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MANAGEMENT AND DISPOSAL ALTERNATIVES FOR NORM WASTES IN OIL PRODUCTION AND GAS PLANT EQUIPMENT

May 1990

PREPARED FOR

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MANAGEMENT AND DISPOSAL ALTERNATIVES FOR NORM WASTES IN OIL PRODUCTION AND GAS PLANT EQUIPMENT

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Natural radioactivity occurring at trace concentrations in underground formations and in oil and gas production streams occasionally accumulates in surface equipment to exceed background levels. The accumulations are dominated by radium and its decay products in sludges and pipe scales, and by thin lead-210 deposits on interior surfaces of gas plant equipment. Such accumulations of naturally-occurring radioactive materials (NORM) have mainly been noted in recent years, and appropriate methods and alternatives for their disposal are not well characterized. NORM concentrations vary from predominantly background levels that require no special precautions to elevated levels that occasionally are similar to levels in uranium mill tailings. This report presents radiological analyses of disposal alternatives that will protect against elevated radiation exposures and facilitate cost-effective precautions that are proportionate to any hazards posed by the NORM.

Four waste forms were considered in the safety analyses, including sludges, scales, production equipment, and gas-plant equipment. Sludges were characterized by relatively low radium contents, ranging from background to several hundred picocuries per gram (pCi/g), and a moderate radon emanation coefficient of 22%. They also have a moderate leach fraction of 10^{-3}. Scales were characterized by occasionally higher radium contents, ranging from background to several thousand pCi/g. Their radon emanation coefficient is typically low (5%), as is their leach fraction (10^{-5}). Production equipment contains residual deposits of sludges or scales with identical radiological properties. In options such as burial, however, NORM in equipment cannot be as concentrated or compacted as in the separated scales, and thus it has different exposure properties. Gas-plant equipment contains only the long-lived radon daughters dominated by lead-210, and thus has very different radiation, leaching, and exposure risk properties. Lead-210 occurs in extremely thin deposits that are plated onto the inside surfaces of selected gas-plant equipment.

Analyses of twelve waste disposal alternatives indicated that many were suited to all four of the waste forms. Alternatives suitable for the sludges and scales included landspreading, landspreading with dilution, injection into inactive wells, and hydraulic fracturing into unused formations. Landspreading was limited to applied surface layers less than 8-inches (20 cm) thick, and landspreading with dilution was identical except that it involved mixing of the applied wastes uniformly in the top 8-inch (20 cm) layer. Injection into deep wells below underground sources of drinking water (USDW) in unusable formations would isolate the NORM from intrusion. Hydraulic fracturing similarly involves injection into unusable formations in a less mobile form. Other alternatives suitable for both equipment and residues include burial at unrestricted sites, at commercial oil-field waste sites, at licensed NORM disposal sites, at low-level radioactive waste disposal sites, in surface mines, and in salt domes. These all provide for relatively large disposal volumes, and differ mainly in their accessibility for exposure. Two other alternatives applying only to NORM in equipment include plugged and abandoned wells and non-retrieval of surface pipe.

Other disposition alternatives for equipment containing NORM include release for general use, release for re-use within the petroleum industry, storage in an oil-field equipment yard, and release for smelting. General use involves incorporation of pipe with NORM scales in the indoor environment. Re-use in the oil industry is a null alternative, leading only to delayed disposal. Storage involves worker handling and refurbishing of the equipment. Release for smelting involves smelter emissions and incorporation of the NORM into metal consumer products such as frying pans and piping.

Each disposal alternative was analyzed in both humid and arid permeable geohydrological settings due to their differences in environmental transport of radioactivity. Analyses of a humid impermeable site were intermediate. Limits for radiation exposures were defined from exposure limit criteria developed for corresponding radiation from other, related sources. Radiation exposures via seven different environmental pathways were considered. These included radon inhalation, external gamma exposure, groundwater ingestion, surface water ingestion, dust inhalation, food ingestion, and skin beta exposure from NORM particles. Exposures via each pathway were analyzed for each disposal alternative using computer calculations of the radiation doses exerted by a prescribed quantity of NORM in each of the waste forms. Computer codes used in the analyses included the RAETRAN code, the PATHRAE-EPA code, the IMPACTS-BRC code, the MICROSHIELD code, and the VARSKIN code.

Maximum NORM concentrations were computed from the radiation exposure limits for each of the four waste types using each disposal alternative in each geohydrological setting. All seven radiation exposure pathways were considered in each analysis. The maximum NORM concentrations corresponded to the greatest concentrations of NORM nuclides that could utilize a given disposal alternative without exceeding the defined radiation exposure limits via the given pathway. The maximum concentrations were defined in terms of radium for the scales, sludges and production equipment and lead-210 for the gas plant equipment because these were the nuclides dominating radiation exposures. The limiting exposure pathway for each disposal alternative was defined to be the one permitting the greatest radiation exposure. Its corresponding maximum NORM concentration was used to define the maximum for the disposal alternative.

Radium concentration limits for disposal range from 29 pCi/g for shallow burial in an unrestricted arid site to over 100,000 pCi/g for non-retrieved well tubing, well injection, hydrofracture, and salt dome disposal. Nearly all of the alternatives are suitable for most NORM wastes due to their generally broad range of suitable radium concentrations. Radium concentration limits generally resulted from the radon, gamma or groundwater ingestion pathways. Lead-210 was generally found to be significant only in the case of disposed gas plant equipment. Its disposal limits exceeded 100,000 pCi/g in nearly all practical cases.

1. INTRODUCTION

Natural radioactivity occurring at trace concentrations in oil and gas production streams occasionally accumulates as scale or sludge in tubing and in surface equipment to exceed background levels. Since the radioactivity is generally low and of natural origin, its accumulation and significance were not noted and studied until recently.[1] The American Petroleum Institute (API) has subsequently sponsored studies to characterize accumulations of naturally-occurring radioactivity in oil-field equipment, and to determine safe methods for their disposal. This report presents the analyses of disposal methods for naturally-occurring radioactive materials (NORM) from oil and gas production. It builds on results of a previous safety analysis of disposal methods for NORM wastes in Texas,[2] including a broader range of petroleum industry wastes, more detailed characterization, and covering a broader range of disposal alternatives.

Understanding the radiological safety of NORM waste disposal alternatives is vital to waste management and disposal decisions. Priorities in these decisions are to protect against harmful radiation exposures and to accomplish the disposal in a practical manner proportionate to any hazards posed by the NORM. Since radiation exposures depend on both the quantity of NORM and on its isolation, disposal safety depends on both the waste characteristics and the disposal method.

NORM concentrations vary from background levels to levels exceeding those of some uranium mill tailings, suggesting a similarly broad range of suitable disposal alternatives. Disposal of wastes containing NORM clearly does not require precautions for common cases in which NORM occurs at background levels. When elevated occurrences are found, their disposal should be handled in a way that protects against significant radiation exposure. The disposal problem is compounded by the lack of standards for pertinent alternative disposal methods or for defining the precautions needed for different kinds of NORM. Although detailed regulations provide for disposal of radioactive wastes that clearly pose health risks,[3,4] there is less guidance on the disposal of wastes containing NORM with elevated radionuclide concentrations. As a result, some wastes containing extremely small amounts of NORM are occasionally sent to elaborate disposal sites at extremely high costs, wasting money, manpower and resources.

This report addresses the problem of what can be done with residues and equipment containing elevated NORM. It systematically identifies the maximum quantities or concentrations of NORM that can utilize various disposal alternatives, implemented at either arid or humid sites. It considers NORM that occurs in sludges from surface equipment, in pipe and tube scales, in cleaned equipment containing residual scales, and on surfaces of gas plant equipment. The waste disposal alternatives analyzed for sludges and scales include landspreading, landspreading with dilution, surface pipe non-retrieval, burial at unrestricted sites, disposal at commercial oil-field waste sites, disposal at licensed NORM disposal sites, disposal at licensed low-level radioactive waste sites, burial in surface mines, placement into wells being plugged and abandoned, injection into inactive wells, hydraulic fracturing into unused formations, and injection into salt domes. Disposal alternatives analyzed for equipment containing NORM residues include release for general use, release for re-use within the petroleum industry, storage in an oil-field equipment yard, release for smelting, and burial with NORM scales and sludges. For each waste disposal alternative, radiation exposures are considered from radon gas inhalation, external gamma-ray exposure, groundwater consumption, surface water consumption, dust inhalation, and food consumption. Using the NORM concentration limits for each disposal alternative, NORM wastes can be reliably managed in the most cost-effective manner while still protecting public radiological safety.

1.1 ORIGIN AND NATURE OF NORM

Naturally-occurring radioactive materials are ubiquitous in the environment, and commonly occur in soils, water, food and air. The NORM that accumulates in surface petroleum production equipment is predominantly radium-226 and radium-228 and their progeny, which come from the uranium-238 and thorium-232 decay chains, respectively (Figure 1-1). Both uranium and thorium occur naturally in underground formations and remain mostly in place. However their radium decay products are slightly soluble, and under

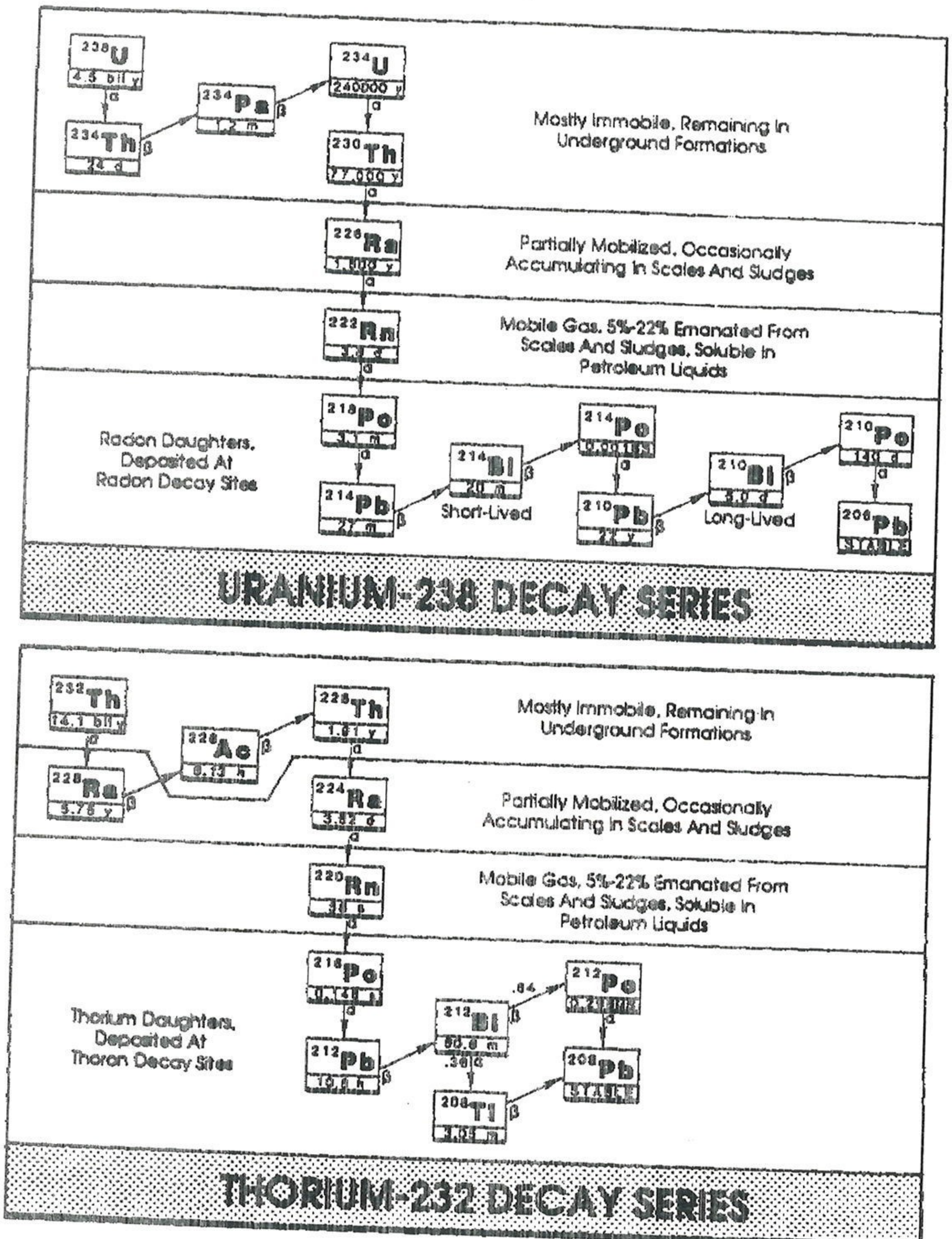

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FIGURE 1-1. PRINCIPAL NUCLIDES, DECAY MODES, AND MOBILITIES OF THE URANIUM - 238 AND THORIUM - 232 DECAY SERIES.

some conditions they become mobilized by liquid phases in the formation. When brought to the surface with liquid production streams these nuclides may remain dissolved at dilute levels, or may precipitate because of chemical changes and reduced pressure and temperature as the fluids are separated and processed. Since radium concentrations in the original formations are highly variable, production fluids also are highly variable and occasionally may exhibit elevated radioactivity. Varied formation and surface chemistries cause additional variations in radioactivity brought to the surface. Fluids injected into formations also affect the mobilization of natural radioactivity, and surface processes further vary the accumulation of any radioactivity in scales, sludges, and waste products. Scales and sludges accumulated in surface equipment thus may vary from background concentrations of NORM to elevated levels depending on formation radioactivity and chemistry and process characteristics. As used in this report, the term NORM refers only to the radionuclides of the uranium and thorium decay chains, ignoring naturally-occurring potassium-40 and other nuclides that occur naturally throughout the environment but have not been known to accumulate in residues from oil and gas production.

