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POTENTIAL RADIOLOGICAL DOSES ASSOCIATED WITH THE DISPOSAL OF PETROLEUM INDUSTRY NORM VIA LANDSPREADING

Final Report, September 1998

By
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December 1998

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CONTENTS

FIGURES

TABLES

NOTATION

The following is a list of acronyms, abbreviations, and initialisms (including units of measure) used in this document.

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

CEDE	committed effective dose equivalent
E&P	exploration and production
EDE	effective dose equivalent
EPA	U.S. Environmental Protection Agency
ICRP	International Commission on Radiological Protection
IOGCC	Interstate Oil and Gas Compact Commission
NMAC	*New Mexico Administrative Code*
NORM	naturally occurring radioactive material
OCD	New Mexico Oil Conservation Division
RCRA	Resource Conservation and Recovery Act
TAC	*Texas Administrative Code*
TPH	total petroleum hydrocarbons

RADIONUCLIDES

Pb-210	lead-210
Ra-226	radium-226
Ra-228	radium-228
Rn-222	radon-222
Th-232	thorium-232
Th-228	thorium-228
U-238	uranium-238

UNITS OF MEASURE

cm	centimeter(s)
d	day(s)
ft	foot (feet)
g	gram(s)
h	hour(s)
in.	inch(es)
kg	kilogram(s)
L	liter(s)
m	meter(s)
mg	milligram(s)

mrem	millirem
pCi	picocurie(s)
ppm	part(s) per million
rem	roentgen equivalent man
s	second(s)
yr	year(s)

Potential Radiological Doses Associated with the Disposal of Petroleum Industry NORM Via Landspreading

by

K.P. Smith, D.L. Blunt, and J.J. Arnish

SUMMARY

S.1 BACKGROUND

As a result of oil and gas production and processing operations, naturally occurring radioactive materials (NORM) sometimes accumulate at elevated concentrations in by-product waste streams. The primary radionuclides of concern in NORM wastes are radium-226 (Ra-226), of the uranium-238 (U-238) decay series, and radium-228 (Ra-228), of the thorium-232 (Th-232) decay series. The production waste streams most likely to be contaminated by elevated radium concentrations include produced water, scale, and sludge. Scales and sludges removed from production equipment often are disposed of by landspreading, a method in which wastes are spread over the soil surface to allow the hydrocarbon component of the wastes to degrade.

In this study, the disposal of NORM-contaminated wastes by landspreading was modeled to evaluate potential radiological doses and resultant health risks to workers and the general public. A variety of future land use scenarios — including residential, industrial, recreational, and agricultural scenarios — were considered. The waste streams considered included scales and sludges containing NORM above background levels. The objectives of this study were to (1) estimate potential radiological doses to workers and the general public resulting from the disposal of NORM wastes by noncommercial landspreading activities and (2) analyze the effect of different land use scenarios on potential doses.

Doses were calculated for the maximally exposed receptor for each scenario. Potential exposure pathways evaluated for the worker included external radiation, incidental ingestion of contaminated soil, inhalation of suspended NORM-contaminated particulates, and inhalation of outdoor radon-222 (Rn-222). Depending on the land use scenario, potential exposure pathways evaluated for the general public included external radiation; inhalation of contaminated particulates; inhalation of indoor and outdoor Rn-222; inadvertent ingestion of contaminated soil; and ingestion of crops, milk, and meat grown on the property. Potential doses were modeled for a unit concentration of 1 pCi/g of Ra-226 in soil; other radionuclides of concern were modeled although their contributions to total dose were minimal. Because dose increases linearly with radium concentration, doses and health risks were extrapolated for a range of radium concentrations.

S.2 CONCLUSIONS

The results of this assessment provide estimates of annual doses and resultant health risks to workers and the general public for a variety of potential land use scenarios. On the basis of these results, the following conclusions can be drawn:

- Potential radiological doses and resultant health risks to workers actively involved in landspreading NORM wastes are below accepted public dose limits when Ra-226 concentrations in soil after landspreading are below 1,000 pCi/g, because landspreading does not require excessive handling of the waste and typical exposure times are limited.
- Potential radiological doses to the general public for all land use scenarios evaluated are reasonably low (i.e., below 60 mrem/yr considering all pathways) when the concentration of Ra-226 in soil after landspreading is 5 pCi/g or less above the background level.
- Potential doses to residents and industrial workers can vary greatly depending on a variety of factors such as type of building construction (e.g., crawl space, basement, slab), construction practices employed (e.g., the degree of excavation and/or regrading, use of clean cover material), and natural processes (e.g., erosion rate).
- Concentrations of Ra-226 in soil after landspreading that are above approximately 10-16 pCi/g for the residential receptor (depending on construction type) and 35 pCi/g for the industrial receptor result in potential radiological doses exceeding 100 mrem/yr, assuming the layer of clean cover material has been allowed to erode away.
- For the residential receptor living in a home with a crawl space, when the cover layer is maintained at a thickness of 0.5 ft, a Ra-226 concentration in soil after landspreading greater than 12 pCi/g may result in doses exceeding 100 mrem/yr, of which 80% is attributed to inhalation of radon. Doubling the cover layer thickness does not appreciably affect the upper limit on Ra-226 concentration.
- For the resident of a home with a basement, when the cover layer is maintained at a thickness of 0.5 ft, doses would not exceed 100 mrem/yr until the Ra-226 concentration in soil exceeded approximately 65 pCi/g. If the cover layer thickness is doubled, this dose limit would not be exceeded until the Ra-226 concentration exceeded several hundred pCi/g. This conclusion would apply to any case in which the NORM waste has been totally excavated from within the footprint of the building.
- Potential radiological doses to the general public associated with a future agricultural land use scenario are negligible except when

concentrations of Ra-226 in soil after landspreading exceed several hundred pCi/g (e.g., 200 pCi/g corresponds to 10 mrem/yr.)

