radioactivity contamination problems. Report sponsor: Nuclear Regulatory Comm; Office of Radiation Programs, Washington DC; Bureau of Radiological Health, Rockville. February 1978.

De Oliveira Godov, J.M. Development of an analytical method for the determination of U-238, U-234, Th-232, Th-230, Th-228, Ra-228, Ra-226, Pb-210, and Po-210 and its application on environmental samples. Kernforschungszentrum

Karlsruhe GMDH (Germany, FR). Hauptabteilung Sicherheit, February 1983.

Demopoulos, G.P. Acid Pressure leaching of a sulphidic uranium ore with emphasis on radium extraction. Hydrometallurgy, v15 n2, December 1985.

Erickson, R.L., and D.R. Sherwood. Interaction of acidic leachate with soil materials at Lucky Mc Pathfinder mill, Gas Hills, Wyoming. Battelle Pacific Northwest Labs. Dept Energy Report, Washington DC, September 1982.

Fyfe, W.S. Immobilization of U-Th-Ra in mine wastes by mineralization. In: Geoscience Research Grant Program; Summary of Research. (ed. E.G. Pye.) Ont Geol Surv Misc Paper, 87, 1979.

Graham, E.R. Radioisotopes and soils. In: Chemistry of the Soil, 2nd edition. Reinhold Pub Corp, New York, 1964.

Hague, K.E., and B. Ipekoglu. Hydrochloric acid leach of Agnew Lake uranium concentrate. Can Centre Mineral Eng Tech Report, Ottawa, October 1981.

Hawley, J.E. Use of phosphate compounds to extract thorium-230 and radium-226 from uranium ore and tailings. Hazen Research, Inc., Nat Sci Found Report, Washington DC, May 1980.

Haywood, F.F., W.A. Goldsmith, R.W. Leggett, R.W. Doane, and W.F. Fox. Sites, Gardiner, Inc., Tampa, Florida. Oak Ridge Nat Lab. Dept Energy Report, Washington DC, March 1981.

Herrisk, J.F. Solubility limits on radionuclide dissolution. Los Alamos Nat Lab. Dept Energy Report. Washington DC, 1984.

Humphrey, H.W., E.L. Adkins, and G.G. Templin. Radiometric determination of exp 226 Ra and exp 228 RA in waste effluent solutions. Nat Lead Co of Ohio, Cincinnati, April 1975.

Joshi, L.U., and A.K. Ganguly. Natural radioactivity and geochemical processes in the marine environment of the West Coast of India. Bhabha Atomic Research Centre, Bombay, 1973.

Kalkwarf, D.R. Solubility classification of airborne products from uranium ores and tailings piles. Battelle Pacific Northwest Labs. Dept Energy Report, Washington DC, January 1979.

Landa, E.R. Leaching of radionuclides from uranium ore and mill tailings. U.S. Geol Surv, Denver, 1982.

Laul, J.C., C.W. Thomas, M.R. Peterson, and R.W. Perkins. Radionuclide disequilibria studies for

investigating the integrity of potential nuclear waste disposal sites: subseabed studies. Battelle Pacific Northwest Labs, Dept Energy Report, Washington DC, September 1981.

Leggett, R.W., W.D. Cottrell, J. Burden, and M.T. Ryan. Formerly utilized MED/AEC sites remedial action program: radiological survey of the former Linde uranium refinery, Tonawanda, New York. Oak Ridge Nat Lab. Dept Energy Final Report, Washington DC, May 1978.

Leggett, R.W., W.D. Cottrell, W.A. Goldsmith, D.J. Christian, and F.F. Haywood. Formerly utilized MED/AEC sites remedial action program. Radiological survey of the Middlesex Municipal Landfill, Middlesex, New Jersey. Oak Ridge Nat Lab. Dept Energy Report, Washington DC, April 1985.

Moffett, D. Disposal of solid wastes and liquid effluents from milling of uranium ores. Can Centre Mineral & Energy Tech. Ottawa, July 1976.

Murphy, K.L., and G.E. Muttamakı. Placement of radium/barium sludges in tailings areas. Atomic Energy Control Board Report, Ottawa, March 1980.