The NORM accumulated in production equipment scales typically contains radium coprecipitated in barium sulfate. Sludges are dominated by silicates or carbonates, but also incorporate trace radium by coprecipitation. Typically, radium-226 is in equilibrium with its decay products but radium-228 has sub-equilibrium decay products. Reduced concentrations of radium-228 daughters result from the occurrence in the thorium-232 decay chain of two radium nuclides separated by the 1.9-year half-life thorium-228 (Figure 1-1). Thus radium mobilized from the formation initially becomes depleted in radium-224 (3.6 days) until more is generated by radium-228 decay through the thorium-228 intermediate. Long-term radiological concern in waste disposal is dominated by the uranium chain due to the long half-life (1,600 years) of radium-226. Both are usually considered together in waste disposal decisions, however, since they are not distinguished by simple field measurements.

NORM deposits also may accumulate in gas-plant equipment from radon-222 (radon) gas progeny, even though the gas is removed from its radium-226 parent. The more mobile radon gas mostly originates in underground formations and becomes dissolved in the organic petroleum fractions in the gas plant. Once in surface equipment, it is partitioned mainly into the propane and ethane fractions by its solubility. Gas-plant deposits differ from oil production scales and sludges by having very low mass, typically consisting of an invisible plate-out of radon daughters on the interior surfaces of pipes, valves and other gas-plant equipment. These deposits accumulate from radon daughters at natural levels from the very large volumes of gas passing through the system. Since radon decays with a 3.8-day half-life, the only nuclide remaining in gas-plant equipment that affects its disposal is lead-210, which has a 22-year half life. Lead-210 decays by beta emission, with only low-intensity, low-energy gamma rays. It thus poses less disposal hazard than other NORM deposits in most cases.

1.2 PRECEDENT FOR UNREGULATED DISPOSAL OPTIONS

Current legislation and regulations have acknowledged the gap between background levels of radioactivity and levels that require regulation. On an international level, the International Atomic Energy Agency has developed a method to determine *de minimis* levels for radioactive waste disposal[5] that is consistent with the methods used here. In the United States, the Atomic Industrial Forum has sponsored studies of *de minimis* disposal of nuclear power reactor wastes[6,7] that consider some of the same disposal alternatives and exposure pathways analyzed in this report. The half-lives of the reactor wastes have similar longevity to the NORM nuclides considered here.[7] In addition, the U.S. Low-Level Radioactive Waste Policy Amendments Act[8] directs the Nuclear Regulatory Commission (NRC) to promulgate regulations to exempt the disposal of waste that is "below regulatory concern" (BRC) from license control, and to develop standards and procedures for considering and acting upon petitions for *de minimis* disposal. The nuclear power industry has responded to the congressional mandate to NRC by preparing a petition for NRC to allow disposal of wastes containing very low levels of radioactivity at facilities other than those licensed under 10 CFR 61.[9] Proposed disposal alternatives include municipal sanitary landfills and burial at the facility. A separate petition for NRC to allow BRC disposal by non-utility industrial and institutional radioactive waste generators also is being prepared.

In other national actions, NRC has examined the consequences of disposing of standard low-level radioactive waste streams in sanitary landfills,[10] and the Environmental Protection Agency (EPA) is developing a general *de minimis* regulation for sanitary landfill disposal as part of their low-level radioactive waste disposal rulemaking.[11] Both of these activities have used methods similar to those used here. The NRC and the state of Texas both have developed *de minimis* biomedical waste disposal rules for tritium (H-3) and carbon-14 that define alternative concentration limits for waste treatment and disposal.[12,13] The Texas Department of Health also has approved regulations permitting disposal of wastes containing only short-lived radionuclides (half-lives less than 1 year) in non-radiological facilities such as sanitary landfills,[14] and permitting local disposal of low-level cesium-137 contaminated soils based on similar safety analyses.[15]

In the foregoing safety and disposal analyses of *de minimis* disposal of radioactive wastes, the analysis methods are similar to those used in this report. As shown in Figure 1-2, radiation exposure limits first are defined, followed by conservative calculations of modeled radiation exposures via all possible pathways for the proposed disposal alternative. In the calculations the source concentration is adjusted until the calculated radiation doses are equal to the defined exposure limits. This procedure defines NORM nuclide concentration limits for each disposal alternative and for each pathway. The final nuclide concentration limit for each disposal alternative and geohydrologic setting is the lowest source concentration limit from the limiting pathway. The present methods thus estimate maximum disposable quantities objectively, and systematically define the best alternatives in the intermediate range between background and regulated levels. For completeness and consistency, NORM disposal concentrations up to 100,000 pCi/gram are presented as calculated in the analyses, even though regulated levels overlap much of the reported range.

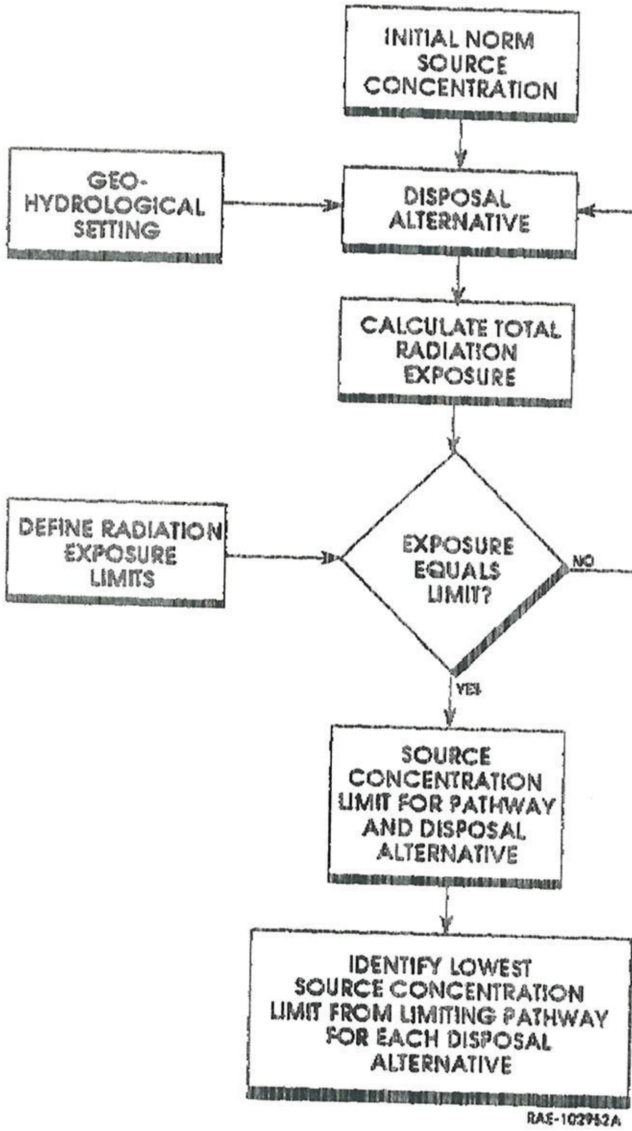

FIGURE 1-2. DETERMINATION OF NUCLIDE CONCENTRATION LIMITS FOR NORM DISPOSAL.

2. WASTE CHARACTERISTICS AFFECTING NORM DISPOSAL

Petroleum industry wastes are divided into four categories based on different characteristics that affect radiation exposures from NORM. The categories include sludges from petroleum production equipment; scales from tubing, pipes, and other production equipment; equipment that contains residual NORM scale; and thin deposits of lead-210 on the inside surfaces of gas-plant equipment. The characteristics that define these categories include radionuclide inventory, mobility, and radiation emissions. The characteristics of each group are described in this chapter to define the basis for estimating radiation exposures for each waste type under each disposal option. Since waste characteristics affect exposures by different pathways, a characteristic may be more important in some disposal alternatives than in others.

2.1 SLUDGES

Sludges accumulated in production equipment typically contain radium-226 and radium-228 concentrations ranging from background levels to several hundred picocuries per gram (pCi/g). Radium-226 concentrations usually are greatest. Since both radium decay chains exhibit similar radioactivities, they are expressed as total radium. The ratio of radium-226 to radium-228 is assumed to be 3. The fraction of radon emanated from sludges typically is about 22%.[2] They typically have a granular consistency dominated by a bulk composition of silicates or carbonates. Bulk dry densities in equipment or disposed deposits are typically about 1.6 g/cm^3, and porosities are about 0.39.[2] Radium in sludges has a distribution coefficient for the solid/aqueous phases of 2,500 cm^3/g and lead has a distribution coefficient of 5,100 to 20,000 cm^3/g.[2,16] The distribution coefficient helps define the leach characteristics for groundwater exposure pathways.

2.2 SCALES

Scales accumulated in tubing, separators, and other equipment contain a broader range of radium-226 and radium-228 concentrations, ranging from background levels to several thousand pCi/g. Again, radium-226 concentrations usually are greatest, but both of the radium chains are expressed together as total radium. Scales exhibit a lower radon emanation fraction of about 5%.[2] They occur in very hard, monolithic precipitates in equipment with a bulk dry density between 2 and 3 g/cm^3. Upon removal and disposal, however, they have a nominal bulk dry density of about 1.6 g/cm^3 due to the porosity of about 0.45 between the broken pieces of scale. Radium in scales has a distribution coefficient for the solid/aqueous phases of 250,000 cm^3/g, which defines its leach characteristics for groundwater exposure pathways.

2.3 PRODUCTION EQUIPMENT

Residual NORM remaining in production equipment after cleaning usually occurs in scales, since these attach tightly to equipment surfaces and are insoluble. Typical scale thicknesses vary from less than 0.1 inch in production tubing to one inch or more in some water lines. Total radium concentrations and radon emanation fractions correspond to those for scales. Densities of disposed equipment vary due to equipment geometry, but porosities typically are large and densities of the NORM waste are small, due to dilution by the equipment mass. The volume of scales remaining in equipment if no mechanical cleaning is done ranges from about 1 percent to 77 percent, with an average of about 6.7 percent of the total equipment volume. Leaching characteristics are similar to those for scale.

2.4 GAS-PLANT EQUIPMENT

Thin deposits of lead-210 deposited from radon daughters on the inside surfaces of gas-plant equipment differ from those of other NORM accumulations in having negligible mass, being invisible, and containing only the last three nuclides of the uranium decay chain (Figure 1-1). Activity concentrations are expressed in units of radioactivity per unit area of equipment, since the deposit mass is not measurable or of interest. Occurrences range from background levels to several hundred thousand disintegrations per minute in a 100 square centimeter area (dpm/100 cm^2). No gaseous radon effluents are associated with these deposits. Leaching characteristics are dominated by the leachability of lead and polonium. Since they occur only in gas-plant equipment, they are usually associated with large equipment masses upon disposal. When removed from equipment surfaces by abrasive cleaning, a metal surface layer approximately 0.004 inches (0.01 cm) thick is assumed to be removed and is part of the NORM waste material for disposal.

3. WASTE DISPOSAL ALTERNATIVES

A broad range of waste disposal alternatives was analyzed to characterize safety precautions ranging from simple to extensive, and to provide potential flexibility in disposal decisions. Separate disposal alternatives were considered for solid residues and for equipment. The technical nature of each disposal alternative defined in this chapter provides a basis for radiation exposure analyses by providing the detailed scenario under which the disposal would occur. The scenarios include typical disposal depths, dimensions, and other characteristics needed to subsequently estimate radiation exposures via different pathways. As the disposal alternatives provide increasing isolation of the NORM, they allow higher concentrations of radium and lead-210 to be disposed. This is illustrated in Figure 3-1.

3.1 DISPOSAL OF SOLID RESIDUES

Disposal of solid sludges and scales removed from petroleum production equipment was considered by each of twelve different alternatives. Many of these apply only to sludges and scales that have been removed from equipment, including landspreading, landspreading with dilution, injection into inactive wells, hydraulic fracturing into unused formations, and injection into salt domes. Others also accommodate sludges and scales remaining in equipment as well as those that have been removed. These include burial at unrestricted sites, disposal at commercial oil-field waste sites, disposal at licensed NORM disposal sites, disposal at licensed low-level radioactive waste sites, and burial in surface mines. Two of the alternatives apply only to residues remaining in equipment. These are placement into wells being plugged and abandoned and non-retrieval of surface pipe.