S.3 RECOMMENDATIONS

On the basis of the above conclusions, the following recommendations are suggested:

- Landspreading activities that result in Ra-226 concentrations of ≥10 pCi/g in soil should be evaluated on a case by case basis to estimate potential future risk to the general public. Future land use scenarios in which individuals are exposed over long periods to a soil Ra-226 concentration level of 10 pCi/g or more (e.g., the residential scenario), may result in unacceptably high doses depending on a variety of factors. These factors include the type of building construction (e.g., crawl space, basement, slab), construction practices employed (e.g., the degree of excavation and/or regrading, use of clean cover material), and natural processes (e.g., erosion rate).
- States that decide to allow landspreading of NORM that results in Ra-226 concentrations greater than 5 pCi/g above background should consider establishing policies that will restrict future land use or, at a minimum, ensure that future land owners are advised of the landspreading activities and the potential associated health risks. Such a policy is especially important because Ra-226 has such a long half-life.

1 INTRODUCTION

As a result of oil and gas production and processing operations, naturally occurring radioactive materials (NORM) sometimes accumulate at elevated concentrations in by-product waste streams. The sources of most of the radioactivity are isotopes of uranium-238 (U-238) and thorium-232 (Th-232), which are naturally present in the subsurface formations from which oil and gas are produced. The primary radionuclide of concern in NORM wastes is radium-226 (Ra-226), of the U-238 decay series. Radium-228 (Ra-228), of the Th-232 decay series, also occurs in NORM waste but is usually present in lower concentrations. Other radionuclides of concern include those that form from the decay of Ra-226 and Ra-228; these decay progeny are shown in Figures 1 and 2, which depict the decay chains of U-238 and Th-232, respectively.

The production waste streams most likely to be contaminated by elevated radium concentrations include produced water, scale, and sludge. Radium, which is slightly soluble, can be mobilized in the liquid phases of a subsurface formation and transported to the surface in the produced water stream. Dissolved radium either remains in solution in the produced water or, if the conditions are right, precipitates out in scales or sludges.

Scales and sludges removed from production equipment often are disposed of by landspreading, a method in which wastes are spread over the soil surface to allow the hydrocarbon component of the wastes to degrade. Currently, only a few of the states that have NORM regulatory programs allow the disposal of NORM by landspreading. In states that do not have NORM regulatory programs, landspreading of NORM wastes typically is unregulated.

In this study, the disposal of NORM-contaminated wastes by landspreading was modeled to evaluate potential radiological doses and resultant health risks to workers and the general public. A variety of future land use scenarios — including residential, industrial, recreational, and agricultural scenarios — were considered. The scope of this dose assessment included the disposal of NORM wastes by on-site landspreading at centralized, noncommercial landfarm facilities. The waste streams considered included scales and sludges containing NORM at levels above background that were recovered from pipelines and storage vessels. The objectives of this study were to (1) estimate potential radiological doses to workers and the general public resulting from the disposal of NORM wastes by noncommercial landspreading activities and (2) analyze the effect of different land use scenarios on potential doses.

1.1 LANDSPREADING PRACTICES

Landspreading is a long-standing waste disposal method that has been available to the petroleum industry. A wide variety of exploration and production (E&P) wastes generated by the petroleum industry have been considered suitable for landspreading, including drill cuttings, produced solids, tank bottoms, pit bottoms, waste crude, pipeline