Murry, F.H., J.R. Brown, W.S. Fyfe, and B.I. Kronberg. Immobilization of I-Th-Ra in mine wastes by phosphate mineralization. Univ West Ont, Dept Geol.

Phillips, C.R., P. L. Sears, and Y. C. Poon. Leaching of uranium ore with emphasis on the fate of radium. Energy Sources, v6 n3, 1982.

Phillips, C.R., and Y.C. Poon. Status and future possibilities for the recovery of uranium, thorium, and rare earths from Canadian ores, with emphasis on the problem of radium. Minerals Sci Eng, v12 n2, April 1980.

Raicevic, D., M. Raicevic, and D.R. McCarthy. Preconcentration of low-grade uranium ores with environmentally acceptable tailings, Part I. Agnew Lake ore. Dept Energy, Mines, and Resources Report, Ottawa, August 1979.

Rainey, R.H., and R.G. Nicol. Separation of daughters of /Sup 232/U from/Sup 233/U by ion exchange. Oak Ridge Nat Lab. Presentation, October 1971.

Scheitlin, F.M., and W.D. Bond. Removal of hazardous radionuclides from uranium ore and/or mill tailings. Oak Ridge Nat Lab. Dept Energy Prog Report, Washington DC, January 1980.

Smithson, G.L. Radiochemical procedures for determination of selected members of the uranium

and thorium series. Can Centre Mineral & Energy Tech, Ottawa, January 1979.

Sears, M.B., E.L. Etnier, G.S. Hill, B.D. Patton, and J.P. Witherspoon. Correlation of radioactive-waste-treatment costs and the environmental impact of waste effluents in the nuclear fuel cycle: conversion of yellow cake to uranium hexafluoride. Part II. The solvent extraction-fluorination process. Oak Ridge Nat Lab. Dept Energy Report, Washington DC, March 1983.

Starik, I., and K. F. Lazarev. Study of the comparative leachability of the isotopes of radium, uranium, and thorium from monazite. In: Metody Oprei Leniya Absolyutnogo Vozrasta Geologicheskikh Obrazsvantz. Moscow, Akad Nauk SSSR Kom PO Opreleniya. ABS Vozrasta Geol Formatsii, 6, 1964.

Stieff, L.R. Studies of an improved polonium-210 analytical procedure and the distribution and transport of uranium and its alpha emitting daughters using nuclear emulsions. Stieff Research & Development Co., Inc. Dept Energy Report, Washington DC, September 1981.

Torma, A.E., I.M. Gundiler, D. J. Kirby, J.J. Santana, and S.Y. Yeu. Hydrochloric acid leaching of a low-grade New Mexico uranium ore. Metallurgy, v37 n2, February 1983.

Tsezos, M. Selective extraction of metals from solution by microorganisms: A brief overview. Can Metallurgical Quarterly, v24 n2, Apr-June 1985.

Vandergraaf, T.T. Mineralogical and geochemical aspects of the disposal of nuclear-fuel waste. The Canadian Mineralogist, 21, 1983.

Wiles, D.R. Radiochemistry of radium and thorium in uranium mine tailings. Water, Air, & Soil Pollution, v20 n1, July 1983.

Willis, C.P. Radium and uranium determination in samples of Utah Roses geothermal water. Idaho Nat Eng Lab. Dept Energy, Washington DC, June 1980.

Ion Exchange

Arnold, W.D. and D.J. Crouse. Radium removal from uranium mill effluents with inorganic ion exchangers. Ind Eng Chem Process Design Devel., 4, July 1965.

Arnold, D.R. The development of high density ion-exchange for CIX process. Proc 3rd Nat Mtg, South Africa Inst Chem Eng, Univ Stellenbosch, 1980.

Campbell, D.O., E.D. Collins, L.J. King, J.B. Knauer, and R.M. Wallace. Evaluation of the use of zeolite mixtures in the submerged demineralizer system (SDS) flowsheet for decontamination of high-

activity-level water at Three Mile Island Nuclear Power Station, Unit 2. Paper, Internat Zeolite Conf, Reno, July 1983,

Haines, A.K. The development of continuous fluidized-bed ion exchange in South Africa. J South Africa Inst Min Metall, 78, July 1978.