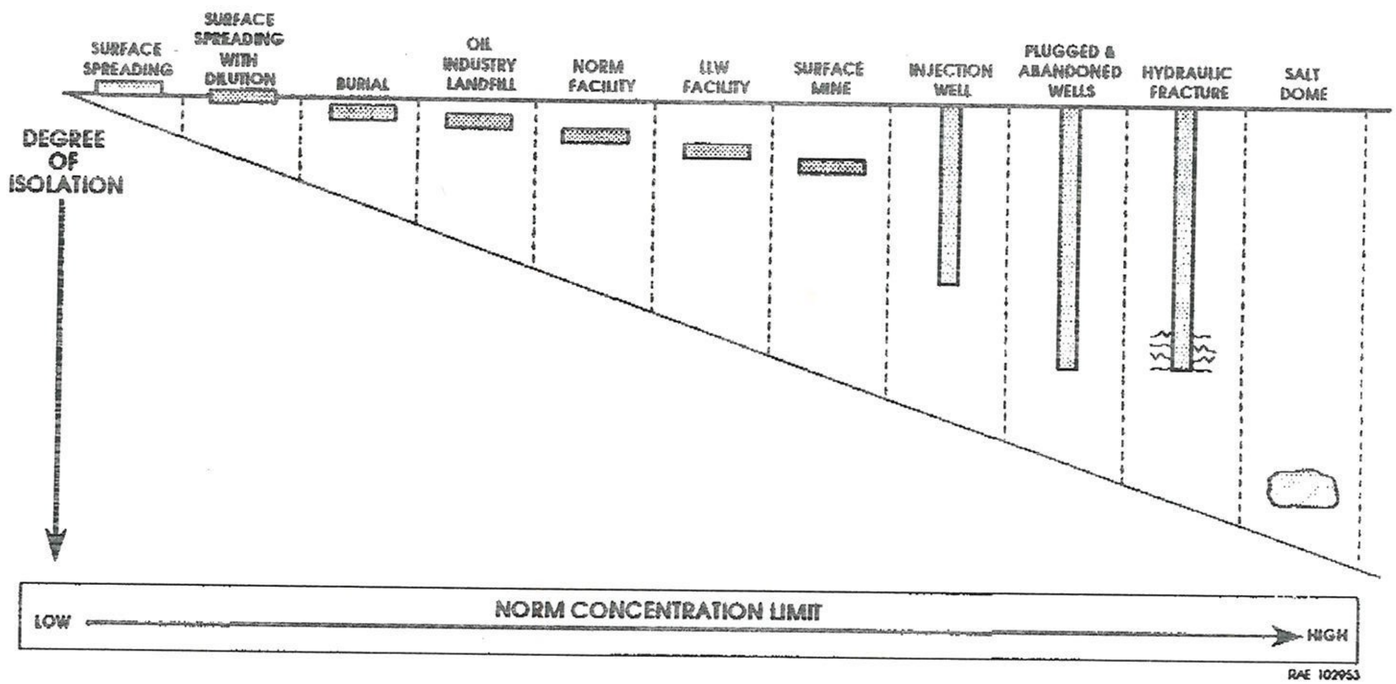

FIGURE 3-1. COMPARISON OF ISOLATION PROVIDED BY NORM DISPOSAL ALTERNATIVES.

3.1.1 Landspreading

Disposal by landspreading involves minimal precautions, and simply consists of spreading sludges and scales on the surface of open lands in a prescribed area. A minimum thickness of one-quarter inch (0.6 cm) is assumed to be the smallest practical layer thickness that can be applied, and applications of layers up to eight inches (20 cm) are considered. The area covered may become arbitrarily large for disposal of a given quantity of material. Analyses of landspreading are based on incremental increases of radium concentrations above background levels, and thus are restricted to one-time disposal in a given area. This suggests record-keeping to avoid repeated spreading in a given area, and possible radiation surveys to characterize pre- and post-spreading radiation levels. Subsequent uses of the affected land are not restricted, permitting home construction, agricultural food production, or any other land uses.

3.1.2 Landspreading With Dilution

Landspreading with dilution includes mixing of the applied wastes thoroughly within the top eight-inch (20 cm) layer of soil. Since the mixing would utilize agricultural equipment of fixed tillage depth, the mixing is defined to extend to eight inches of waste plus soil. Thus maximum dilution would involve 1 inch of waste plus 7 inches of soil, and a maximum deposition may involve 7 inches of waste and 1 inch of soil, or in the equivalent to surface spreading, 8 inches of waste. The area covered may be arbitrarily large. Analyses of landspreading with dilution also are based on incremental increases of radium concentrations above background levels, and thus are restricted to one-time disposal in a given area. This again suggests record-keeping to avoid repeated use of a given area, and possible radiation surveys to characterize pre- and post-application radiation levels. Subsequent uses of the affected land are not restricted, permitting home construction, agricultural food production, or any other land uses.

3.1.3 Non-Retrieval of Surface Pipe

Surface pipe containing scales and sludges may be buried at shallow depths. Upon retirement from active service, the pipes may be cleaned of petroleum products but left in place for disposal. If left unretrieved, later land uses could involve home construction over the pipe, with possible perforation to expose its contents to a crawl-space or basement area. Since surface pipes may be made from mineral fiber, perforation or cutting during construction may go unnoticed. The open pipe may extend for several hundred feet from the structure, and may permit air flow from other perforations through the pipe and into the structure. A pipe of 3-inches (7.6 cm) inside diameter is considered to represent the surface pipe for this disposal alternative. Scale deposits in the pipe are assumed to be 2-1/2-inch (1.3 cm) thick, and to have a density of 3 g/cm^3. The house was assumed to be at a negative pressure of 6 Pa relative to the atmosphere.

3.1.4 Burial with Unrestricted Site Use

Burial with unrestricted site use may occupy any available land area, and have a range of possible burial depths and waste thicknesses. The depth of burial is defined as the thickness of earthen cover placed over the waste after burial. The completed burial site has its cover level with the surrounding terrain, minimizing erosion potential. Due to the visual similarity of many sludges and scales to natural earthen materials, it is assumed that inadvertent intrusion could occur at the burial site in the absence of permanent institutional controls. An 8-foot depth corresponds to an inadvertent intrusion limit that ordinarily is not exceeded by common activities such as excavations for public utilities, house foundations, graves, etc. Subsequent land use for the burial site includes construction of a house with a basement over the waste, intersecting the waste layer if it is located within the top 6 feet. For regions in which homes can have basements, the top 6 feet of cover may not be considered in determining NORM concentration limits.

3.1.5 Disposal at a Commercial Oil Field Waste Site

Disposal at a commercial oil field waste site involves burial with other wastes that may not contain NORM, but would serve to dilute the solid NORM wastes. Since NORM wastes are about 7 percent of total oil industry wastes, it is assumed that dilution by a factor of fifteen occurs, and that waste deposits exceed a thickness of 10 feet (305 cm). The completed waste site has an earthen cover that is level with surrounding terrain to minimize erosion. For estimating exposures from transporting wastes to the disposal site, a distance of 100 miles is assumed.

3.1.6 Disposal at a Licensed NORM Waste Disposal Site

The NORM waste disposal site is defined by the EPA regulations for disposal of uranium and thorium mill tailings and related byproduct materials.[4] It is designed to be effective for 1000 years to the extent reasonably achievable, or in any event, for at least 200 years. It is designed to limit radon fluxes to the atmosphere to 20 pCi/m^2/s, averaged over the disposal area and over any one-year period. The impoundment usually is designed with an earthen cover for radon control and suitable liners and siting criteria to protect local groundwater from contaminant leaching and migration. After closure, the site is deeded to the state for permanent monitoring and restricted future use. No intrusive activities or construction of occupiable structures on the site are permitted. For estimating exposures from transporting wastes to the disposal site, a distance of 300 miles is assumed.

3.1.7 Disposal at a Licensed Low-Level Radioactive Waste Disposal Site

The low-level radioactive waste (LLW) disposal site is defined and licensed under Nuclear Regulatory Commission regulations[3] with numerous protective features and restrictions that ultimately restrict the feasible locations and numbers of such facilities. Presently there are only three LLW facilities in the United States (Hanford, WA; Beatty, NV; and Barnwell, SC), although others are being considered by some states and interstate compacts. Due to the limited number of LLW sites, transportation of wastes to the site also must be considered. A haul distance of 900 miles is assumed. Future site uses are restricted from intrusion, and site features are sufficient to warn the inadvertent intruder of the presence of anomalous materials even without institutional control.

3.1.8 Burial in Surface Mines

Burial of NORM sludges and scales in surface mines involves placement at the bottom of mine excavations and subsequent burial by accumulated earthen overburden. Typical burial depths are 50 feet (15 m) or greater, and areas are sufficient to accommodate relatively large volumes of wastes. Because of the significant burial depths, the potential for erosion or intrusion into the wastes is remote. No land use restrictions are applied related to the NORM content of the wastes.

3.1.9 Plugged and Abandoned Wells

Well tubing with accumulated scale may be left in place or placed in a well being plugged and abandoned. Scales in the tubing remain nearly completely inaccessible from surface intrusion. Reclamation of the well site includes sealing several feet of the well with concrete grout or other suitable material, precluding significant access to materials at greater depths or surrounding formations. The well is capped, preventing inadvertent intrusion into the well.

3.1.10 Well Injection

Well injection consists of injecting slurries of the sludges or scales into a deep permeable formation below underground sources of drinking water (USDW) with no fresh water or mineral value. The formation is confined by impermeable layers that are likely to remain intact. Therefore formations selected for injection are limited to areas and horizons in which deeper formations also have little or no economic value. The injection is consistent with EPA standards for underground injection controls for Class II wells.[17] During operations and at closure, the injection facility is monitored for leakage, and at closure, cement and clay are used to seal the top region of the well. The well is cut below the ground surface and capped, preventing inadvertent intrusion into the injection well.

3.1.11 Hydraulic Fracturing

Hydraulic fracturing consists of adding sludges and pulverized scales to a carrier fluid (typically brine) and pumping the mixture into a well at sufficiently high pressure to create a fracture in a permeable formation below all USDWs. The fracture formed by this process is normally vertical, confined above and below by impermeable shale formations, 0.5 m thick, and extends several hundred feet from the well. After the scale/water mixture is displaced into the fracture, pressure is reduced and the fracture closes. The scale is trapped between the fracture walls and is incapable of re-entering the well bore. A well used for this purpose can be fractured multiple times. When the well is no longer required for this or any other purpose, it is plugged with cement to prevent migration of fluids in the well bore. Hydraulic fracturing has been used to dispose of intermediate level ($3x10^8$ pCi/g) radioactive wastes.[18]

3.1.12 Injection into Salt Domes

Salt dome cavities have been used to store petroleum products, and have been proposed for disposal of intermediate and high level radioactive wastes due to their inherent isolation of the wastes from groundwater and from the surrounding environment. The salt provides impermeable containment of the wastes at depths of hundreds to thousands of feet. The salt formation tends to self-anneal any containment defects that may occur, further assuring containment of the wastes. Sludges, scales, and equipment containing NORM can be placed in the salt domes. No site restrictions are applied.

3.2 ALTERNATIVES FOR EQUIPMENT CONTAINING NORM

Alternatives for disposal or use of equipment containing NORM residues include release for general use, release for re-use within the petroleum industry, storage in an oil-field equipment yard, release for smelting, and burial with NORM scales and sludges. Selection among these alternatives depends in part on the quantity of NORM remaining in the equipment. For example, release for unrestricted use requires that any residual NORM is at very low levels, while burial with NORM scales and sludges permits potentially higher concentrations of NORM residues.

3.2.1 Release for General Use

General use of petroleum equipment could occur under a variety of conditions. A conservative but plausible scenario for exposure to NORM remaining in former petroleum equipment is that of residential use of the equipment. It is assumed that a piece of larger pipe or other equipment containing scale is used inside the house for structural support of a floor, ceiling, etc. Residents in the house are assumed to spend 2.2 hours per day within one meter of the structural pipe or equipment containing NORM. Thus, they are exposed 800 hours/year to gamma emissions from the indoor NORM as well as continually to the radon gas generated.

3.2.2 Release for Re-Use Within the Petroleum Industry

Simple release of equipment containing NORM for re-use within the petroleum industry constitutes a null action, since continued use constitutes non-disposal and since the equipment eventually will be either cleaned or disposed appropriately by the new owners. Therefore, the buyer should be informed of the presence of NORM in the equipment.

3.2.3 Storage in an Oil-Field Equipment Yard

Oil-field equipment removed from service frequently is stored in oil-field equipment yards. This may be for cleaning, refurbishing, transfer to other fields, sale to other companies or for other uses, or disposal. As a result of this storage and the associated handling of equipment, both equipment yard employees and offsite residents potentially are exposed to gamma emissions and respirable dusts from NORM in the equipment. The equipment may be capped to contain any sludges and scales, or may be left open. Yard workers spend about 500 hours per year near or working on the equipment. Adjacent residents also are exposed to gamma radiation and dusts from the yard.

3.2.4 Release to a Smelter

Although some smelting operations may produce steel for new oil-field equipment from old equipment that contains NORM, other operations may produce consumer products in which residual NORM is more significant. When separated by smelting, residual NORM mainly accumulates in the slag. The smelting alternative is defined to produce water pipes and frying pans for public use, potentiating the gamma and ingestion exposure pathways. This use of iron containing radioactive materials is specified by the NRC in the IMPACTS-BRC methodology.[19] The smelting process produces airborne dust that is respirable by both onsite workers and offsite residents. Slag from the smelting process is within gamma exposure proximity to workers and also produces respirable dust.