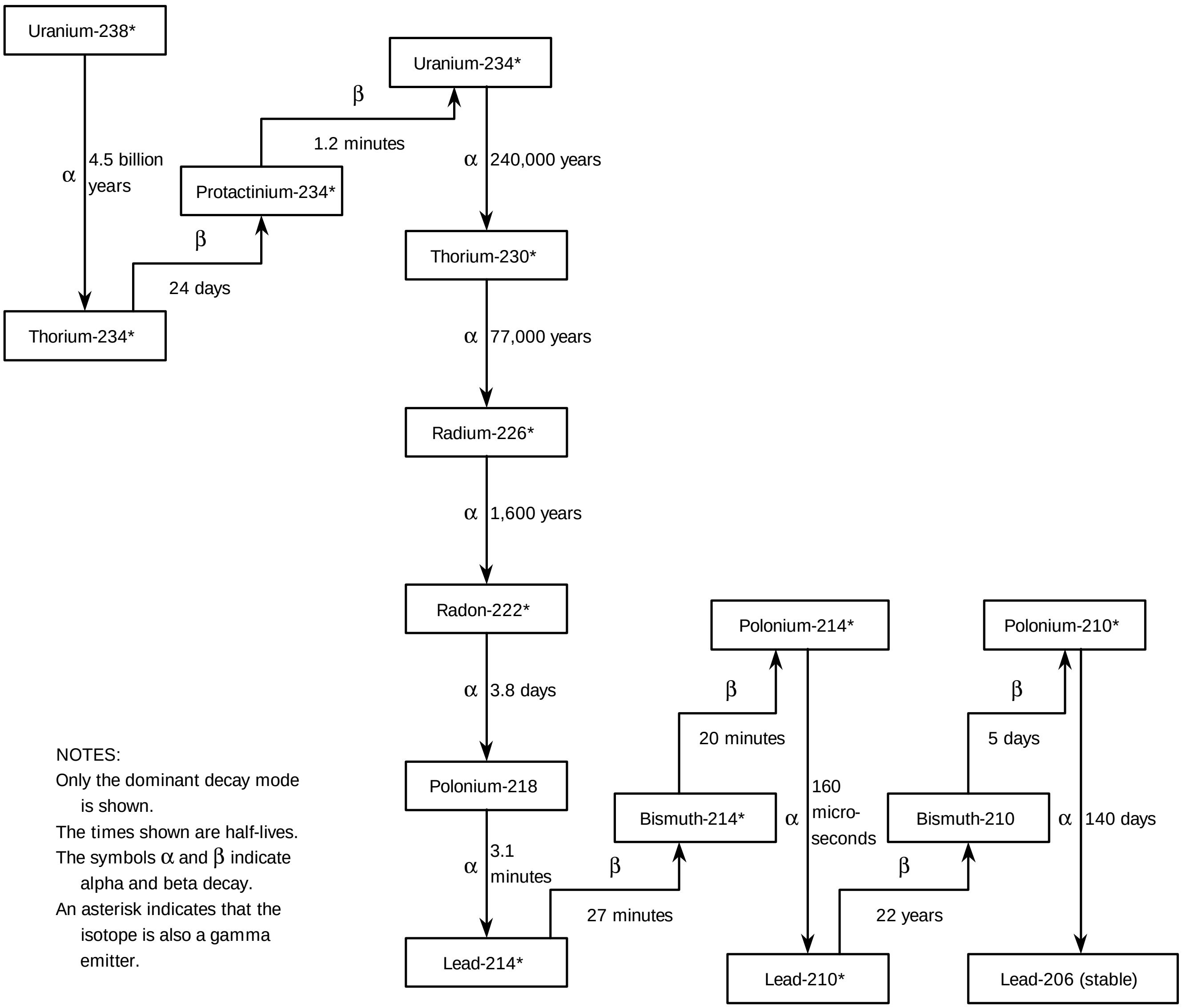

FIGURE 1 Uranium-238 Decay Series

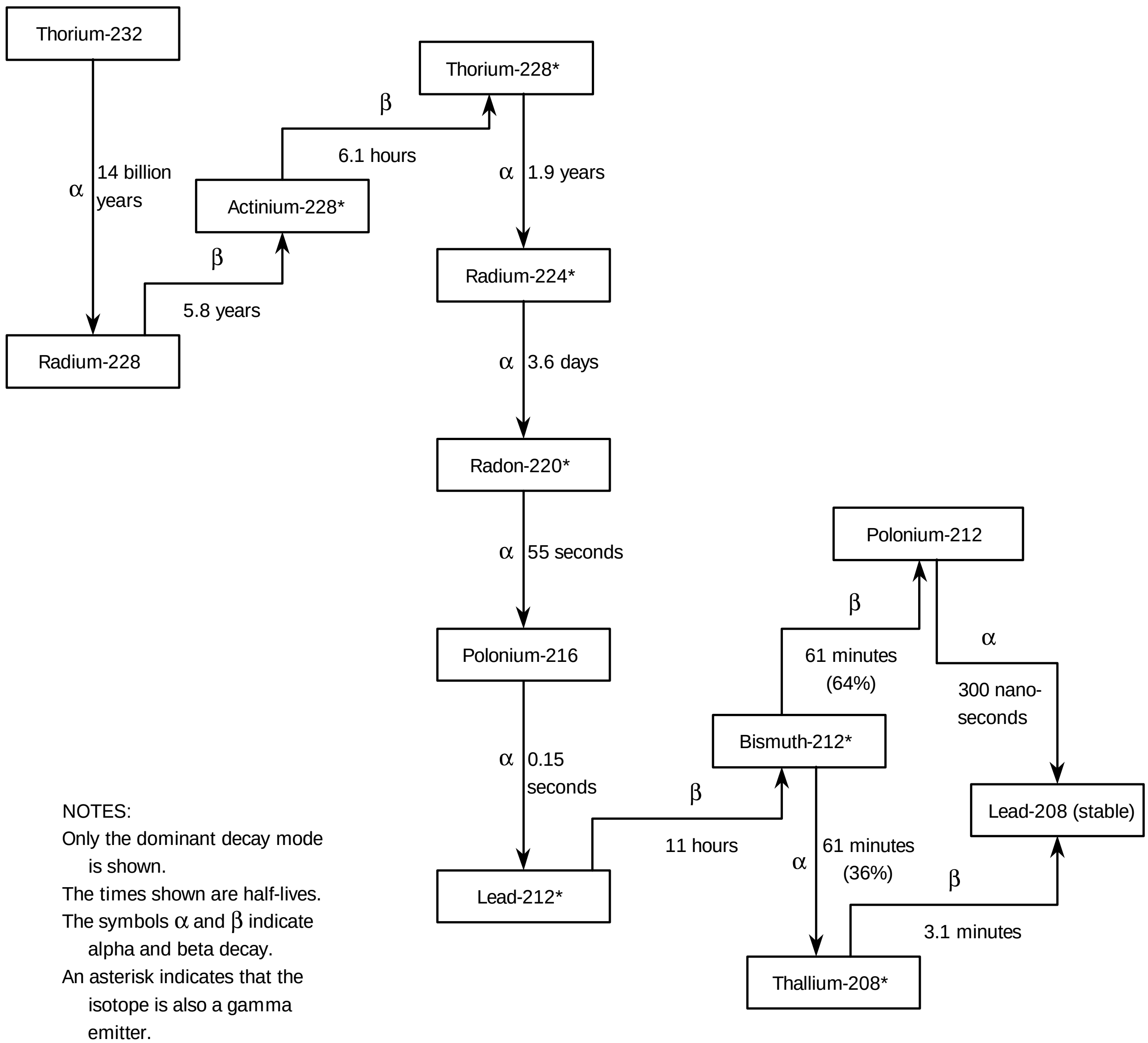

FIGURE 2 Thorium-232 Decay Series

scales and sludges, other wastes removed from piping (i.e., pigging wastes), and soils contaminated with spilled hydrocarbons or produced water. Operators may pretreat these wastes to maximize the economic recovery of hydrocarbons. In many instances, on-site landspreading is the least intensive and least expensive disposal option for the petroleum industry.

Landspreading is a relatively simple process that depends on the availability of oxygen and water and the presence of specific types of naturally occurring bacteria in the soil. Sometimes the practice entails nothing more than spreading the wastes over a specific tract of land by using standard earth-moving equipment. Usually, the objective is to spread the wastes as thinly as possible; the thinner the layer, the quicker the hydrocarbons biodegrade. To accelerate the biodegradation process further, operators often disk or till the layer of waste into the shallow surface soils. In some instances, depending on local soil conditions, aridity, or land use needs, operators may add water and/or fertilizers (e.g., nitrogen-rich manure) to the landspreading treatment zone to further enhance biodegradation.