Hooper, E.W. The application of inorganic ion exchangers to the treatment of alpha-bearing waste streams. Paper, Internat Atomic Energy Assoc Comm Mtg, On Inorganic Ion Exchangers and Adsorbents for Chem Processing in the Nuclear Fuel Cycle. IAEA TC-518-10, Vienna, 1984.

Hooper, E.W., B.A. Phillips, S.P. Dagnall, and N.P. Monckton. An assessment of the application of inorganic ion exchangers to the treatment of intermediate level wastes. AERE R11088, May 1984.

James, H. The determination of trace amounts of cobalt and other metals in high purity water using ion-exchange membranes. Analyst, 98, April 1973.

Martinola, F., and G. Kuhne. Properties and application of powdered IX Resins. Internat Conf Ion Exchange in Process Industries, SCI, London, July 1969.

Naden, D., G. Willey, and G.M. Newrick. The use of fluid bed ion exchange to reduce uranium recovery costs. 105 AIME Annual Meeting, Las Vegas, February 1970.

Naden, D. and M.R. Bandy. Choice and design of solid ion exchange plants for the recovery of uranium. J Chem Tech Biotechnol, 29, 1979.

Nott, B.R. Electrodialytic decontamination of spent ion exchange resins from CANDU primary heat transport purification circuits. Paper, Internat Sym Water Chemical & Corrosion Problems Nucl Reactor Systems & Components, Vienna, November 1982.

Phillips, B.A., E.W. Hooper, S.P. Dagnall, and N.P. Monckton. Study of the behavior of inorganic ion exchangers in the treatment of medium active effluents, Part 1: preliminary performance. Atomic Energy Research Establishment (UK) G2872, 1984.

Ritcey, G.M., M.J. Slater, and B.H. Lucas. A comparison of the processing and economics of uranium recovery from leach slurries by continuous ion exchange and solvent extraction. 120th Internat Symp on Hydrometallurgy, Chicago, February 1976.

Rosembaun, J.B. and J.R. Ross. A counter-current column for fluid bed ion exchange of uranium slurries. Internat Symp Hydrometallurgy. AIME, Chicago, 1973.

Physical Extraction

Screening

Allen, T. Particle Size Measurement. 2nd ed, Chapman & Hall, 1974.

ANSI/ASTM E11-70. Standard specification for wire cloth sieves for testing purposes. In: Annual Book of ASTM Standards, 41, 1977.

Bandholz, J.J. Horizontal screen blinding - cause and cures. Rock Prod, 72, February 1969.

Beven, D.J., and T. Martyn. The dry screening centrifuge. Mine & Quarry, 1, May-June 1972.

Dehlen, B.L.A. Rubber in vibrating screens - an efficient weapon against wear, noise, and dust. Screening Grading Bulk Materials. Inst Mech Eng, London, 1975.

Ephithite, H.J. The applications of rubber in the screening of bulk materials. Screening Grading Bulk Materials. Inst Mech Eng, London, 1975.

Gluck, S.E. Some technological factors affecting the economics of screening. J Met, 18, March 1966.

Gluck, S.E. Vibrating screens. Chem Eng, 75, February 15, 1968.

Hoffman, C.W., and W.R. Hinken. Probability sizing - principles, problems, and development in the mining industry. Trans AIME/SME, 244, June 1969.

Keller, L.D. Fine screening: the current state of the art. AIME/SME Preprint 71-B-25, AIME 1971.

Matthews, C.W. Screen installations to meet maintenance and environmental requirements. Rock Prod, 73, April 1970.

Pritchard, A.N. Choosing the right vibrating screen. Mine & Quarry, 9, December 1980.

Pritchard, A.N. Vibrating screens in the mining industry. Mine & Quarry, 9, October 1980.

Schulz, C.W., and R.B. Tippin. Fundamentals of statistical screening. Trans AIME/SME, 247, December 1970.

Shaw, S.R. The rotating probability screen - a new concept in screening. Mine & Quarry, 12, October 1983.

Sullivan, J.F. Screening technology handbook. Triple/S Dynamics, Inc., 1975.

Classification

Bradley, D. The hydrocyclone. Pergamon Press, Oxford, 1965.

Edmiston, K.J. International guide to hydrocyclones. World Mining, 36, April 1983.