3.2.5 Burial with NORM Sludges and Scales

Equipment containing residual NORM scales may be buried under any of several disposal alternatives with sludges and scales that contain NORM. When the NORM is still deposited in equipment, however, the waste properties differ from those of the separated sludges and scales. Equipment that could be buried with NORM wastes was categorized and estimated to result in a disposed bulk density of 4 g/cm^3, with a porosity of 0.5. Production equipment included in this estimate included flow lines, manifolds, meters, pumps, separators, stock tanks, vapor recovery units, injection wells and pumps, production wells, tubing, heater treaters, sump equipment, water lines and storage tanks. Gas-plant equipment was estimated to have similar bulk disposal densities and porosities. The dilution of scale by the metal equipment mass was estimated to amount to a factor of 15.

4. RADIATION EXPOSURE LIMITS AND PATHWAYS

Human radiation exposures from disposed NORM wastes can occur via each of several different pathways for nearly all of the waste disposal alternatives. For example, NORM used in building materials can directly expose occupants to gamma radiation, and also can generate radon gas, which diffuses throughout indoor air and causes alpha radiation exposure to the lungs. The magnitude of radiation exposure is proportional to the amount of NORM causing it, and conceptually can be permitted to reach prescribed exposure limits without posing undue health risks. This chapter presents the allowable radiation exposure limits based on criteria developed for corresponding radiation from other types of wastes, and characterizes each of seven different exposure pathways by which the radiation exposures may occur. These limits and pathways provide the basis for computing the maximum NORM concentrations for each exposure pathway in each disposal alternative. The limiting pathway, which yields the lowest maximum NORM concentration, then can be chosen to define the NORM concentration limits for each disposal alternative. The calculations of radiation exposures via each pathway utilize several different computer codes, which also are identified in this chapter.

The geohydrological setting of the NORM disposal site affects the importance of particular radiation exposure pathways in addition to the characteristics of the NORM and the nature of the disposal alternative. Three geohydrological settings were considered in the risk assessments. These settings are:

- Humid site with permeable soil
- Humid site with impermeable soil
- Arid site with permeable soil

These settings are the same that the U.S. Environmental Protection Agency (EPA) has used previously in assessing the effects of radioactive waste disposal in the United States.[20] An initial risk assessment revealed that the risks in a humid impermeable setting are always intermediate between the risks of the other two settings. Consequently, the final risk assessments were performed only for the humid permeable and arid permeable geohydrological settings. The key pathway parameters that depend on the geohydrological settings are the radon diffusion coefficient, the water infiltration rate, the nuclide travel times in groundwater, the surface soil erosion rate, and the surface river flow rate. Values used for these parameters are given in Table 4-1. The environmental data are from Reference 16, except for the radon diffusion coefficients and nuclide travel times in the arid region. River flow rates were reduced from Reference 16 values.

4.1 RADIATION EXPOSURE LIMITS

Radiation exposure limits provide the basis on which maximum NORM disposal limits are defined. The radiation concentration and exposure limits used in this study (Table 4-2) are based on relevant and generally applicable guidelines and criteria developed for other waste types. For example, the radon inhalation limit is an indoor radon concentration of 2 pCi/l. This value is based on the EPA recommendation that homes exceeding 4 pCi/l should consider remediation.[21] Since there are natural sources of radon other than NORM waste, and since the average indoor radon concentration in the US approaches 2 pCi/l,[22] the criterion for radon from the disposed NORM is the difference between 4 pCi/l and 2 pCi/l, i.e. 2 pCi/l. This concentration is consistent with a surface radon flux of 2 pCi/m^2 sec entering a dwelling from underlying soil.

For doses to the general public from exposures to contaminated drinking water, the concentration limit is 5 pCi/l of radium, consistent with EPA's interim drinking water standards.[23] For doses to the general public from all other pathways, the safety limit is 25 mrem/yr, consistent with the EPA nuclear fuel cycle standard.[24] The safety limit for inadvertent intruders is 100 mrem/yr, because of the lower probability that the intrusion event would occur. An intruder is an individual who spends a significant amount of time at the NORM disposal site without being aware of the disposed NORM.

TABLE 4-1

PATHWAY PARAMETERS THAT DEPEND ON GEOHYDROLOGICAL CONDITIONS

Parameter	Humid Site Value	Arid Site Value
Radon Gas Diffusion Coefficient (top 2 feet)	0.0091 cm^2/sec	0.036 cm^2/sec
Radon Gas Diffusion Coefficient (greater than 2-ft depth)	0.005 cm^2/sec	0.020 cm^2/sec
Water Infiltration Rate	0.45 m/yr	0.035 m/yr
Radium Transit Time in Groundwater	9,000 yr	22,000 yr
Lead (Pb) Transit Time in Groundwater	3,500 yr	9,000 yr
Soil Erosion Rate	0.2 mm/yr	0.045 mm/yr
River Flow Rate	1.0×10^5 m^3/yr	1×10^6 m^3/yr

TABLE 4-2

RADIATION CONCENTRATION AND EXPOSURE LIMITS

Exposure Pathway	Limit	Reference for Relevant Limit
Indoor Radon Inhalation	2 pCi/liter	21
Radon Flux Into a Dwelling	2 pCi/m^2/sec	21
Groundwater Ingestion (^{226}Ra + ^{228}Ra)	5 pCi/l	23
General Public Exposure, All Other Pathways	25 mrem/yr	24
Inadvertent Intruders, All Other Pathways	100 mrem/yr	25

4.2 RADON INHALATION PATHWAY

The radon gas inhalation pathway (Figure 4-1) involves radon escaping the NORM and migrating to air that is inhaled by an inadvertent intruder or by occupants in a house built over the NORM. It also includes inhalation of radon escaping from NORM contained in a piece of equipment located inside the home. The radon generation and migration is calculated with the RAETRAN code.[26] An emanation coefficient used by the code defines the fraction of radon generated that is free to migrate as a gas. Typical values of 0.05 and 0.22 were used to represent scales and sludges, respectively.[2] A diffusion coefficient characterizes the ability of radon to migrate through the NORM and surrounding soils. Radon diffusion coefficients are given in Table 4-1. RAETRAN solves the diffusive - advective differential equation for radon migration. It is similar to the code used by the NRC for uranium mill tailings impoundments.[27]

4.3 EXTERNAL GAMMA EXPOSURES

External gamma doses are calculated using the standard EPA methodology contained in the PATHRAE-EPA code[28] for simple geometric configurations, such as shown in Figure 4-2. External gamma doses for more complex configurations are calculated with the MICROSHIELD code.[29] Cover soils attenuate the gamma radiation by about a factor of ten for every foot of cover. PATHRAE uses gamma dose conversion factors in its analysis. The gamma dose conversion factor for each nuclide gives the annual dose from a large planar source of unit activity (1 pCi/m^2). The dose factors for ingestion, inhalation and external gamma exposures are given in Table 4-3. Gamma-ray attenuation factors for soil also are given in Table 4-3. External gamma exposures to the truck driver transporting the NORM to disposal sites were calculated with the NRC's IMPACTS-BRC code.[19]

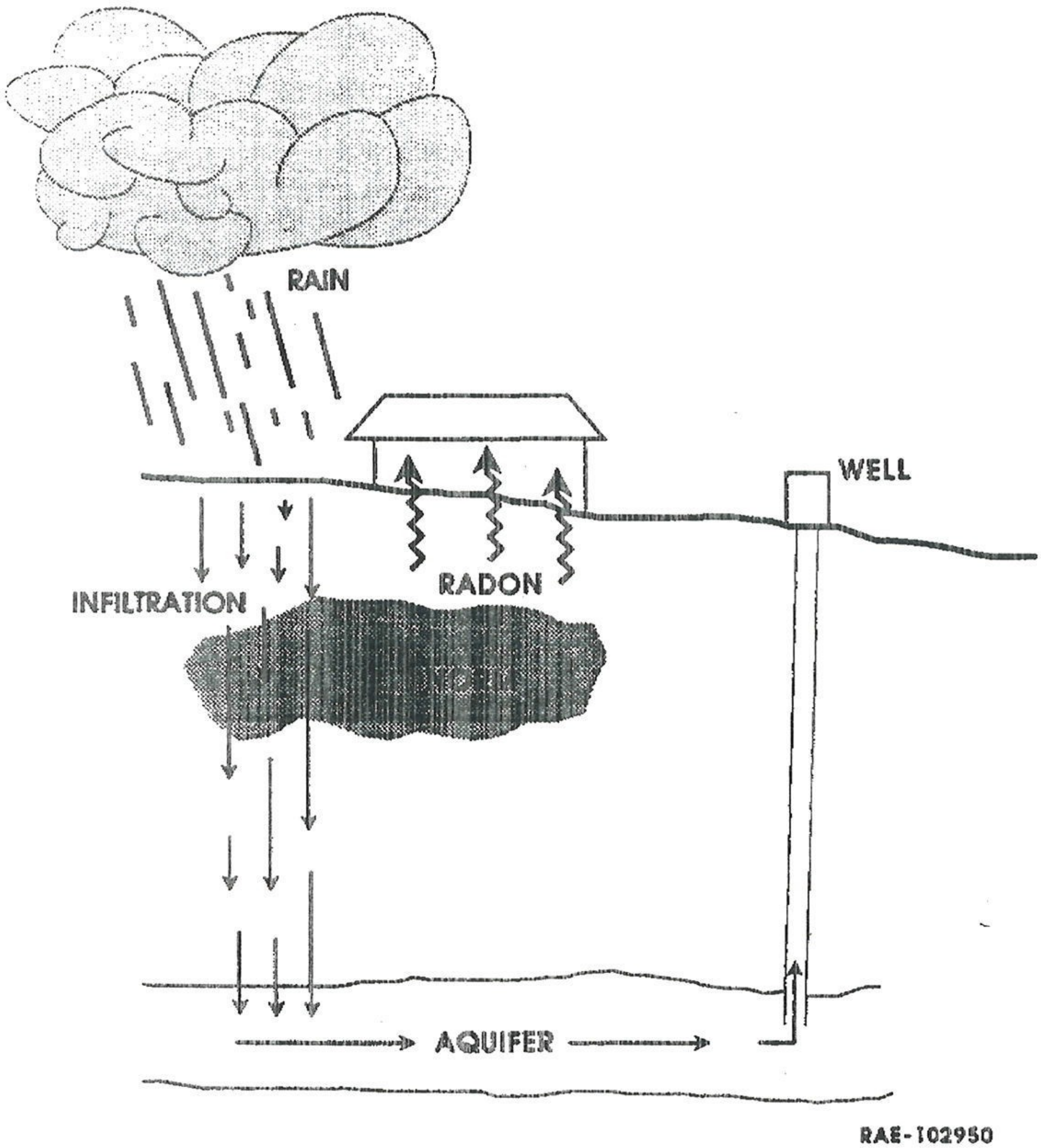

FIGURE 4-1. ILLUSTRATION OF RADON AND GROUNDWATER EXPOSURE PATHWAYS.

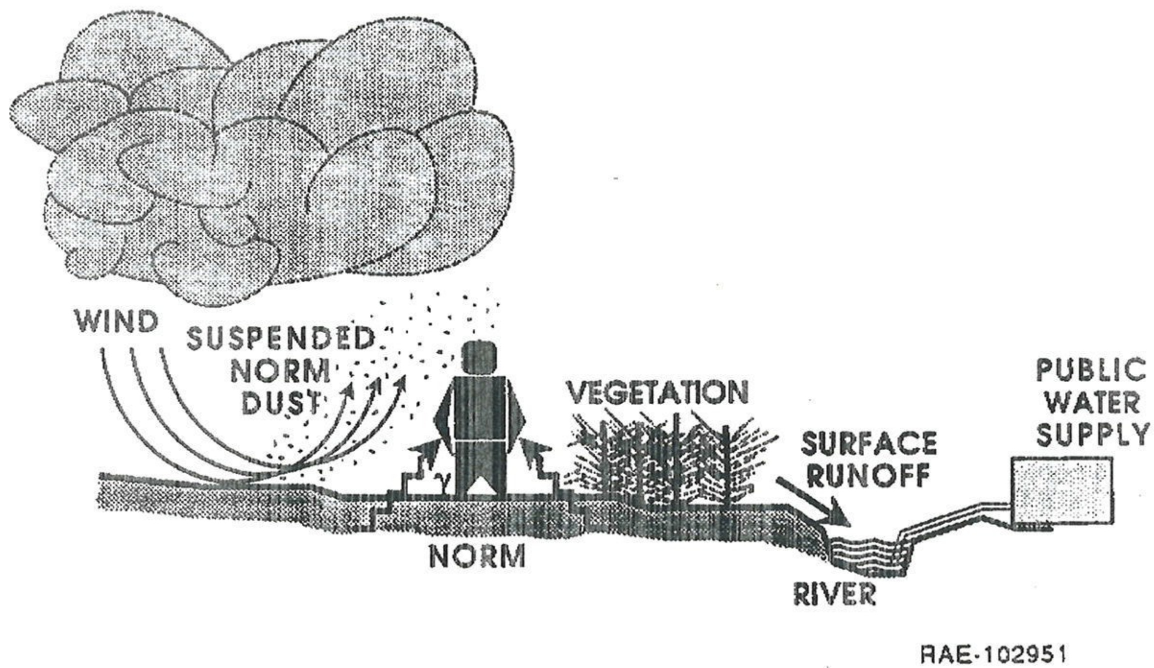

FIGURE 4-2. ILLUSTRATION OF EXTERNAL GAMMA, DUST INHALATION, SURFACE WATER, AND FOOD CONSUMPTION PATHWAYS.