In practice, landspreading of E&P wastes occurs on well sites or lease sites that are at the point of waste generation or near it; at centralized, noncommercial landfarms; and at commercial landspreading facilities. The regulations governing which options are available to an operator vary from state to state. In the case of on-site landspreading, wastes typically are disposed of on a specific tract of land only one time. Usually the size of the tract is limited; however, the potential exists for larger tracts of land to be involved. At centralized facilities, the tract of land typically is used repeatedly to support continuing disposal operations.

The suitability of a specific tract of land for landspreading activities is addressed in most state regulations governing the disposal of E&P wastes. The factors that usually are considered include site topography, depth to groundwater, distance to surface water, surrounding land use, permission of surface owner, and soil conditions. The controlling soil conditions include electrical conductivity, exchangeable sodium ratio, and sodium absorption ratio.

1.2 REGULATORY CONTROLS

1.2.1 Landspreading Regulations

Most states have implemented regulations governing landspreading practices to limit the potential for environmental contamination. Requirements vary from state to state with respect to permit requirements, application restrictions, siting restrictions, and final treatment levels. Some states require permits before any landspreading activities may take place. Others require permits only for certain activities, such as landspreading at centralized, noncommercial facilities or landspreading of wastes containing hydrocarbons above a specified level. When a permit is required, almost all states require written permission from the surface owner to be included in the permit application.

Almost all states stipulate that only nonhazardous E&P wastes may be disposed of via landspreading. These nonhazardous wastes include E&P wastes that are exempt from regulation as hazardous waste under the Resource Conservation and Recovery Act (RCRA) and related state statutes[1] and nonexempt wastes that are not listed as hazardous and do not exhibit any hazardous characteristics.[2] A few states set additional restrictions on the hydrocarbon and chloride contents of E&P wastes that can be landspread. For example, in Texas, water-based drilling fluids containing ≤3,000 mg/L of chlorides; drill cuttings, sand, and silt derived from operations that use drilling fluids containing ≤3,000 mg/L of chlorides; and wash water may be disposed of via landspreading without a permit at the lease site where they were generated [Title 16, *Texas Administrative Code (TAC)*, Part I, Chapter 3, Rule 8, Section (d)(3)(c)]. Disposal of these wastes via off-site landspreading requires a permit from the Texas Railroad Commission. Disposal of any other E&P waste by landspreading, whether on-site or off-site, requires a permit; these permits include limits on hydrocarbons. Other states also regulate the resultant or final concentrations of hydrocarbons. For example, in Colorado, landspreading treatment is considered to be complete when the residual oil concentration in soil is less than 1,000 ppm of total petroleum hydrocarbons (TPH) in areas classified as sensitive and less than 10,000 ppm of TPH in other areas (Rule 907 promulgated by the Colorado Oil and Gas Conservation Commission). By comparison, the Interstate Oil and Gas Compact Commission (IOGCC 1994) recommends that the concentration of oil and grease in the waste/soil mixture following landspreading should not exceed 1%, by weight.

Almost all state regulations stipulate that landspreading should be conducted in a manner that is protective of human health and the environment. When a permit is required for landspreading, the permit application typically must include information describing the wastes, landspreading site, and application method. Required site information may include descriptions of slope, soil texture, depth to groundwater, distance from surface water, or adjacent land use. In general, a permit will be issued only if the applicant has adequately demonstrated that the landspreading activity will not pollute surface or subsurface waters or adjoining property and does not present an unacceptable risk to public health and the environment.

1.2.2 NORM Regulations

Currently, no federal regulations specifically address the handling and disposal of NORM wastes. In the absence of federal regulations, individual states have taken responsibility for developing their own regulatory programs. These programs have been evolving rapidly over the last few years. Many states have promulgated NORM

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[1] Most E&P wastes, including produced water, drill cuttings, drilling fluids, and other associated wastes such as pipe scale and sludge, were exempted from regulation as hazardous waste under RCRA by virtue of the 1980 Bevill Amendment. Most states with primacy RCRA programs have adopted a similar exemption. These wastes can be referred to collectively as “exempt E&P wastes.”

[2] Under RCRA and related state statutes, the hazardous characteristics of concern include ignitability, corrosivity, reactivity, and toxicity.

regulations, and many others are reviewing NORM issues within their borders and the need for specific regulations.

The existing state regulatory programs establish standards for (1) NORM exemption standards or action levels; (2) the licensure of parties possessing, handling, or disposing of NORM; (3) the release of NORM-contaminated equipment and land; (4) worker protection; and (5) NORM disposal. The action level defining when E&P wastes must be managed as NORM wastes varies from state to state. In general, state action levels range from 5 to 30 pCi/g of total radium (i.e., Ra-226 plus Ra-228). Several states have established two action levels dependant upon the radon emanation rate of the waste.[3] In these states, the action level is 5 pCi/g total radium if the radon emanation rate exceeds 20 pCi/m^2/s and 30 pCi/g total radium if the radon emanation rate is below that level.

The state standards for release of contaminated land generally are consistent with similar standards defined by the Uranium Mill Tailings Radiation Control Act of 1978 (Title 42, *United States Code* 7901, et seq.). In most states, land previously contaminated with NORM may be released for unrestricted use provided the total radium concentration in the top 15 cm of soil is ≤5 pCi/g, averaged over any 100 m^2. As was the case for NORM action levels, several states have established two release standards based on the radon emanation rate of the NORM remaining in the soil. If the radon emanation rate is above 20 pCi/m^2/s, the release standard is 5 pCi/g of total radium, and if the radon emanation rate is below that level, the release standard is 30 pCi/g.

Although the IOGCC (1994) recommends that wastes containing NORM in excess of a state's established action levels should not be landspread, two states allow the landspreading of NORM at noncommercial sites under specific conditions. In Texas, landspreading of NORM waste is allowed without a permit on the lease site where the waste was generated, provided the resultant total radium concentration in the soil is ≤5 pCi/g above background levels [16 TAC 3.94(e)(2)(A)]. Off-site surface disposal of NORM is allowed in Texas provided the same dilution standards are met and a permit is obtained [16 TAC 3.94(g)]. The permit application must describe the physical nature, volume, and activity level of the waste; background activity level; and dust control measures and include written permission from the surface owner.

