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Management and Disposal Alternatives for Naturally Occurring Radioactive Material (NORM) Wastes in Oil Production and Gas Plant Equipment

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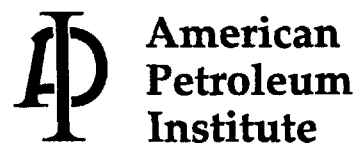
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EXECUTIVE SUMMARY

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.

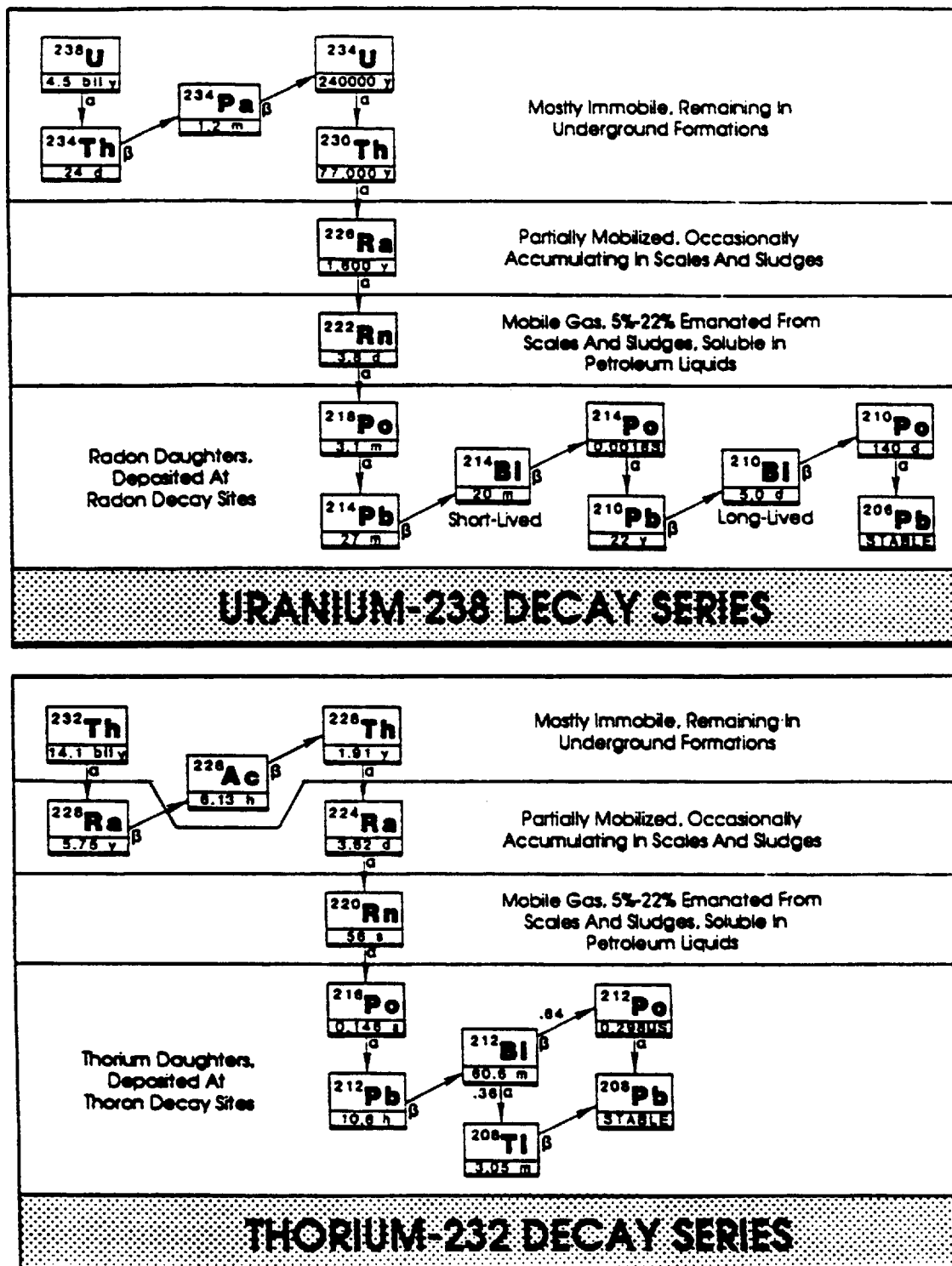
NORM concentrations vary from background levels to levels exceeding those of some uranium mill tailings, suggesting a similarly broad range of suitable disposal alternatives. Disposal of wastes containing NORM clearly does not require precautions for common cases in which NORM occurs at background levels. 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.