TABLE 4-3

NUCLIDE DOSE FACTORS
(Reference 16)

Nuclide	Ingestion Dose Factors (mrem/pCi)	Inhalation Dose Factors (mrem/pCi)	Direct Gamma Dose Factors (mrem/yr per pCi/m^2)	Gamma Attenuation Coefficient (m^{-1})
Ra-226	1.1E-03	7.9E-03	4.8E-11	2.1E+01
Rn-222	0.0E+00	0.0E+00	2.5E-12	1.4E+01
Pb-214	5.8E-07	6.7E-06	1.7E-09	1.4E+01
Bi-214	2.4E-07	6.3E-06	8.8E-09	9.2E+00
Po-214	0.0E+00	0.0E+00	5.3E-13	1.1E+01
Pb-210	5.1E-03	1.3E-02	1.9E-11	5.0E+01
Bi-210	5.9E-06	1.9E-04	0.0E+00	0.0E+00
Po-210	1.6E-03	8.1E-03	5.4E-14	1.1E+01
Ra-228	1.2E-03	4.2E-03	4.2E-18	5.0E+01
Ac-228	2.1E-06	2.9E-04	5.5E-09	1.0E+01
Th-228	3.8E-04	3.1E-01	1.8E-11	2.2E+01
Ra-224	3.3E-04	2.9E-03	7.1E-11	1.9E+01
Rn-220	0.0E+00	0.0E+00	3.3E-12	1.3E+01
Po-216	0.0E+00	0.0E+00	9.3E-14	0.0E+00
Pb-212	4.1E-05	1.6E-04	1.0E-09	1.9E+01
Bi-212	9.9E-07	2.1E-05	1.1E-09	1.1E+01
Tl-208	0.0E+00	0.0E+00	1.9E-08	8.3E+00

4.4 GROUNDWATER PATHWAY

The groundwater pathway, shown in Figure 4-1, involves infiltrating precipitation that comes in contact with the NORM and leaches a small portion of it. The infiltrating water then continues downward where it enters an aquifer and is eventually carried to a well, where it is withdrawn and ingested. For the burial disposal options, the aquifer and well uptake are assumed to dilute the NORM concentrations by a factor of four.

The NORM leach rates depend on the matrix of the waste and the infiltration rate. The leach rate for scale is estimated using the solubility limit for $BaSO_4$:

$$\lambda_L(\text{scale}) = \frac{(BaSO_4 \text{ mass dissolved in one year's infiltrating water})}{\text{Mass of } BaSO_4 \text{ scale in facility}}$$

$$\lambda_L(\text{scale}) = \frac{(\text{Sol})I}{d\,X_t} \qquad (4\text{-}1)$$

where

$\lambda_L(\text{scale})$	=	Leach rate (yr^{-1})
I	=	Infiltration rate (m/yr)
Sol	=	$BaSO_4$ solubility limit (2×10^{-6} g/cm^3 water)
d	=	Scale density (2 g/cm^3)
X_t	=	Waste thickness (100 cm)

Substituting the values into Equation 4-1 and multiplying by ten for conservatism yields:

$$\lambda_L(\text{scale}) = 1 \times 10^{-5}\, I \qquad (4\text{-}2a)$$

The λ_L for sludge is assumed to be a factor of 100 higher than for scale.[16] This is consistent with the PATHRAE-EPA data base for radium.[28]

$$\lambda_L(\text{sludge}) = 1 \times 10^{-3}\, I \qquad (4\text{-}2b)$$

4.5 SURFACE WATER PATHWAY

The surface water pathway in PATHRAE-EPA involves erosion by precipitation runoff of a portion of surface soil containing NORM. As shown in Figure 4-2, the runoff drains to a river that is subsequently used. In the arid region, wind erosion to an adjacent farm is also examined.

4.6 NORM DUST INHALATION

The inhalation pathway for workers and reclaimers working around NORM wastes or equipment containing NORM assumes a prescribed dust loading in the air they breathe and a given number of hours of exposure to the dust. The dust loadings and exposure times for different individuals are presented in Table 4-4. For offsite atmospheric transport of the NORM dust, the resident at the boundary of the NORM storage yard is assumed to be downwind ten percent of the time. A concentration/source ratio (C/Q) of 1.2×10^{-5} sec/m^3 was computed for the smelter.

4.7 FOOD PATHWAY

The food pathway used in this study refers to the consumption of food grown in soil that contains NORM. The pathway involves dissolution of the nuclides and uptake by the roots of the vegetation. The ingestion pathway differs from the water pathways for vegetative uptake of NORM by not including long migration distances between the NORM deposit and the receptor vegetation or consumer. The EPA soil-to-plant transfer factor for NORM nuclides (3.1×10^{-4} pCi/kg vegetation per pCi/kg soil) is used in these analyses.[16] This pathway is also calculated with PATHRAE-EPA.

TABLE 4-4

INHALED DUST CONCENTRATIONS AND EXPOSURE TIMES

Exposed Individual	Dust Loading (mg/m^3)	Exposure (hours/year)
Smelter Worker	0.5[a]	900
Reclaimer-Resident	0.06	3000
Reclaimer Constructor	0.5[a]	500
NORM yard worker	0.1[a]	500
Resident at Boundary of NORM yard	0.06	900

a. Eight-hour time-weighted average for occupational workers.

4.8 SKIN DOSE FROM NORM PARTICLES

Small particles of the NORM may settle on the skin of a worker or other individual. The beta radiation from the particle then gives a radiation dose to the skin. The magnitude of the dose depends on the total activity in the particle and on the amount of time it is in contact with the skin. It is assumed the particle remains on the skin for 100 hours. This is a conservatively longer time than experimental studies have shown.[30] The skin dose is calculated with the VARSKIN code, developed under NRC sponsorship.[31]

5. NORM CONCENTRATION LIMITS FOR DISPOSAL

Radiation exposures were calculated for each pathway described in Chapter 4 applied to all NORM disposal and equipment disposition alternatives described in Chapter 3. The exposures were calculated for the waste types described in Chapter 2, and considered disposal at both arid and humid sites. The resulting maximum radium concentrations that correspond to radiation exposure limits are given in the Appendix for all disposal alternatives, NORM waste types, pathways and geohydrologic settings. The maximum NORM concentration for each waste disposal or equipment disposition alternative then was chosen from the limiting pathway (pathway with lowest maximum NORM concentration) for each alternative and waste type. These NORM limits are presented in Tables 5-1 and 5-2 for the humid and arid sites, respectively. The NORM disposal limits are presented in terms of maximum concentrations of radium-226, since this is the dominant isotope controlling all limiting radiation exposures.

The radium concentration limits range from 29 pCi/g for burial in an arid permeable region to more than 100,000 pCi/g for plugged and abandoned wells, well injection, hydraulic fracturing and salt dome disposal in any region. The radium concentration limits generally resulted from the radon, gamma or groundwater exposure pathways. The radon and gamma pathways dominate for disposal alternatives with less than 6.6 feet (2 m) of cover below the intrusion zone, and the groundwater pathway dominates for alternatives with more than 6.6 feet of cover.

Disposal limits resulting from surface NORM deposits in gas-plant equipment are summarized separately in Table 5-3 in terms of maximum lead-210 concentrations. The surface lead-210 activity dominates exposures to gas-plant equipment because lead-210 is the first long-lived radon daughter, accumulating from decay of radon gas that was dissolved in processing streams.

TABLE 5-1

RADIUM SOURCE CONCENTRATION LIMITS FOR DISPOSAL AT A HUMID PERMEABLE SITE (pCi/g)

Disposal Alternative		Sludge	Scale	Equipment and Scale
1.	Landspreading[a] (see Figure 5-1)	120	120	NA[b]
2.	Landspreading With Dilution[a,c] (see Figure 5-2)	260	260	NA
3.	Non-retrieved Surface Pipe	5,500	13,300	NA
4.	Burial With Unrestricted Site Use[d] (see Figure 5-3)	350	2,000	29,000
5.	Commercial Oil Industry Waste Facility[d] (see Figure 5-4)	5,000	28,000	100,000[e]
6.	NORM Disposal Facility	3,500	20,000	100,000
7.	Commercial LLW Disposal Facility	50,000	50,000	100,000
8.	Surface Mine	3,500	100,000	100,000
9.	Plugged and Abandoned Well	100,000	100,000	100,000
10.	Well Injection	100,000	100,000	NA
11.	Hydraulic Fracturing	100,000	100,000	NA
12.	Salt Dome Disposal	100,000	100,000	100,000

a. Four barrels per 100 m^2 (33 ft x 33 ft) giving a 0.25 inch (0.63 cm) average layer thickness.
b. NA = Not Applicable.
c. Diluted by mixing in the top 8-inch (20-cm) soil layer.
d. For 6.6 feet (2 m) of depth beneath the intrusion zone.
e. If the limit is greater than 100,000 pCi/g, it is reported as 100,000 pCi/g.

TABLE 5-2

RADIUM SOURCE CONCENTRATION LIMITS
FOR DISPOSAL AT AN ARID PERMEABLE SITE (pCi/g)

Disposal Alternative		Sludge	Scale	Equipment and Scale
1.	Landspreading[a] (see Figure 5-1)	120	120	NA[b]
2.	Landspreading With Dilution[a,c] (see Figure 5-2)	260	260	NA
3.	Non-retrieved Surface Pipe	2,700	6,700	NA
4.	Burial With Unrestricted Site Use[d] (see Figure 5-3)	29	130	440
5.	Commercial Oil Industry Waste Facility[d] (see Figure 5-4)	410	1,800	6,200
6.	NORM Disposal Facility	1,000	4,500	68,000
7.	Commercial LLW Disposal Facility	50,000	50,000	100,000[e]
8.	Surface Mine	100,000	100,000	100,000
9.	Plugged and Abandoned Well	100,000	100,000	100,000
10.	Well Injection	100,000	100,000	NA
11.	Hydraulic Fracturing	100,000	100,000	NA
12.	Salt Dome Disposal	100,000	100,000	100,000

a. Four barrels per 100 m^2 (33 ft x 33 ft) giving a 0.25 inch (0.63 cm) average layer thickness.
b. NA = Not Applicable.
c. Diluted by mixing in the top 8-inch (20-cm) soil layer.
d. For 6.6 feet (2 m) of depth beneath the intrusion zone.
e. If the limit is greater than 100,000 pCi/g, it is reported as 100,000 pCi/g.

TABLE 5-3

LEAD-210 SOURCE CONCENTRATION LIMITS FOR WASTE DISPOSAL[a]
(pCi/g)

Disposal Alternative	Humid Region	Arid Region
1. Landspreading	59,000	79,000
2. Landspreading With Dilution	32,000	42,000

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a. For all other disposal alternatives, there is no practical lead-210 concentration limit.

5.1 CONCENTRATION LIMITS FOR NORM DISPOSAL

Details of the NORM concentration limits and their variation with certain disposal practices give further insight into useful ways of implementing certain disposal alternatives. These are described in the following sections.

5.1.1 Limits for Landspreading

The radium concentration limits for landspreading of wastes are given in Tables 5-1 and 5-2 for a NORM thickness of 0.63 cm. The limit decreases with increasing NORM thickness as shown in Figure 5-1. The gamma pathway is most limiting for sludge and scale in either region.

5.1.2 Limits for Landspreading With Dilution

Concentration limits for landspreading with dilution depend on the amount of NORM waste that is mixed into a unit area of surface soil. The limits in Tables 5-1 to 5-3 are for a waste loading of 4 barrels per 100 m^2 of area. Figure 5-2 gives the radium concentration limits as a function of the waste loading. Once again the gamma pathway is limiting for all conditions. The lead-210 concentration limits vary in a similar manner. For Pb-210, the food pathway is most restrictive in a humid region and the surface water pathway dominates in the arid region, mainly due to the smaller flow rate in the river.

5.1.3 Limits for Non-Retrieved Surface Pipe

Surface pipe containing NORM scales, buried just below the ground surface, allows radon to enter a dwelling built where the pipe is. The radon pathway is limiting, although the pipe potentially can also contaminate groundwater. The radium concentration limit from groundwater is much less restrictive.