In New Mexico, in accordance with requirements contained in the NORM regulations promulgated by the Environment Department [Title 20, *New Mexico Administrative Code (NMAC)*, Chapter 3, Part 1, Subpart 14, Section 1407(A)], on-site surface disposal of NORM-contaminated soils is allowed provided a general license is obtained, a Subpart 13 permit is obtained, and the operator complies with the requirements of Oil Conservation Division (OCD) Rule 711 that govern surface waste management facilities. Under this regulation, general licensees may blend or disk NORM-contaminated soil in place, provided the soils at the site were contaminated with NORM prior to promulgation of the regulation (i.e., August 3, 1995) and provided the

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3 The radon emanation rate is a measure of the radon activity (pCi/m^2/s) produced in the pore space.

exemption standard for Ra-226 in soil of 30 pCi/g above background is not exceeded. Under 19 NMAC 15.I.714(c)(1), the NORM disposal rules promulgated by the OCD, the disposal of NORM is allowed at centralized surface waste management facilities, provided it is disposed of in a manner that is protective of the environment, public health, and fresh waters. The OCD further requires that the facility must operate under a Rule 711 permit. Despite these provisions in the regulations, to date, landspreading disposal of NORM by permit has not occurred in New Mexico.

1.2.3 Radiation Dose Standards

Under existing regulations for workers classified as radiation workers by state or federal law, doses are required to be as low as reasonably achievable, not to exceed an annual dose of 5 rem/yr, as specified in Title 10, *Code of Federal Regulations*, Part 20. [4] This limit would apply to workers who handle NORM only if they were classified as radiation workers by state regulations; otherwise, NORM workers are subject to dose limits that apply to the general public. The currently accepted public dose limit recommended by the International Commission on Radiological Protection (ICRP 1991) is 100 mrem/yr from all sources.[5] In addition, the Conference of Radiation Control Program Directors, Inc. (1997) has proposed a public dose limit of 100 mrem/yr from all licensed sources, including NORM.

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[4] The unit "rem" stands for roentgen equivalent man. It is a unit of radiation dose that incorporates both the amount of ionizing radiation absorbed by tissue and the relative ability of that radiation to produce particular biological change. The unit is frequently applied to total body exposure for all types of ionizing radiation.

[5] A millirem is equal to one thousandth of a rem.

2 CHARACTERIZATION OF NORM WASTES

Numerous surveys have been conducted by industry and state agencies to characterize the occurrence and distribution of NORM. Unfortunately, most of the data from these surveys are not readily available, primarily because they were collected by private companies and are considered proprietary. This limited accessibility, coupled with the fact that the available data have not been aggregated to a national level, makes it difficult to fully characterize NORM wastes, particularly with respect to calculating average NORM activity levels.

The most comprehensive study conducted to date (Otto 1989) measured external gamma exposures from contaminated equipment and converted those readings to total radium concentrations on the basis of several assumptions. The data from that survey cannot be used to derive statistically representative source term concentrations because (1) the survey did not provide adequate coverage of some geographic areas, (2) it was limited to those companies that responded, (3) statistically designed sampling schemes were not used, and (4) the conversion from external gamma readings to radium concentration depends heavily on several highly variable factors (e.g., equipment geometry, shielding factors, internal distribution of radium). In addition, the survey is considered to be biased toward high concentrations because measurements were collected only from equipment expected to contain NORM on the basis of the field’s tendency to produce scale or large volumes of water (Otto 1989).

Available data are adequate to determine that, in general, NORM concentrations are greatest in the scales and sludges that form in water-handling equipment and that activity levels decrease with distance from the wellhead. Total radium concentrations are dependent on the amount of radium present in the subsurface formation, formation water chemistry, extraction processes, treatment processes, and age of production. In general, radium solubility increases in water that has (1) a high saline content and (2) either low or high pH values. Radium precipitation rates increase with decreasing temperature and pressure conditions, such as those encountered when subsurface fluids are brought to the surface. Extraction processes (e.g., waterfloods, steam floods, chemical floods) and treatment processes that alter a formation's water chemistry or effect temperature or pressure changes may increase or decrease radium mobility. Most radium is brought to the surface in solution in produced water (i.e., the water produced along with the hydrocarbons). As a result, a higher water production rate, such as is characteristic of older fields, can result in increased NORM concentrations.

2.1 SCALE

NORM contamination of scale can occur when dissolved radium in produced water coprecipitates with barium, strontium, or calcium sulfates. These sulfates form hard, insoluble deposits on the inside of piping, filters, brine disposal/injection wells, and other water handling equipment. Over time, scale deposits thicken and may need to be removed to ensure that equipment continues to operate properly.

Total radium concentrations in scale typically range from undetectable levels to several thousand pCi/g (Baird et al. 1990). However, concentrations as high as 410,000 pCi/g have been reported by the U.S. Environmental Protection Agency (EPA 1993). The density of scale is approximately 2.6 g/cm^3 (EPA 1993).

The amount of radon-222 (Rn-222) emanating out of the pore spaces is relatively small compared to the emanation fraction for a typical soil (e.g. 0.25). A recent study measured the Rn-222 emanation fraction in scale; measurements ranged from 0.02 to 0.06 (Rood and Kendrick 1996).[6] At these low levels, if NORM scale was mixed into a soil layer, the rate of radon emanation from the soil would be well below the 20 $pCi/m^2/s$ standard contained in some state regulations (see Section 1.2.2).

2.2 SLUDGE

Sludge deposits consist of accumulations of heavy hydrocarbons, tight emulsions, produced formation sand, and minor amounts of corrosion and scaly debris that settle out of suspension in some oil field equipment. NORM accumulates in sludge inside piping, separators, heater/treaters, storage tanks, and any other equipment where produced water is handled. It occurs when the radium coprecipitates with barium, strontium, or calcium in the form of insoluble sulfates or in the form of slightly more soluble silicates and carbonates.