Fitch, E.B., and D.G. Stevenson. Gravity separation equipment. In: solid/liquid separation equipment scale-up. Uplands Press, 1977.

Heiskanen, K. Two stage classification. World Mining, 32, June 1979.

Kelsall, D.F., and J.C.H. McAdam. Design and operating characteristics of a hydraulic cyclone elutriator. Trans Inst Chem Eng, 41, 1963.

Kelsall, D.F. The theory and applications of the hydrocyclone. In: Solid/liquid separation; a review and bibliography. (Ed. J.B. Poole and D. Doyle). HMSO, 1966.

Lynch, A.J. Mineral Crushing and Grinding. Elsevier, Amsterdam, 1977.

Trawinski, H. Theory, applications, and practical operation of hydrocyclone. Eng Min J, 177, September 1976.

Wills, B.A. Factors affecting hydrocyclone performance. Min Mag, 142, February 1980.

Flotation

Arbiter, N., C.C. Harris, and R. Yap. Hydrodynamics of flotation cells. Trans AIME/SME, 244, 1969.

Arbiter, N. and N. Weiss. Design of flotation cells and circuits. Trans AIME, Vol 247, 1970.

Arbiter, N. and C.C. Harris. Design and Operating Characteristics of Large Flotation Cells. AIME/SME, Preprint, 79, 1979.

Carnahan, T.G., and K.P.V. Lei. Flotation - nitric acid leach procedure for increasing uranium recovery from a refractory ore. U.S. Dept. of the Interior, Bureau of Mines, R.I. 8331, 1979.

Eccles, A.G. In: Milling Practice in Canada. (ed. D.E. Pickett). CIM, 1978.

Ettelt, G.A. Activated sludge thickening by dissolved-air flotation. Indiana Waste Conf, Purdue Univ. 1964.

Finkelstein, N.P. and G.W. Poling. The role of dithiolates in the flotation of sulphide minerals. Mineral Sci Eng 9, 1977.

Flint, L.R. Factors influencing the design of flotation equipment. Mineral Sci Eng, 5, 1973.

Fuerstenau, D.W., ed. Froth Flotation - 50th Anniversary Vol. AIME/SME, 1962

Fuerstenau, M.C., and W.F. Cummins. The role of basic aqueous complexes in anionic flotation of quartz. Trans AIME/SME, 238, 1967.

Fuerstenau, M.C., ed. Flotation - A.M. Gaudin Memorial Volume, AIME/SME, 1976.

Glembotskii, V.A., V.I. Klassen, and I.N. Plaskin. Flotation, Primary Sources, 1963.

Glembotskii, V.A., V.I. Klassen, and I.N. Plaskin. Flotation. Primary Sources, 1972.

Harris, G.H. Xanthates. In: Encyclopedia of Chemical Technology. 22, John Wiley, New York, 1970.

Honeywell, W.R., and S. Kaiman. Flotation of uranium from Elliot Lake ores. Dept of Mines and Tech. Surveys, Mines Branch, Canada, Reprint series R S 3, 1966.

Klassen, V.I. and V.A. Mokrousov. An Introduction to the Theory of Flotation. Butterworths, 1963.

Klimpel, R.R. Selection of chemical reagents for flotation. AIME/SME Preprint No 80-34, 1980.

Kuhn, A. Electroflotation - the technology and waste treatment applications. Chem Processing, 9, 6/74 and 5, 7/74.

Leja, J. Some electrochemical and chemical studies related to froth flotation with xanthates. Mineral Sci Eng, 5(J) 1973.

Leja, J. Surface Chemistry of Froth Flotation. Plenum Press, New York, 1982.

Lynch, A.J., N.W. Johnson, E.V. Manlapig, and C.G. Thorne. Mineral and Coal Flotation Circuits. Elsevier, Amsterdam, 1981.

Manser, R.M. Handbook of silicate flotation. Warren Spring Lab, 1975.

Palmer, R.B. et al. Mechanisms involved in the flotation of oxides and silicates with anionic collectors. Trans AIME/SME, 258, 1975.

Rulev, N.N. Theoretical substantiation of experimentally established laws governing the

flotation of small particles. (trans.) Koll. Zh. 40(6) 1978.