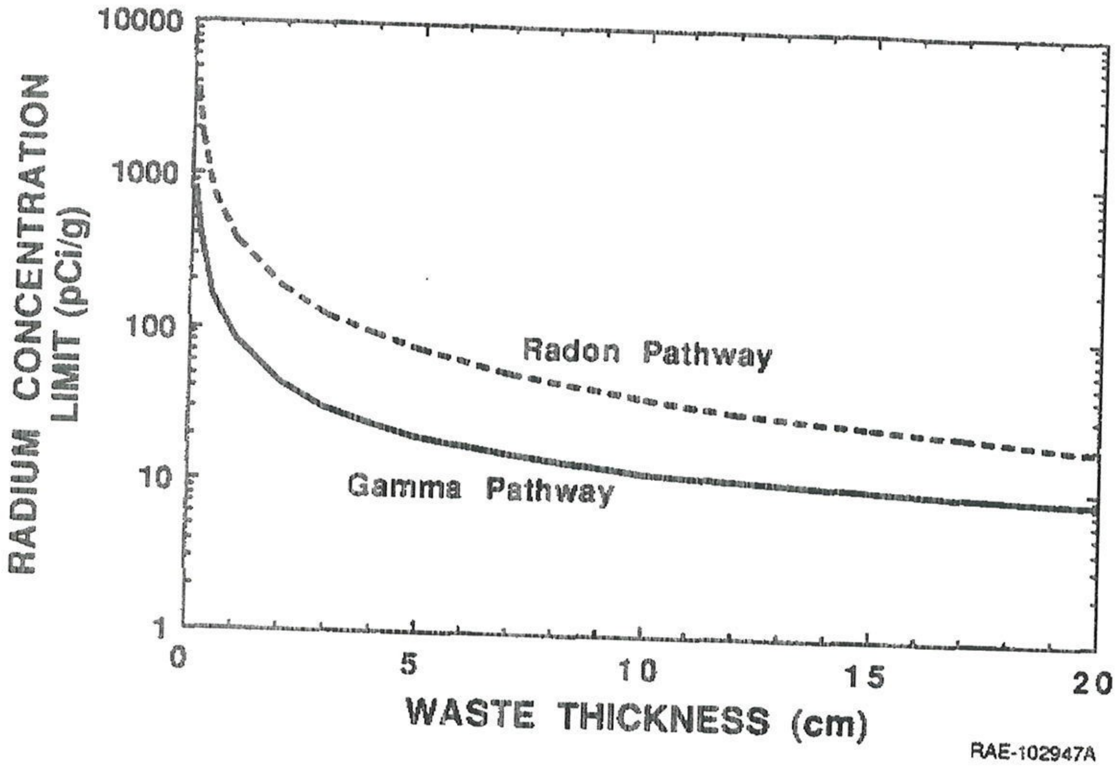

FIGURE 5-1. RADIUM CONCENTRATION LIMITS AS A FUNCTION OF WASTE THICKNESS FOR THE LANDSPREADING OPTION.

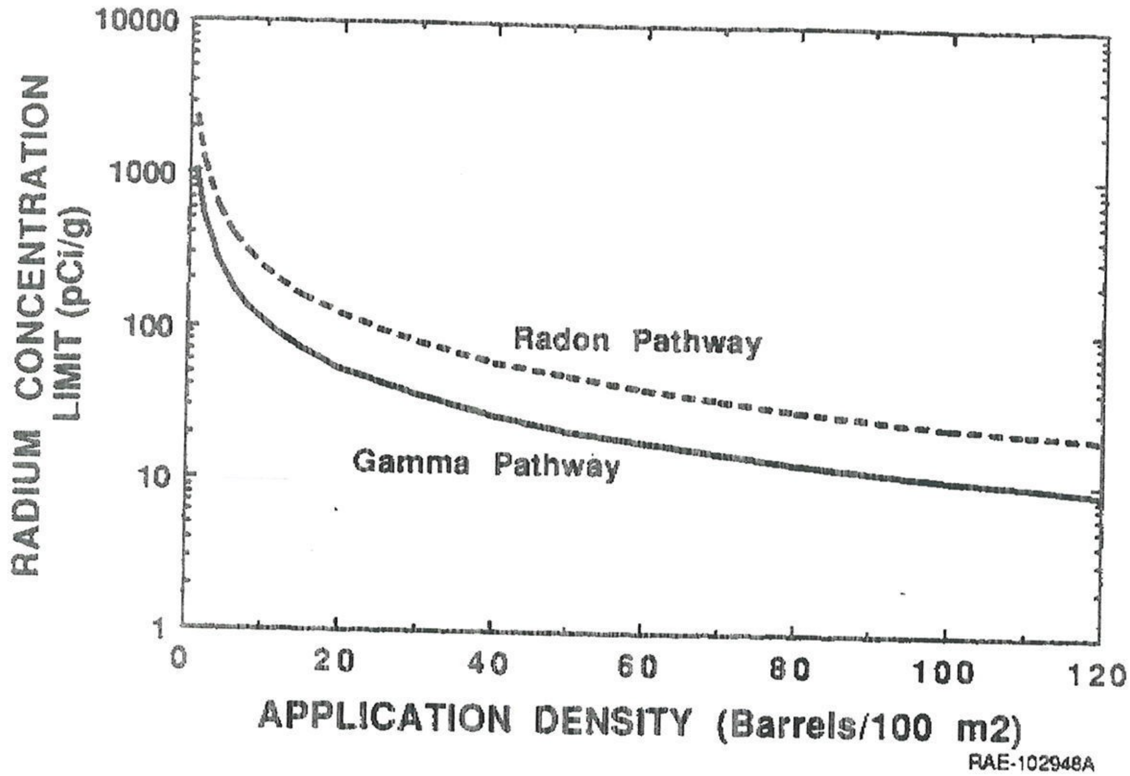

FIGURE 5-2. RADIUM CONCENTRATION LIMITS AS A FUNCTION OF APPLICATION DENSITY FOR THE LANDSPREADING WITH DILUTION OPTION.

5.1.4 Limits for Burial with Unrestricted Site Use

For the burial alternative, undiluted NORM wastes or equipment are placed in a pit and covered with earthen fill. Since it is assumed that at some future time the land will be occupied by inadvertent intruders, the amount of cover becomes an important parameter in determining the dominant pathways and radium concentration limits. For the present analysis it is assumed that the top of the NORM wastes are at least 6.6 ft (2 m) below the inadvertent intrusion zone. At these depths the radon pathway limits except for sludge in a humid permeable region. Therefore, as shown in Figure 5-3, the limiting concentration increases significantly with the amount of cover below the intrusion zone until the concentration for the groundwater pathway is reached, in the humid region.

5.1.5 Limits for Burial in a Commercial Oil-Field Waste Site

Burial at a commercial oil-field waste site differs from the previous burial alternative in that other oil industry wastes are also discarded in the pit, resulting in a dilution of the average NORM concentrations in the pit. According to a preliminary survey, only about 7 percent of oil industry wastes contain NORM. The dilution by other wastes results in a factor of 14 increase in the safe NORM disposal concentration limits. Figure 5-4 shows the variation of these limits with the thickness of earthen cover.

5.1.6 Limits for Small Amounts of NORM

The alternatives considered in subsections 5.1.1 - 5.1.5 assume that the area of the disposed NORM is relatively large (at least 100 m^2). If the disposal area is less than 100 m^2, a higher radium concentration can be accommodated and still meet the radiation exposure limits. The factor by which the disposal concentration limits may be increased for small-area, small-quantity disposal is shown in Figure 5-5. This factor should be applied to the radon and external gamma exposure pathways to determine the limiting radium concentration. For example, a small quantity of sludge disposed by landspreading over a 1-m^2 area in a humid environment has a 120 pCi/g radium limit from the gamma pathway according to Tables 5-1

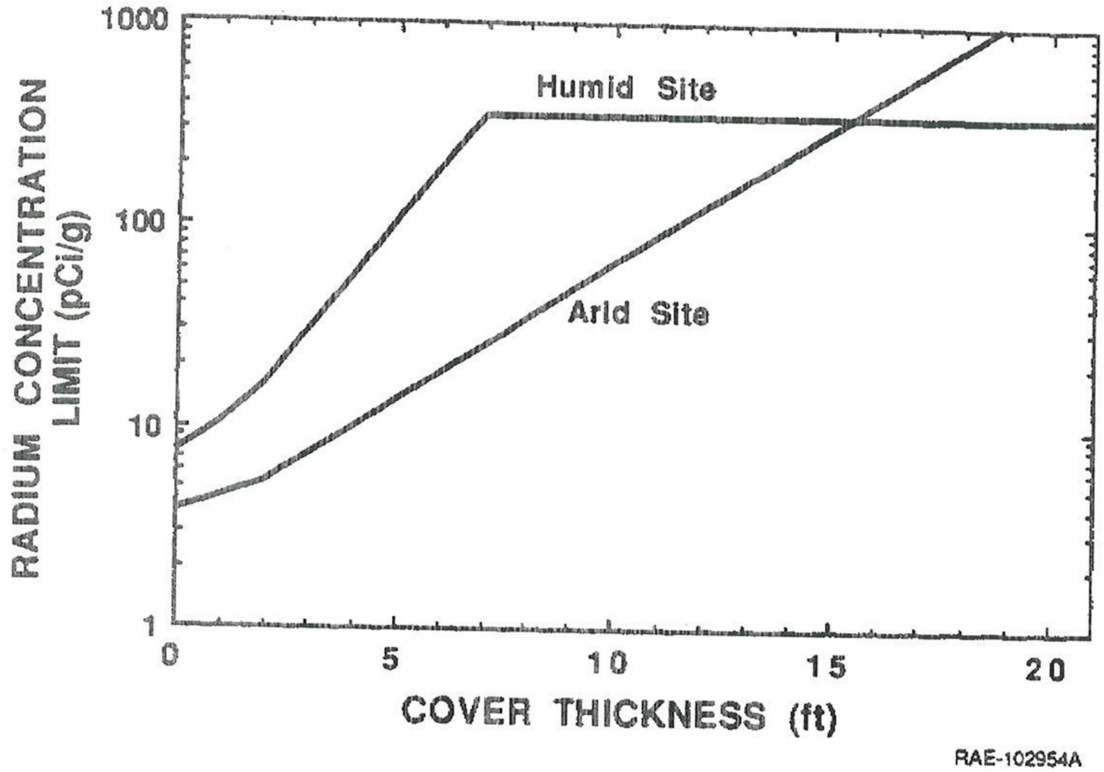

FIGURE 5-3. RADIUM CONCENTRATION LIMITS AS A FUNCTION OF COVER THICKNESS FOR WASTE BURIAL.

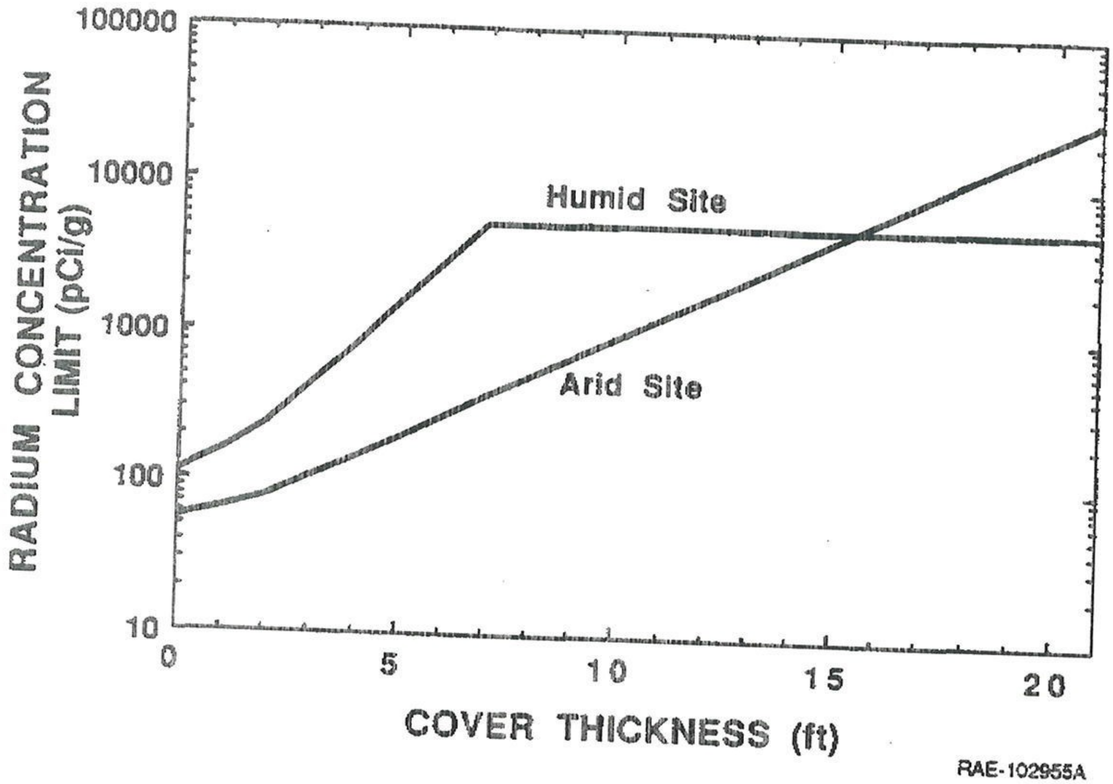

FIGURE 5-4. RADIUM CONCENTRATION LIMITS AS A FUNCTION OF COVER THICKNESS FOR OIL INDUSTRY WASTE DISPOSAL FACILITY.