Typically, NORM concentrations range from undetectable levels to 300 pCi/g (Baird et al. 1990), although sludge samples with Ra-226 concentrations as high as 700,000 pCi/g have been documented (Fisher and Hammond 1994). The density of sludge is approximately 1.6 g/cm^3 (Baird et al. 1990; EPA 1993). The amount of Rn-222 emanating from sludge has been speculated to be higher than the amount emanating from scale because sludge is more granular. The typical Rn-222 emanation fraction for sludge used in other studies is 0.2 (Baird et al. 1990; EPA 1993; Smith et al. 1996); actual measurements of radon emanation from sludge have not been performed.

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[6] The radon emanation fraction is the ratio of the amount of radon escaping into the internal porosity of a material to the total amount of radon produced by the decay of Ra-226 within the material.

3 ASSESSMENT METHODOLOGY

3.1 ESTIMATION OF RADIOLOGICAL DOSES AND CARCINOGENIC RISKS

Radiation exposure pathways can be separated into external and internal components. External exposure, which occurs when the radioactive material is outside of the body, is a concern primarily only for gamma radiation because it can easily penetrate tissue and reach internal organs. Internal exposure occurs when radioactive material is taken into the body through inhalation or ingestion. For internal exposure, alpha and beta particles are the dominant concern, because their energy is almost completely absorbed in cells, potentially causing biological harm.

For internally deposited radioactive contaminants, exposure is measured in terms of the 50-year committed effective dose equivalent (CEDE). This concept, developed by the ICRP (1977), represents the weighted sum of the dose equivalent in various organs. The CEDE considers the radiosensitivity of different organs, biological effectiveness of different types of radiation, and variable retention time in the body for different radionuclides. For external pathways, no long-term residence of radionuclides in the body occurs, and the measure of dose is the effective dose equivalent (EDE). Both CEDE and EDE are expressed in units of rem. For this assessment, maximum individual dose equivalents were calculated for workers and the general public. Collective doses were considered to be beyond the scope of this study and were not calculated.

The major radiological health concern from exposure to NORM is potential induction of cancer. The development of radiation-induced cancer is a stochastic process and is considered to have no threshold dose (i.e., the probability of occurrence, not the severity of effect, increases with dose, and there is no dose level below which the risk is zero). The relationship between radiation dose and development of cancer is well characterized for high doses of most types of radiation, but for low doses, it is not well defined and is subject to a large degree of uncertainty. Low levels of radiation exposure may present a health risk, but it is difficult to establish a direct cause-and-effect relationship because of the lack of data and the presence of compounding environmental stresses. In the absence of definitive data, the risk from low levels of radiological exposure are estimated by extrapolating from data available for increased rates of cancers observed at higher doses. For this assessment, radiation doses were converted to carcinogenic risks by using risk factors identified in ICRP Publication 60 (1991). The ICRP risk factor for the public is 5×10^{-7} per mrem, and for workers, it is 4×10^{-7} per mrem. Risks are expressed as the increased probability of fatal cancer over a lifetime.

3.2 IDENTIFICATION OF SCENARIOS AND EXPOSURE PATHWAYS

For this study, the disposal of NORM-contaminated wastes by landspreading was modeled to evaluate potential doses and health risks to workers and the public for a variety of land use scenarios. Dose calculations were conducted for the maximally exposed receptor for each scenario. An on-site worker performing landspreading operations was evaluated. This receptor would be involved with activities such as the loading, unloading, transport, application, or tilling of NORM waste and any necessary maintenance activities such as watering and fertilization. Potential exposure pathways identified for the worker included external radiation, incidental ingestion of soil, inhalation of suspended NORM-contaminated particulates, and inhalation of outdoor Rn-222. Because landspreading is not a labor-intensive process, a maximum upper-bound exposure time of 10 8-hour workdays per year was considered for this receptor.

Four future land use scenarios were evaluated: residential, industrial, recreational, and agricultural. Residential use of land on which NORM had been disposed of was evaluated as the most conservative scenario (i.e., the scenario expected to result in the greatest risk). Assumptions underlying the residential land use scenario were that individuals live on the site; drink the groundwater or surface water; and produce most of their food, including vegetables, milk, meat, and fish, on the site. Two types of home construction were evaluated to investigate their effect on indoor Rn-222 concentrations: a home with a crawl space directly over the NORM waste, and a home with a basement excavated below the contamination. The resident was assumed to spend 18 hours each day on the site (of which 12 hours was spent indoors), seven days per week. The pathways of exposure evaluated for the residential receptor included external radiation; inhalation of contaminated particulates; inhalation of indoor and outdoor Rn-222; inadvertent ingestion of contaminated soil; and ingestion of crops, milk, and meat grown on the contaminated property. Although this scenario may not represent a realistic future use of land that has been used to dispose of NORM wastes by landspreading, it was evaluated to represent a maximally exposed individual. These residential land use assumptions are commonly used by risk assessors to evaluate the potential dose to a maximally exposed individual.

The industrial land use scenario considered a building constructed on a concrete slab directly over the land on which NORM had been landspread. The receptor was assumed to work on-site eight hours per day, five days per week. Exposure time was assumed to be divided equally between indoor and outdoor activities. The pathways of exposure evaluated for the industrial receptor included external radiation, inhalation of contaminated particulates, inhalation of indoor and outdoor Rn-222, and inadvertent ingestion of contaminated soil.

The recreational land use scenario evaluated a visitor who spends 20 days per year recreating on the land. Because most parcels of land are limited in size and are not located in the vicinity of surface water (in accordance with state regulations), an exposure time of one hour was assumed for each visit. This time interval is reasonable given that recreational opportunities would not include activities such as fishing and swimming. The pathways of exposure evaluated for the visitor included external radiation, inhalation of contaminated particulates, inadvertent ingestion of contaminated soil, and inhalation of outdoor Rn-222.

Landspreading is commonly performed in areas used primarily for agricultural purposes (i.e., raising cattle and crops). The agricultural scenario considered a receptor who lives off the site but consumes food that had been raised on land that had been used for landspreading of NORM-contaminated waste. Twenty-five percent of the meat and produce ingested by the receptor was assumed to be from the site.