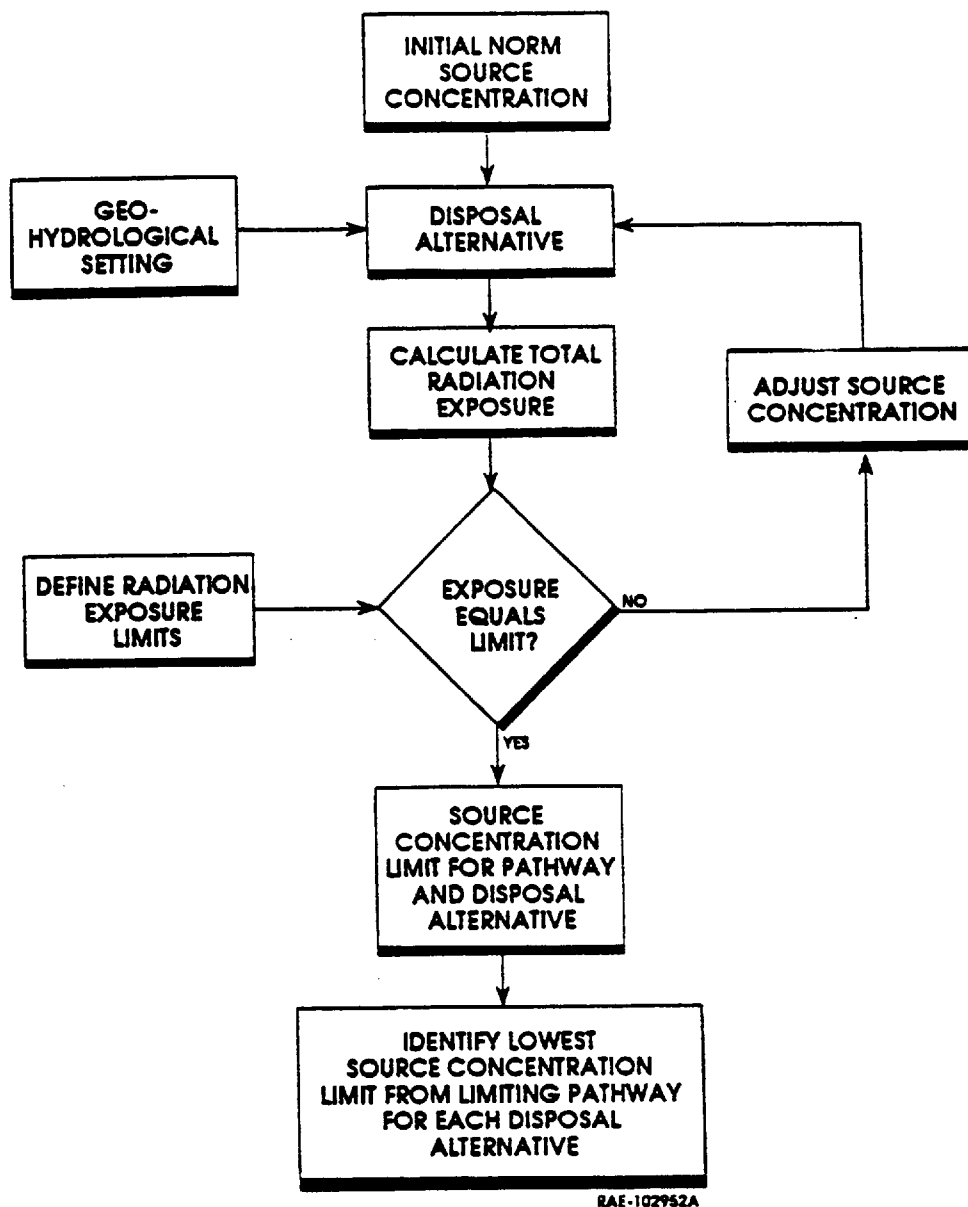


FIGURE 1-2. DETERMINATION OF NUCLIDE CONCENTRATION LIMITS FOR NORM DISPOSAL.