Sastry, K.V.S., ed. Agglomeration 77. AIME/SME, 1977.

Somasundavan, P., ed. Beneficiation of Mineral Fines. AIME/SME, 1979.

Sorensen, E. On the adsorption of some anionic collectors on fluoride minerals. J Coll Interface Sci; 45, 1973.

Trahar, W.J. and J.L. Warren. The flotability of very fine particles; a review. Internat J Mineral Processing, 3, 1976.

Trahar, W.J. A rational interpretation of the role of particle size in flotation. Internat J Mineral Processing, 8, 1981.

Wyman, R.A. The floatability of twenty-one nonmetallic minerals. Canadian Mines Branch, Tech Bull TB108, 1969 .

Gravity Concentration

Aplan, F.F. The state of the art and the future of gravity concentration. In: Research Needs in Mineral Processing. (ed. P. Somasundarian, and D.W. Fuerstenau). Nat Sci Found, New York, 1975.

Batzer, D.J. Investigation into jig performance. Trans IMM, 72, 1962-63.

Burt, R.O. A study of the effect of deck surface and pulp pH on the performance of a fine gravity concentrator. Internat J Mineral Processing, 5, 1978.

Kirchberg, H. and W. Berger. Study of the operation of shaking concentration tables. Paper 25, Internat Mineral Processing Congr, London, 1960.

Mayer, F.W. Fundamentals of a potential theory of the jiggling process. Proc 7th Internat Mineral Processing Congr, Vol I, Gordon and Breach, New York, 1965.

Michell, F.B. Table flotation. Mineral Mag, 73, 1945.

Michell, F.B. and D.G. Osborne. Gravity concentration in modern mineral processing. Chem Ind, 58, 1975.

Muller, L.D., C.P. Sayles, and R.H. Mozley. A pulsed deck gravity concentrator and comparative performance analysis. Vol I, Proc. 7th Internat Mineral Processing Congr, New York, 1964

Nair, J.S., S.N. Degaleeson, and K.K. Majumdar. Automatic splitter for wet tabling of radioactive ores. Trans Inst Minerals and Metals, 83, 1974.

Ottley, D.J. Technical, economic and other factors in the gravity concentration of tin, tungsten, columbium, and tantalum ores. Minerals Sci Eng, 11, April 1979.

Rao, S.R. and L.L. Sirois. Study of surface chemical characteristics in gravity separation. CIM Bull, 67, June 1974.

Richards, R.H., and S.B. Locke. Textbook of mineral dressing. McGraw-Hill, New York, 1940.

Terrill, I.J., and J.B. Villar. Elements of High-Capacity Gravity Separation. CIM Bull, 68, May 1975.

Terry, R.L. Minerals concentration by wet tabling. Mineral Processing, 15, July-August 1974.

Tiernon, C.H. Concentrating tables for fine coal cleaning. Mining Eng, 32, August 1980.

Welsh, R. and A. Deurbrouck. Photo-electric concentrator for the wet concentrating table. U.S.B.M. Rep on Investigations 7623, 1972.

Wiard, E.S. Theory and practice of ore dressing. McGraw-Hill, New York, 1915.

Sedimentation

Adorjan, L.A. A Theory of sediment compression. Proc 11th Internat Min Process Congr, Univ Cagliari, 1975.

Coe, H.S. and G.H. Clevenger. Methods for determining the capacities of slime settling tanks. Trans AIME TMS. 55, 1916.

Emmett, R.C. and R.P. Klepper. Technology and performance of the hi-capacity thickener, Mining Eng, 32, August 1980.

Fitch, E.B. and D.G. Stevenson. Gravity separation equipment. In: Solid/Liquid Separation Equipment Scale-Up, Upland Press, 1977.

Keane, J.M. Sedimentation: theory, equipment, and methods. World Mining, 32, November 1979.

Keane, J.M. Recent developments in solids/liquid separation. World Mining, 110, October 1982.

Robins, W.H.M. The theory of the design and operation of settling tanks. Trans Inst Chem Eng, 42, 1964.

Scott, K.J. Theory of Thickening. Trans IMM(C), 77, June 1968.