3.3 SOURCE CONCENTRATION

As stated in Section 2, radium concentrations in NORM waste are highly variable, ranging from near background levels to several hundred thousand pCi/g. For this assessment, doses were modeled for a unit concentration of 1 pCi/g of Ra-226 in soil. Doses and health risks are presented in this report for a range of Ra-226 concentrations up to 2,000 pCi/g. Because dose increases linearly with increasing Ra-226 concentration and because dose is presented for a unit concentration of Ra-226 for each scenario, the reader can extrapolate the calculations to estimate potential doses from any given Ra-226 concentration. Doses are presented for Ra-226 because it is the primary radionuclide associated with NORM and it presents a long-term hazard. Although Ra-228 also is commonly present, concentrations are usually lower and, with a half-life of 5.8 years, it does not present a long-term hazard. Even so, the contribution from Ra-228 is addressed in the analysis; a 3:1 concentration ratio of Ra-226 to Ra-228 is assumed (EPA 1993).

Dose calculations were performed for the principal radionuclides in the decay series. The term “principal” refers to those radionuclides in the decay series with half-lives of more than one year; these include Ra-226, lead-210 (Pb-210), Ra-228, and thorium-228 (Th-228). The chain of decay products of a principal radionuclide (i.e., the associated radionuclides) extending to (but not including) the next principal radionuclide were assumed to be in secular equilibrium[7] with the principal radionuclide. Secular equilibrium was also assumed between Ra-228 and Th-228. Ingrowth of Pb-210, which has a longer half-life (22 years), was assumed for 10 years at the start of analysis.

Source concentrations do not include background radium concentrations in soil. According to the National Council on Radiation Protection and Measurements (1987), the average background concentration of Ra-226 in soil in the United States and Canada is 1.8 pCi/g.

3.4 METHODOLOGY AND EXPOSURE ASSUMPTIONS

For all scenarios, radiological doses were modeled by using the RESRAD computer code, Version 5.782 (Yu et al. 1993). The RESRAD code is a pathways

[7] Secular equilibrium refers to the stable relationship established in nature between a radioactive element that has a long half-life and a decay product that has a much shorter half-life. For example, Ra-226 has a half-life of about 1,600 years. As this element decays and emits radiation, Rn-222, which has a half-life of about 3.8 days, is produced. Over time (after seven progeny half-lives), an equilibrium is established between the concentrations of these two elements such that the activity of each element is equal.

analysis code that implements the methodology for determining concentrations of residual radioactivity in soil prescribed in U.S. Department of Energy Order 5400.5 (1990). The exposure pathways available for analysis included external radiation; inhalation of resuspended dust and Rn-222; ingestion of crops, milk, and meat grown on the contaminated property; incidental ingestion of contaminated soil; ingestion of fish from a nearby pond; and ingestion of surface water or groundwater. Doses were projected over a period of 1,000 years following initial NORM placement. For the residential and industrial scenarios, an annual dose was estimated for each year following the landspreading assuming that a home or industrial facility could be built at any time in the next 1,000 years. For example, the annual dose was calculated for a resident inhabiting a home built in the first year after landspreading, in the second year, in the third year, and so on until the one thousandth year. This methodology allowed the assessment to account for radioactive decay and erosion of the cover material over time.

For landspreading workers, airborne emissions could be generated during the application and tilling of the NORM waste. Airborne emissions generated during landspreading activities were calculated on the basis of an estimated mass loading factor. The dose to workers from the inhalation of NORM was estimated by using the following equation:

$$D_{inh} = B \times t \times M_L \times C_N \times DCF_{inh},$$

where

D_{inh} = committed effective dose equivalent from inhalation from a ground release (mrem),

B = breathing rate (m^3/h),

t = exposure time (h),

M_L = mass loading factor (g/m^3),

C_N = radioactivity concentration of NORM (pCi/g), and

DCF_{inh} = inhalation dose conversion factor (mrem/pCi) for the radionuclide of interest.

The calculation assumes that the amount of particulates in air would eventually reach a saturation level called the mass loading factor and that this level would be maintained during the work period. The mass loading factor was based on an upper-bound estimate for gardening activities of 500 ug/m^3 established by the U.S. Nuclear Regulatory Commission (1992).

The exposure parameters used to model the landspreading scenarios are presented in Table 1. Calculations were based on a 2-acre (8,093-m^2) area of land; contamination was assumed to be distributed homogeneously throughout the contaminated zone. For all scenarios, the thickness of the contaminated zone was assumed to be 0.67 ft (0.20 m). For the residential and industrial scenarios, the contaminated zone was assumed to be

TABLE 1 Exposure Parameters Used to Model Landspreading Scenarios

	Scenario[b]					
Input Parameter[a]	Worker	Resident	Industrial	Recreational	Agricultural	Reference/Rationale
Area (m^2)	8,093	8,093	8,093	8,093	8,093	General practice
Cover depth (m)	NA	0.15	0.15	NA	NA	Engineering judgment
Contaminated zone thickness (m)	0.20	0.20	0.20	0.20	0.20	General practice
Density (g/cm^3)	2.0	2.0	2.0	2.0	2.0	Mixture of soil/scale from EPA (1993)
Exposure time (h/d)						Engineering judgment
Indoor	0	12	4	0	NA	
Outdoor	8	6	4	1	NA	
Exposure frequency (d/yr)	10	365	250	20	NA	RESRAD default
Building air exchange rate (volume per hour)	NA	0.5	0.5	NA	NA	RESRAD default
Ingestion rate						RESRAD default
Soil (g/d)	0.1	0.1	0.1	0.1	NA	
Meat (kg/yr)	NA	63	NA	NA	63	
Plant (kg/yr)	NA	160	NA	NA	160	
Inhalation rate (m^3/h)	0.96	0.96	0.96	0.96	0.96	RESRAD default
Rn-222 emanation fraction	0.04	0.04	0.04	0.04	0.04	Rood and Kendrick (1996)
Plant/soil transfer factor						Auxier & Associates, Inc. (1996)
Radium	NA	6.8×10^{-5}	NA	NA	6.8×10^{-5}	
Lead	NA	3.3×10^{-5}	NA	NA	3.3×10^{-5}	
Thorium	NA	1.7×10^{-6}	NA	NA	1.7×10^{-6}	
Fraction of food from site	NA	0.5	NA	NA	0.25	Engineering judgment

[a] RESRAD default values were used for input parameters not listed.