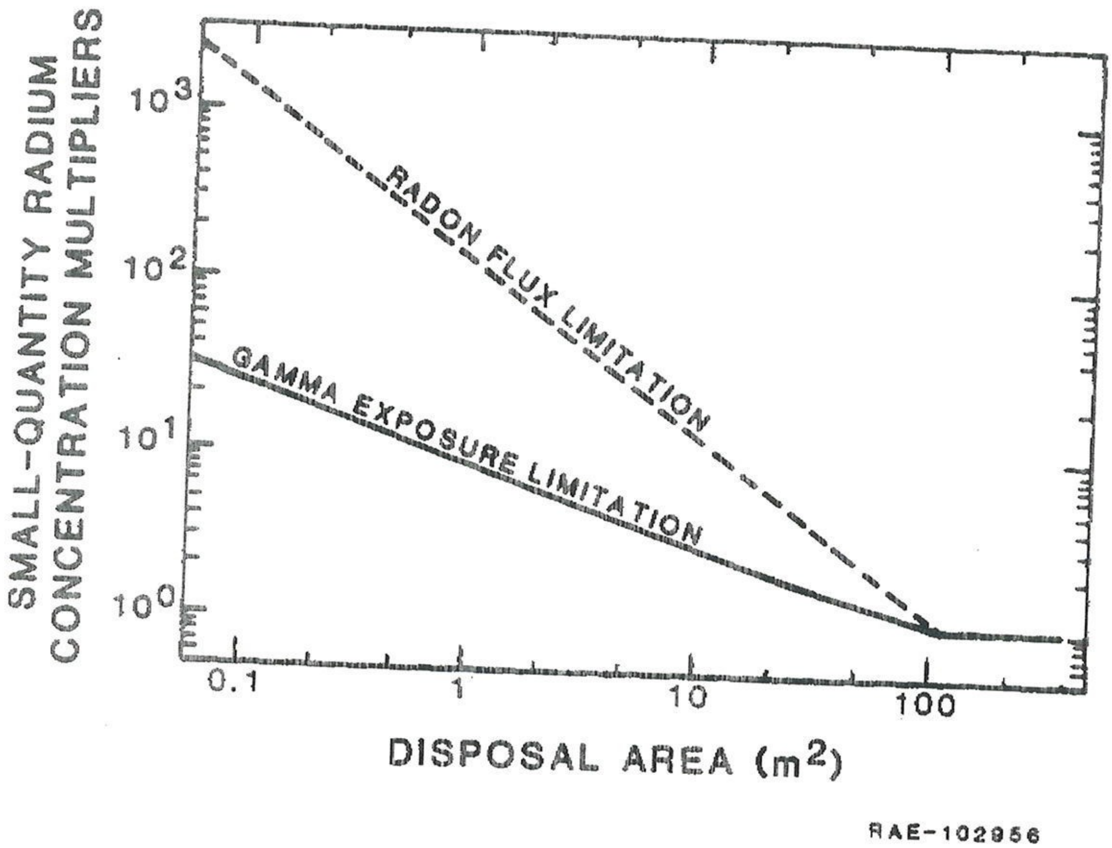

FIGURE 5-5. RADIUM CONCENTRATION MULTIPLIERS FOR SMALL-QUANTITY, SMALL-AREA NORM DISPOSAL, AS LIMITED BY RADON ACCUMULATION AND BY GAMMA EXPOSURES.

and A-1. Application of the small quantity gamma multiplier in Figure 5-5 increases this limit to about 1,200 pCi/g.

5.1.7 Limits for Landspreading With Cover

If an earthen cover is placed over the landspread NORM, higher concentration limits can be used. The factor by which the disposal concentration limits for landspreading may be increased is shown in Figure 5-6 as a function of the cover thickness. For example, if a 1-ft (30-cm) cover is placed over landspread NORM, the concentration limit factor is 2.9, increasing the concentration limit from 120 pCi/g to 350 pCi/g. The cover multiplier factor in Figure 5-6 includes the effects of disturbing the cover and mixing the NORM into it.

5.1.8 Limits for Disposal at a Commercial NORM Facility

Disposal at a commercial NORM facility is similar to the burial with unrestricted use alternative except that the licensed NORM facility will eventually be government owned and will always have restricted site use. Additional restrictions on burial depth and groundwater protection also are applied. Restricted site use eliminates the gamma, food, inhalation and surface water pathways and increases the radon safety limit by a factor of 10 in the humid area and by a factor of about 30 in the arid region, with more cover. The extra facility engineering also reduces the leach rates by about a factor of 10. The groundwater pathway controls for sludge in the humid region and the radon pathway controls in the arid region.

5.1.9 Limits for a Commercial LLW Disposal Facility

The extra packaging, waste form and facility design requirements of a commercial LLW disposal facility decrease NORM radon releases and waste leach rates. The gamma pathway controls in all instances. Radium concentration limits range from 50,000 pCi/g to more than 100,000 pCi/g.

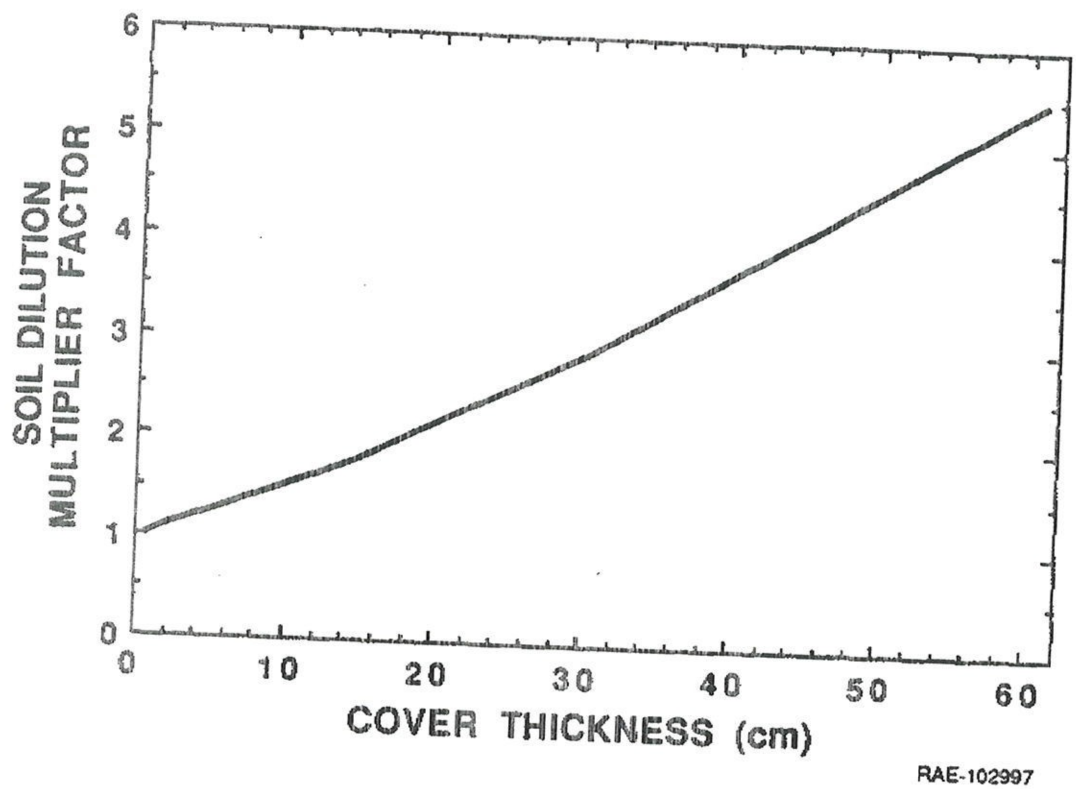

FIGURE 5-6. MULTIPLIER FACTORS FOR RADIUM CONCENTRATION LIMITS AFTER DILUTION BY VARYING THICKNESSES OF SOIL COVER.

5.1.10 Limits for Surface Mine Disposal

The surface mine will have at least 50 feet of earthen cover, precluding significant radon and gamma emissions or erosion. The only pathway of potential significance is the groundwater pathway. Since no extra consideration is given for waste form or packaging, the concentration limits are lower than for disposal in a commercial LLW facility, ranging from 3,500 pCi/g for sludge in a humid environment to over 100,000 pCi/g.

5.1.11 Plugged and Abandoned Wells

Leaving tubing containing NORM scales in a plugged and abandoned well is another alternative for which the groundwater is the only pathway of potential significance. For this pathway, about 3 µCi/g of radium in the scale is the concentration limit. This value is a factor of 30 higher than the practical limit of 100,000 pCi/g. Radon concentrations in the groundwater were calculated to be 3.5×10^{-4} pCi/liter per pCi/g of radium in the scale. For a radium concentration of 100,000 pCi/g the radon concentration in the groundwater is 36 pCi/liter. The mean radon concentration in community water systems from wells is 420 pCi/liter.[23] Therefore, the radon in the groundwater is not significant.

5.1.12 Limits for Well Injection

The radium limits for the well injection alternative are the same as for non-retrieved well tubing, assuming that any injected sludge is below USDWs. If it is within a useable aquifer, then the limit for sludge becomes as low as 30,000 pCi/g.

5.1.13 Limits for Hydraulic Fracturing

No radium concentration limit was calculated for hydrofracture because the migration time to the aquifer was too long. Even if more rapid flow occurred along a formation fault, the radium concentration limit still would far exceed 100,000 pCi/g.

5.1.14 Limits for Salt Dome Disposal

The main purpose for selecting a salt dome in which to place the NORM wastes and contaminated equipment is that the presence of the salt means that there is no water in the formation. Thus there is no practical radium concentration limit for this alternative.

5.2 LIMITS FOR EQUIPMENT DISPOSITION ALTERNATIVES

Several alternatives for equipment burial are included in the previous sections. If the equipment is sold for reuse in the oil industry, then no further concentration limits apply because the buyer eventually will utilize one of the other disposal alternatives in this report. The buyer should be aware of the presence of the NORM, however, and realize that he must eventually dispose of the NORM in a proper manner. Other means of disposing or handling equipment containing NORM are considered in the following sections. Concentration limits for these equipment disposition alternatives are summarized in Table 5-4.

5.2.1 Smelter

Smelting the equipment containing NORM causes doses to the workers from inhaled NORM dust and from gamma radiation in the smelter and near the slag pile. Airborne dust also causes exposures to nearby residents. Furthermore, a small amount of the radionuclides are retained in the iron. The scrap metal-smelter scenario from the impacts-BRC code was used to calculate doses to the public from recycling the metal. The recycled metal is used to make frying pans and pipes for culinary water systems. the maximum radium concentration for each receptor is given in Table 5-5.

TABLE 5-4

RADIUM AND Pb-210 CONCENTRATION LIMITS FOR EQUIPMENT DISPOSITION ALTERNATIVES

Alternative	Radium Concentration Limit (pCi/g)	Pb-210 Concentration Limit (10^3 dpm/100 cm^2)
1. Smelter	40,000	30,000
2. Storage in NORM Yard	5,500	
3. Equipment Re-Use in Dwelling	100	

TABLE 5-5

MAXIMUM RADIUM CONCENTRATIONS FROM SMELTING

Receptor	Maximum Concentration (pCi/g)
Smelter Worker	40,000
Slag Pile Worker	70,000
Nearby Resident	49,000
Individual Using Recycled Metal	Greater than 100,000

5.2.2 NORM Storage Yard

External gamma exposure is the main pathway for doses from equipment in a NORM storage yard. Doses from dust inhalation are a very small fraction of the doses from the gamma pathway. The gamma exposure to the worker would allow a radium concentration limit of 5,500 pCi/g, and the gamma exposure to the individual at the yard boundary would allow a concentration limit exceeding 100,000 pCi/g.

Another source of radiation exposure to a decontamination worker or member of the public is a skin dose from a NORM particle on the skin. Beta radiation is the cause of the localized skin dose. The skin dose of 36 rad per µCi·hr of exposure to a NORM particle was calculated using the VARSKIN code. For a 10-mg particle with a radium concentration of 100,000 pCi/g residing on the skin for 100 hours, the localized skin dose over a 1 cm^2 area is only 0.36 rad.

5.2.3 Equipment Re-Use in a Dwelling

If a piece of equipment containing NORM were used or kept in a dwelling the major pathways would be direct gamma and radon. Assuming an individual spends about 3 hours a day near the equipment, gamma radiation is the dominant pathway and results in a radium concentration limit of 100 pCi/g. The radon pathway gives a radium concentration limit of 4,600 pCi/g.

APPENDIX

RADIUM SOURCE AND LEAD-210 SOURCE CONCENTRATION LIMITS FOR ALL WASTE FORMS, SITE CHARACTERISTICS, DISPOSAL ALTERNATIVES, AND EXPOSURE PATHWAYS

TABLE A-1

RADIUM SOURCE CONCENTRATION LIMITS
SLUDGE -- HUMID PERMEABLE SITE
(pCi/g)

Disposal Alternative	Pathway					
	Radon Inhalation	External Gamma	Dust Inhalation	Food	Groundwater	Surface Water
1. Landspreading[a]	570	120	100,000	47,000	25,000	100,000
2. Landspreading With Dilution[a,b]	590	260	100,000	25,000	25,000	100,000
3. Non-retrieved Surface Pipe	5,500	---[c]	---	---	94,000	---
4. Burial With Unrestricted Site Use[d]	450	---	---	---	350	---
5. Commercial Oil Industry Waste Facility[d]	6,400	---	---	---	5,000	---
6. NORM Disposal Facility[e]	4,500	---	---	---	3,500	---
7. Commercial LLW Disposal Facility	70,000	50,000	---	---	51,000	---
8. Surface Mine	---	---	---	---	3,500	---
9. Plugged and Abandoned Well	---	---	---	---	100,000	---
10. Well Injection	---	---	---	---	100,000	---
11. Hydraulic Fracturing	---	---	---	---	100,000	---
12. Salt Dome Disposal	---	---	---	---	100,000	---

a. Four barrels per 100 m^2 (33 ft x 33 ft) giving a 0.25 inch (0.63 cm) average layer thickness.
b. Diluted by mixing in the top 8-inch (20-cm) soil layer.
c. If no entry is given, limiting concentration exceeds 100,000 pCi/g.
d. For 6.6 feet (2 m) of depth beneath the intrusion zone.
e. For 6.6 foot (2 m) burial depth.