Filtration

Adamson, G.F.S. Some recent papers on flocculation. *Mine & Quarry*, 10, March 1981.

Akers, R. Flocculation. I Chem E Services, London, 1975.

Clement, M. and J. Bonjer. Investigation on mineral surfaces for improving the dewatering of slimes with polymer flocculants. *Proc 11th Internat Min Process Congr, Univ Cagliari*, 1975.

Dahlstrom, D.A. and C.E. Silverblatt. Continuous vacuum and pressure filtration. In: *Solid/Liquid Separation Equipment Scale-Up* (ed. D. Purchas), Uplands Press, 1977.

Daykin, K.W. et al. Steam-assisted vacuum filtration. *Mine & Quarry*, 7, March 1978.

Dexter, R.H. and D.G. Osborne. Principles of the selective flocculation of minerals from mixtures using high molecular weight polyelectrolytes. *J Camborne Sch Mines*, 73, 1973.

Gregory, J. In: *The Scientific Basis of Filtration*. (ed. K.J. Ives), Noordhoff, Leyden, 1975.

Hunter, T.K. and M.J. Pearse. The use of flocculants and surfactants for dewatering in the mineral processing industry. *Proc IVth Internat Min Process Congr, Paper IX-11, CIM, Toronto, October 1982*.

Lightfoot, J. Practical aspects of flocculation. *Mine & Quarry*, 10, April 1981.

Moss, N. Theory of flocculation. *Mine & Quarry*, 7, May 1978.

Paananen, A.D., and W.A. Turcotte. Factors influencing selective flocculation-desliming practice at the Tilden Mine. *Min Eng*, 32, August 1980.

Purchas, D.B. Filter media, a survey. *Filtr. Sept.* 1965.

Purchas, D.B. *Industrial filtration of liquids*. Leonard Hill Books, London, 1971.

Read, A.D., and G.T. Hollick. Selective flocculation. *Mine & Quarry*, 9, April 1980.

Silverblatt, C.E., H. Risbud, and F.M. Tiller. Batch, continuous processes for cake filtration. *Chem Eng*, 81, April 29, 1974.

Abbreviations and Symbols

AEC	U. S. Atomic Energy Commission
ATSDR	Agency for Toxic Substances and Disease Registry
CDC	Centers for Disease Control
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (Superfund)
Ci	Curie
cm	Centimeter (10^{-3} meter)
cu ft	Cubic foot
cu m	Cubic meter
cu yd	Cubic yard
DOE	Department of Energy
EPA/USEPA	U. S. Environmental Protection Agency
FS	Feasibility Study
ft	Foot or feet
FUSRAP	Formerly Utilized Sites Remedial Action Program (Department of Energy)
g	Gram
hr	Hour
kg	Kilogram (1000 grams)
kg/hr	Kilograms per hour
kW	Kilowatt (1000 watts)
MED	U. S. Army Corps of Engineers, Manhattan Engineering District
μm	Micron (micrometer, 10^{-6} meter)
mm	Millimeter (10^{-3} meter)
NJDEP	New Jersey Department of Environmental Protection
NRC	Nuclear Regulatory Commission
NPL	National Priorities List
ORNL	Oak Ridge National Laboratory
pCi	Picocurie (10^{-12} Curie)
pCi/g	Picocuries per gram
pCi/l	Picocuries per liter
RI	Remedial Investigation
RI/FS	Remedial Investigation/Feasibility Study
SARA	Superfund Amendments and Reauthorization Act of 1986
sq ft	Square foot
sq m	Square meter
sq yd	Square yard
UMTRAP	Uranium Mill Tailings Remedial Action Project (Department of Energy)
μR	Microroentgen (10^{-6} roentgen)
USGS	U. S. Geological Survey
WL	Working level

Conversions

<u>To Convert From(A)</u>	<u>To(B)</u>	<u>Multiply (A) By</u>
acre	hectare	0.4047
cu ft	cu m	0.02832
cu yd	cu m	0.7646
°F	°C	$(^{\circ}\text{F}-32) \times 5/9$
ft	m	0.3048
kW	kg-calories/min	1.434
mile	meters	1609
sq ft	sq m	0.0929
tons	kg	1016
°C	°F	$(^{\circ}\text{C} \times 9/5) + 32$
Curies	disintegrations per minute	2.2×10^{12}
meter	yd	1.094
kg	lb	2.2046
mg/l	parts per million	1.0
atmosphere (atm)	kilo Pascal (kPa)	101