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/cm³, and porosities are about 0.39.⁽²⁾ Radium in sludges has a distribution coefficient for the solid/aqueous phases of 2,500 cm³/g and lead has a distribution coefficient of 5,100 to 20,000 cm³/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/cm³. Upon removal and disposal, however, they have a nominal bulk dry density of about 1.6 g/cm³ 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 cm³/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 cm²). 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.

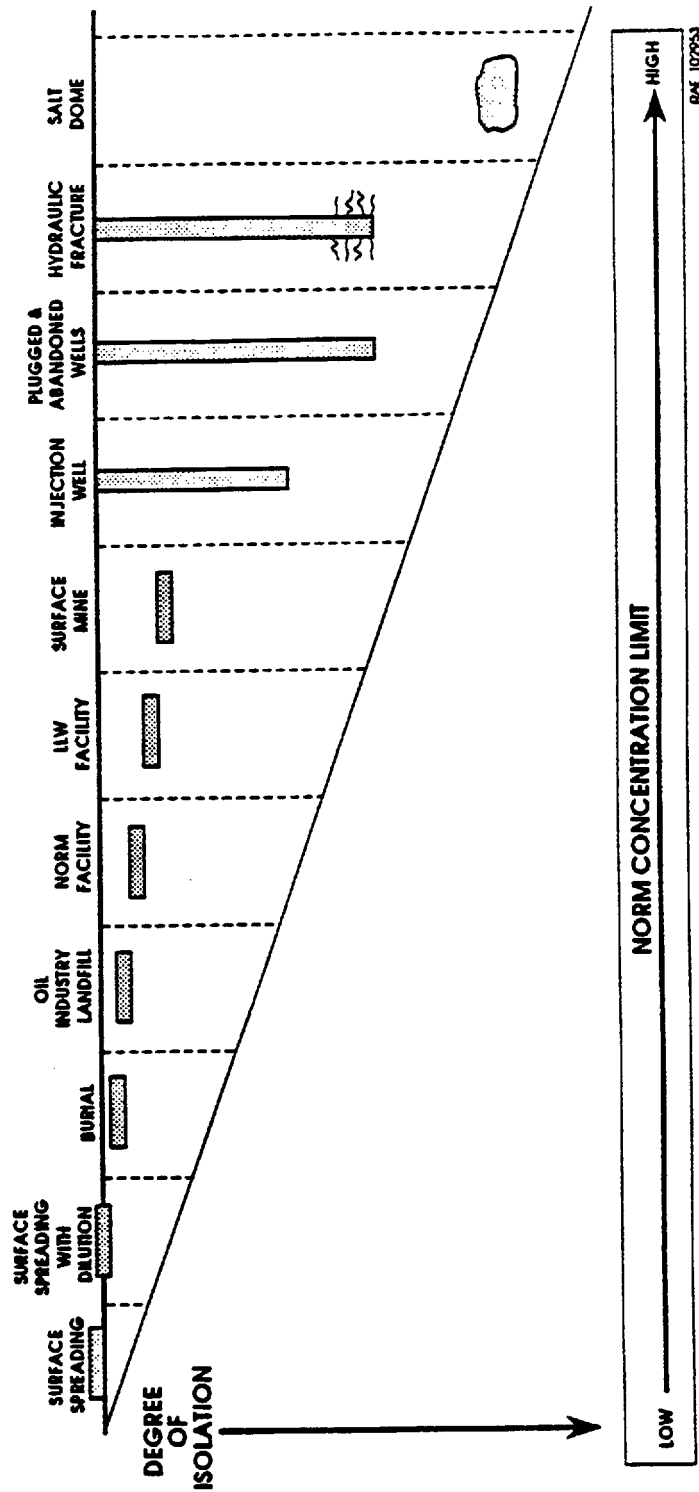


FIGURE 3-1. COMPARISON OF ISOLATION PROVIDED BY NORM DISPOSAL ALTERNATIVES.