TABLE A-2

RADIUM SOURCE CONCENTRATION LIMITS
SCALE -- HUMID PERMEABLE SITE
(pCi/g)

Disposal Alternative	Pathway					
	Radon Inhalation	External Gamma	Dust Inhalation	Food	Groundwater	Surface Water
1. Landspreading[a]	2,500	120	100,000	100,000	100,000	100,000
2. Landspreading With Dilution[a,b]	2,600	260	100,000	100,000	100,000	100,000
3. Non-retrieved Surface Pipe	13,300	---[c]	---	---	100,000	---
4. Burial With Unrestricted Site Use[d]	2,000	---	---	---	34,000	---
5. Commercial Oil Industry Waste Facility[d]	28,000	---	---	---	---	---
6. NORM Disposal Facility[e]	20,000	---	---	---	100,000	---
7. Commercial LLW Disposal Facility	100,000	50,000	---	---	100,000	---
8. Surface Mine	---	---	---	---	100,000	---
9. Plugged and Abandoned Well	---	---	---	---	100,000	---
10. Well Injection	---	---	---	---	100,000	---
11. Hydraulic Fracturing	---	---	---	---	100,000	---
12. Salt Dome Disposal	---	---	---	---	100,000	---

a. Four barrels per 100 m^2 (33 ft x 33 ft) giving a 0.25 inch (0.63 cm) average layer thickness.
b. Diluted by mixing in the top 8-inch (20-cm) soil layer.
c. If no entry is given, limiting concentration exceeds 100,000 pCi/g.
d. For 6.6 feet (2 m) of depth beneath the intrusion zone.
e. For 6.6 foot (2 m) burial depth.

TABLE A-3

RADIUM SOURCE CONCENTRATION LIMITS
EQUIPMENT AND SCALE -- HUMID PERMEABLE SITE
(pCi/g)

Disposal Alternative	Pathway					
	Radon Inhalation	External Gamma	Dust Inhalation	Food	Groundwater	Surface Water
1. Burial With Unrestricted Site Use[b]	29,000	100,000	---[a]	---	1,600	---
2. Commercial Oil Industry Waste Facility[b]	100,000	---	---	---	---	---
3. NORM Disposal Facility[c]	100,000	---	---	---	---	---
.. Commercial LLW Disposal Facility	100,000	---	---	---	---	---
5. Surface Mine	---	---	---	---	---	---
6. Plugged and Abandoned Well	---	---	---	---	---	---
7. Well Injection	---	---	---	---	---	---
8. Hydraulic Fracturing	---	---	---	---	---	---
9. Salt Dome Disposal	---	---	---	---	---	---

a. If no entry is given, limiting concentration exceeds 100,000 pCi/g.
b. For 6.6 feet (2 m) of depth beneath the intrusion zone.
c. For 6.6 foot (2 m) burial depth.

TABLE A-4

RADIUM SOURCE CONCENTRATION LIMITS
SLUDGE -- ARID PERMEABLE SITE
(pCi/g)

Disposal Alternative	Pathway					
	Radon Inhalation	External Gamma	Dust Inhalation	Food	Groundwater	Surface Water
1. Landspreading[a]	570	120	10,000	66,000	---[b]	100,000
2. Landspreading With Dilution[a,c]	570	260	100,000	33,000	---	100,000
3. Non-retrieved Surface Pipe	2,700	---	---	---	---	---
4. Burial With Unrestricted Site Use[d]	29	---	---	---	96,000	---
5. Commercial Oil Industry Waste Facility[d]	410	---	---	---	---	---
6. NORM Disposal Facility[e]	1,000	---	---	---	---	---
7. Commercial LLW Disposal Facility	50,000	50,000	---	---	---	---
8. Surface Mine	---	---	---	---	100,000	---
9. Plugged and Abandoned Well	---	---	---	---	100,000	---
10. Well Injection	---	---	---	---	100,000	---
11. Hydraulic Fracturing	---	---	---	---	100,000	---
12. Salt Dome Disposal	---	---	---	---	100,000	---

a. Four barrels per 100 m^2 (33 ft x 33 ft) giving a 0.25 inch (0.63 cm) average layer thickness.
b. If no entry is given, limiting concentration exceeds 100,000 pCi/g.
c. Diluted by mixing in the top 8-inch (20-cm) soil layer.
d. For 6.6 feet (2 m) of depth beneath the intrusion zone.
e. For 11.5 foot (3.5 m) burial depth.

TABLE A-5

RADIUM SOURCE CONCENTRATION LIMITS
SCALE -- ARID PERMEABLE SITE
(pCi/g)

Disposal Alternative	Radon Inhalation	External Gamma	Dust Inhalation	Food	Groundwater	Surface Water
	Pathway					
1. Landspreading[a]	2,500	120	10,000	42,000	100,000	8,400
2. Landspreading With Dilution[a,b]	2,500	260	100,000	21,000	100,000	510
3. Non-retrieved Surface Pipe	6,700	---[c]	---	---	100,000	---
4. Burial With Unrestricted Site Use[d]	130	---	---	---	---	---
5. Commercial Oil Industry Waste Facility[d]	1,800	---	---	---	---	---
6. NORM Disposal Facility[e]	4,500	---	---	---	---	---
7. Commercial LLW Disposal Facility	100,000	50,000	---	---	---	---
8. Surface Mine	---	---	---	---	100,000	---
9. Plugged and Abandoned Well	---	---	---	---	100,000	---
10. Well Injection	---	---	---	---	100,000	---
11. Hydraulic Fracturing	---	---	---	---	100,000	---
12. Salt Dome Disposal	---	---	---	---	100,000	---

a. Four barrels per 100 m^2 (33 ft x 33 ft) giving a 0.25 inch (0.63 cm) average layer thickness.
b. Diluted by mixing in the top 8-inch (20-cm) soil layer.
c. If no entry is given, limiting concentration exceeds 100,000 pCi/g.
d. For 6.6 feet (2 m) of depth beneath the intrusion zone.
e. For 11.5 foot (3.5 m) burial depth.

TABLE A-6

RADIUM SOURCE CONCENTRATION LIMITS
EQUIPMENT AND SCALE -- ARID PERMEABLE SITE
(pCi/g)

Disposal Alternative	Pathway					
	Radon Inhalation	External Gamma	Dust Inhalation	Food	Groundwater	Surface Water
1. Burial With Unrestricted Site Use[b]	440	---[a]	---	---	---	---
2. Commercial Oil Industry Waste Facility[b]	6,200	---	---	---	---	---
3. NORM Disposal Facility[c]	68,000	---	---	---	---	---
4. Commercial LLW Disposal Facility	100,000	---	---	---	100,000	---
5. Surface Mine	---	---	---	---	100,000	---
6. Plugged and Abandoned Well	---	---	---	---	100,000	---
7. Well Injection	---	---	---	---	100,000	---
8. Hydraulic Fracturing	---	---	---	---	100,000	---
9. Salt Dome Disposal	---	---	---	---	100,000	---

a. If no entry is given, limiting concentration exceeds 100,000 pCi/g.
b. For 6.6 feet (2 m) of depth beneath the intrusion zone.
c. For 11.5 foot (3.5 m) burial depth.

TABLE A-7

LEAD-210 SOURCE CONCENTRATION LIMITS
SCALE - HUMID PERMEABLE SITE
(pCi/g)

Disposal Alternative	Pathway			
	External Gamma	Dust Inhalation	Food	Surface Water
1. Landspreading[a]	79,000	---[b]	59,000	---
2. Landspreading With Dilution[a,c]	---	---	32,000	---
3. Non-retrieved Surface Pipe	---	---	---	---
4. Burial With Unrestricted Site Use[d]	---	---	---	---
5. Commercial Oil Industry Waste Facility[d]	---	---	---	---
6. NORM Disposal Facility[e]	---	---	---	---
7. Commercial LLW Disposal Facility	---	---	---	---
8. Surface Mine	---	---	---	---
9. Plugged and Abandoned Well	---	---	---	---
10. Well Injection	---	---	---	---
11. Hydraulic Fracturing	---	---	---	---
12. Salt Dome Disposal	---	---	---	---

a. Four barrels per 100 m^2 (33 ft x 33 ft) giving a 0.25 inch (0.63 cm) average layer thickness.
b. If no entry is given, limiting concentration exceeds 100,000 pCi/g.
c. Diluted by mixing in the top 8-inch (20-cm) soil layer.
d. For 6.6 feet (2 m) of depth beneath the intrusion zone.
e. For 6.6 foot (2 m) burial depth.

TABLE A-8

LEAD-210 SOURCE CONCENTRATION LIMITS
SCALE - ARID PERMEABLE SITE
(pCi/g)

Disposal Alternative	Pathway			
	External Gamma	Dust Inhalation	Food	Surface Water
1. Landspreading[a]	79,000	---[b]	83,000	---
2. Landspreading With Dilution[a,c]	---	---	42,000	---
3. Non-retrieved Surface Pipe	---	---	---	---
4. Burial With Unrestricted Site Use[d]	---	---	---	---
5. Commercial Oil Industry Waste Facility[d]	---	---	---	---
6. NORM Disposal Facility	---	---	---	---
7. Commercial LLW Disposal Facility	---	---	---	---
8. Surface Mine	---	---	---	---
9. Plugged and Abandoned Well	---	---	---	---
10. Well Injection	---	---	---	---
11. Hydraulic Fracturing	---	---	---	---
12. Salt Dome Disposal	---	---	---	---

a. Four barrels per 100 m^2 (33 ft x 33 ft) giving a 0.25 inch (0.63 cm) average layer thickness.
b. If no entry is given, limiting concentration exceeds 100,000 pCi/g.
c. Diluted by mixing in the top 8-inch (20-cm) soil layer.
d. For 6.6 feet (2 m) of depth beneath the intrusion zone.

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Appendix: 8

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Chapter 3: Cementing

Cementing is one of the most critical steps in well completion. Sadly, coming at the end of drilling and in the haste to put a well on production, rarely is the time and commitment taken to get a good job. We then spend significantly more time correcting it or battling the effects of a bad cement job.

Cement fills and seals the annulus between the casing string and the drilled hole. It has three general purposes: (1) zone isolation and segregation, (2) corrosion control, and (3) formation stability and pipe strength improvement. Cement forms an extremely strong, nearly impermeable seal from a thin slurry. The properties of the cement slurry and its behavior depends on the components and the additives in the cement slurry. This chapter will focus on the basics of the cementing process. For further information on cement and the cementing process the reader is referred to the Society of Petroleum Engineering's Cementing Monograph.[1]

Most cements used in the oil industry are a type of portland cement. The name portland was taken from an English channel island with a limestone quarry that was used as source of stone for the development of portland cement. Portland cement is produced from limestone and either clay or shale by roasting at 2600 to 3000°F. The high temperature fuses the mixture into a material called clinker cement.[1] After the roasting step, the rough clinker product is ground to a size specified by the grade of the cement. The final size of the cement particles has a direct relationship with how much water is required to make a slurry without producing an excess of water at the top of the cement or in pockets as the cement hardens. The crystals seen in set cement include:[1] C_3S - tricalcium silicate, C_2S - dicalcium silicate, C_4AF - tetracalcium aluminoferrite, C_3A - tricalcium aluminate, MgO - periclase or magnesium oxide, and CaO - free lime.

Not all cements, even those made from the same components, will react in the same manner when mixed with water. Basically, the differences are in the fineness of the grind of the cement, impurities in the water and in some minor additives added during the cement manufacturing process. Figure 3.1 gives the API designated classes for cements. These classifications of cement were in response to deeper and hotter downhole conditions. Note that the useful depths given in the data are derived from average pumping times of neat (no additives) cement for average temperatures involved at these depths. Actual well environment controls the limits of the cement. Also, additives such as accelerators and retarders can be used to modify the behavior of the cement. In this manner, a class H cement, for example, can be used to much greater depths than the 8000 ft limit seen in the table.

Figure 3.1: API Cement Classes

Class A:	For use from surface to 6000 ft (1830 m) depth*, when special properties are not required.
Class B:	For use from surface to 6000 ft (1830) depth, when conditions require moderate to high sulfate resistance.
Class C:	For use from surface to 6000 ft (1830 m) depth, when conditions require high early strength.
Class D:	For use from 6000 ft to 10,000 ft depth (1830 m to 3050 m), under conditions of high temperatures and pressures.
Class E:	For use from 10,000 ft to 14,000 ft depth (3050 m to 4270 m), under conditions of high temperature and pressures.
Class F:	For use from 10,000 ft to 16,000 ft depth (3050 m to 4880 m), under conditions of extremely high temperatures and pressures.
Class G:	Intended for use as a basic cement from surface to 8000 ft (2440 m) depth. Can be used with accelerators and retarders to cover a wide range of well depths and temperatures.
Class H:	A basic cement for use from surface to 8000 ft (2440 m) depth as manufactured. Can be used with accelerators and retarders to cover a wider range of well depths and temperatures.
Class J:	Intended for use as manufactured from 12,000 ft to 16,000 ft (3600 m to 4880 m) depth under conditions of extremely high temperatures and pressures. It can be used with accelerators and retarders to cover a range of well depths and temperatures.