Key Chemical Elements

Name	Abbreviation
Actinium	Ac
Aluminum	Al
Arsenic	As
Barium	Ba
Beryllium	Be
Bismuth	Bi
Boron	B
Bromine	Br
Cadmium	Cd
Calcium	Ca
Carbon	C
Chlorine	Cl
Chromium	Cr
Cobalt	Co
Copper	Cu
Fluorine	F
Helium	He
Hydrogen	H
Iodine	I
Iron	Fe
Lead	Pb
Lithium	Li
Magnesium	Mg
Manganese	Mn
Mercury	Hg
Molybdenum	Mo
Nickel	Ni
Niobium	Nb
Nitrogen	N
Oxygen	O
Palladium	Pd
Phosphorus	P
Platinum	Pt
Plutonium	Pe
Polonium	Po
Potassium	K
Radium	Ra
Radon	Rn
Selenium	Se
Silicon	Si
Sodium	Na
Strontium	Sr
Sulfur	S
Thorium	Th
Tin	Sn
Titanium	Ti
Tungsten	W
Uranium	U
Vanadium	V
Zinc	Zn

Glossary

Air Avid	To increase by addition of chemicals the affinity of fine particles for air bubbles.
Alpha particle	A positively-charged subatomic particle emitted during decay of certain radioactive elements. For example, an alpha particle is released when radon-222 decays to polonium-218. An alpha particle is indistinguishable from a helium atom nucleus and consists of two protons and two neutrons.
Alpha radiation	The least penetrating type of radiation. Alpha radiation can be stopped by a sheet of paper or outer dead layer of skin.
Background radiation	The radioactivity in the environment, including cosmic rays from space and radiation that exists elsewhere - in the air, in the earth, and in man-made materials. In the U.S., most people receive 100 to 250 millirems of background radiation per year.
Ball decks	A tray of rubber balls that bounce against the bottom surface of a screen, thus eliminating blinding.
Beneficiation	Preparation of ore for smelting
Beta particle	A negatively-charged subatomic particle emitted during decay of certain radioactive elements. A beta particle is identical to an electron.
Beta radiation	Emitted from a nucleus during fission. Beta radiation can be stopped by an inch of wood or a thin sheet of aluminum.
Blinding	Plugging of the screen apertures with slightly oversized particles.
Detection level	The minimum concentration of a substance that can be measured with a 99% confidence that the analytical concentration is greater than zero.
Dose Equivalent	The product of the absorbed dose, the quality factor, and any other modifying factors. The dose equivalent is a quantity for comparing the biological effectiveness of different kinds of radiation on a common scale. The unit of dose equivalent is the rem. A millirem (mrem) is one one-thousandth of a rem.
Entry routes	Pathways by which soil gas can flow into a house. Openings through the flooring and walls where the house contacts the soil.
Exfiltration	The movement of indoor air out of the house.
External radiation	Radiation originating from a source outside the body, such as cosmic radiation. The source of external radiation can be either natural or man-made.
Gamma radiation	A form of electromagnetic, high-energy radiation emitted from a nucleus. Gamma rays are essentially the same as x-rays and require heavy shieldings, such as concrete or steel, to be stopped.
Grizzly screen	Screen made of heavy fixed bars, used to remove oversized stones, tree stumps, etc.
ground water	Subsurface water that is in the pore spaces of soil and geologic units.
Half-life	The length of time in which any radioactive substance will lose one-half its radioactivity. The half-life may vary in length from a fraction of a second to thousands of years.
Indoor air	That air that occupies the space within the interior of a house or other building.

Ion exchange	The reversible exchange of ions contained in a crystal for different ions in solution, without destroying the crystal structure or disturbing the electrical neutrality.
Internal radiation	Radiation originating from a source within the body as a result of the inhalation, ingestion, or implantation of natural or man-made radionuclides in body tissues.
Isotopes	Different forms of the same chemical element that are distinguished by having different numbers of neutrons in the nucleus. A single element may have many isotopes. For example, the three isotopes of hydrogen are protium, deuterium, and tritium.
Mesh	Number of wires per inch in a screen.
Microrem(μ R)	A unit of radiation "dose equivalent" that is equal to one one-millionth of a rem.
Microrem per hour (μ R/hr)	A unit of measure of the rate at which "dose equivalent" is being incurred as a result of exposure to radiation.
Millirem (mrem)	A unit of radiation "dose equivalent" that is equal to one one-thousandth of a rem.
NARM	Naturally-occurring or accelerator-produced radioactive materials mean any radioactive material except for material classified as source, by-products, or special nuclear material under the Atomic Energy Act of 1954, as amended.
ORNL	Oak Ridge National Laboratory
Picocurie (pCi)	A unit of measurement of radioactivity. A curie is the amount of any radionuclide that undergoes exactly 3.7×10^{10} radioactive disintegrations per second. A picocurie is one trillionth (10^{12}) of a curie, or 0.037 disintegrations per second.
Picocurie per liter (pCi/l)	A common unit of measurement of the concentration of radioactivity in a gas or liquid. A picocurie per liter corresponds to 0.037 radioactive disintegrations per second in every liter.
Plutonium	A heavy, radioactive, man-made metallic element. Its most important isotope is fissionable ^{238}Pu , which is produced by the irradiation of ^{238}U . Routine analysis cannot distinguish between the ^{239}Pu and ^{240}Pu isotopes, hence, the term $^{239,240}\text{Pu}$.
Radiation	Refers to the process of emitting energy in the form of rays or particles that are thrown off by disintegrating atoms. The rays or particles emitted may consist of alpha, beta, or gamma radiation.
Radioactivity	A property possessed by some elements, such as uranium, whereby alpha, beta, or gamma rays are spontaneously emitted.
Radionuclide	Any naturally occurring or artificially produced radioactive element or isotope.
Radon	A colorless, odorless, naturally occurring, radioactive gaseous element formed by radioactive decay of radium atoms. Chemical symbol is Rn, atomic weight 222, half-life 3.82 days.
Radon progeny, Radon daughter	A term used to refer collectively to the intermediate products in the radon decay chain. Each "daughter" is an ultrafine radioactive particle that decays into another radioactive "daughter" until finally a stable nonradioactive molecule of lead is formed and no further radioactivity is produced.
REM	An acronym for Roentgen Equivalent Man; a unit of radiation exposure that indicates the potential impact on human cells.
Revolving Screen	A screen with a surface that revolves around an axis; the screen surface may be inclined or vertical.

Rotary sifter	Circular motion applied to a rectangular or circular screen surface.
Scalping	Removal of small amounts of oversized material from feed.
Shaking screens	Several screen surfaces in a series, usually slightly inclined, with different apertures and a slow linear motion essentially in place of the screen.
Sieve bends	Screens with stationary parallel bars at a right angle to the feed flow; the surface may be straight, with a steep incline, or curved to 300°.
Soil gas	Those gaseous elements and compounds that occur in the small spaces between particles of the earth or soil. Rock can contain gas also. Such gases can move through or leave the soil or rock depending on changes in pressure. Radon is a gas that forms in the soil wherever radioactive decay of radium occurs.
Tailings	Sand-like waste resulting from uranium production, represents about 98% of the ore that enters the mill.
Uranium	A naturally radioactive element with the atomic number of 92 (number of protons in nucleus) and an atomic weight of approximately 238. The two principal naturally occurring isotopes are the fissionable U-235 (0.7% of natural uranium) and the fertile U-238 (99.3% of natural uranium).
Vibrating screen	An inclined or horizontal rectangular screening surface with a high-speed vibrating motion that lifts particles off the surface.
Working level (WL)	A unit of measure of the exposure rate to radon and radon progeny defined as the quantity of short-lived progeny that will result in 1.3×10^5 MeV of potential alpha energy per liter of air. Exposures are measured in working level months (WLM); e.g., an exposure to 1 WL for 1 working month (173 hours) is 1 WLM. These units were developed originally to measure cumulative work place exposure of underground uranium miners to radon and continue to be used today as a measurement of human exposure to radon and radon progeny.