[b] NA indicates not applicable.

covered with a layer of clean soil 0.5-ft (0.15-m) thick immediately following the landspreading action to provide for future construction of a building. Exposure parameters used for each scenario were based on a review of the literature, discussions with industry representatives, and engineering judgment. Sensitivity analyses were performed on several parameters, including the thickness of the contaminated zone and of the cover, Rn-222 emanation coefficient, building air exchange rate, size of the area involved in landspreading, and plant-to-soil transfer ratio.

4 RESULTS

4.1 DOSES AND HEALTH RISKS TO LANDSPREADING WORKERS

Radiological doses to workers involved in landspreading operations were estimated for external radiation, ingestion of soil, and inhalation of airborne particulates. The total dose from all pathways for a unit concentration of 1 pCi/g of Ra-226 was estimated to be 0.10 mrem/yr. The increased risk of a worker developing a fatal cancer corresponding to a unit concentration was estimated to be 4×10^{-8}. This estimate was based on 80 hours of exposure over the course of a year. The major contributor to the dose was external radiation; inhalation and ingestion contributed only about 1% of the total dose. The presence of Ra-228 in the waste would increase the dose from external radiation by an estimated 35% (0.14 mrem/yr), assuming a 3:1 concentration ratio between Ra-226 and Ra-228, for the first five years after disposal. The doses for the worker scenario tended to be overestimated, since the calculations did not account for any shielding from a truck or tractor. In reality, some shielding would be present, and it would attenuate some of the gamma radiation emanating from the soil.

4.2 DOSES AND HEALTH RISKS TO THE PUBLIC

4.2.1 Residential Scenario

Two types of home construction were evaluated for the residential scenario: a home with a crawl space situated directly on top of the contaminated zone, and a home with a basement excavated below the contaminated layer of NORM. In both cases, it was assumed that immediately following the landspreading action, a layer of clean soil 0.5-ft thick would be spread over the contaminated zone to regrade the surface for future construction. The placement of additional clean cover material on the site before construction was not accounted for in this assessment.

For each construction type, an annual dose was estimated for each year following landspreading assuming that the home was built and inhabited during that year; the results are depicted in Figures 3 and 4. External radiation and radon inhalation were the two dominant pathways. All other pathways combined contributed less than 5% of the total dose for the residential scenarios. Groundwater-dependent pathways did not contribute to dose because of the relative immobility of radium.

For both construction types, the dose from external radiation was the same, resulting from both outdoor and indoor exposures to gamma radiation. For residents of homes built at any point during the first 30 years after landspreading, the external radiation dose was estimated at less than 2 mrem/yr per pCi/g of Ra-226. By 100 years after landspreading, the dose from external radiation increased to approximately 3 mrem/yr per pCi/g, and by 150 years after landspreading, the dose from external radiation peaked at just under 6 mrem/yr per pCi/g. This increase in external radiation

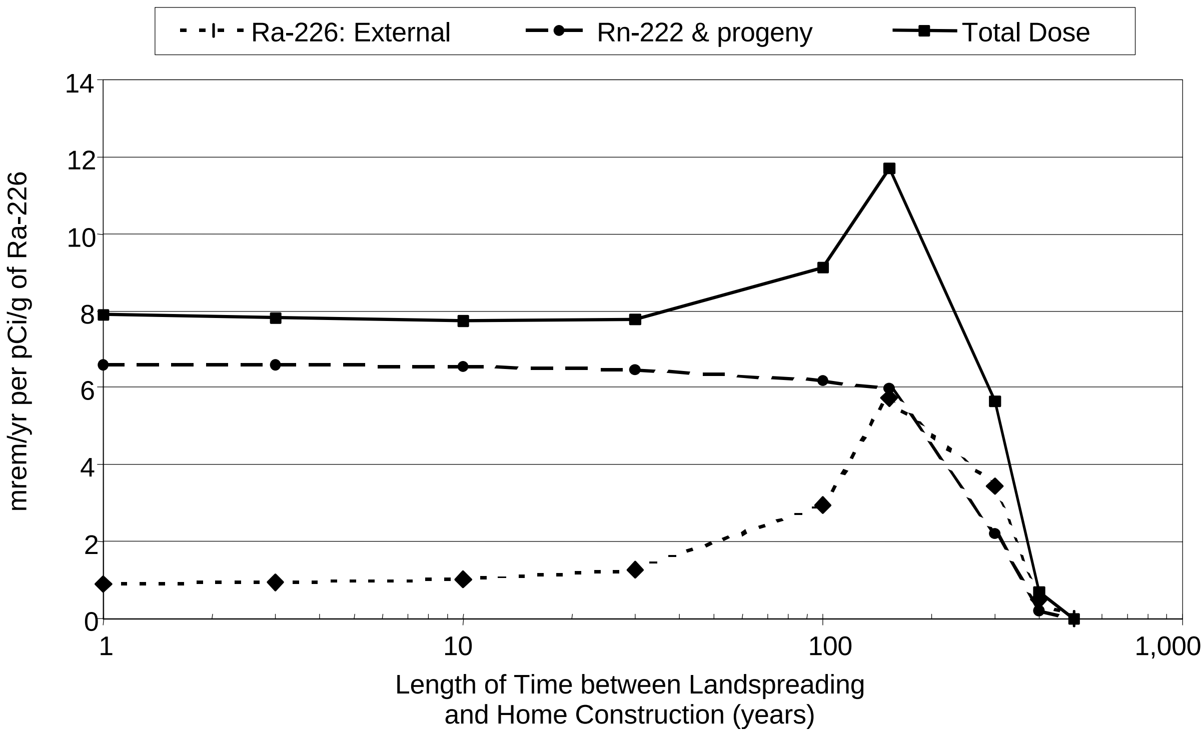

FIGURE 3 Potential Doses to a Resident of a Home with a Crawl Space Located over the Contaminated Zone

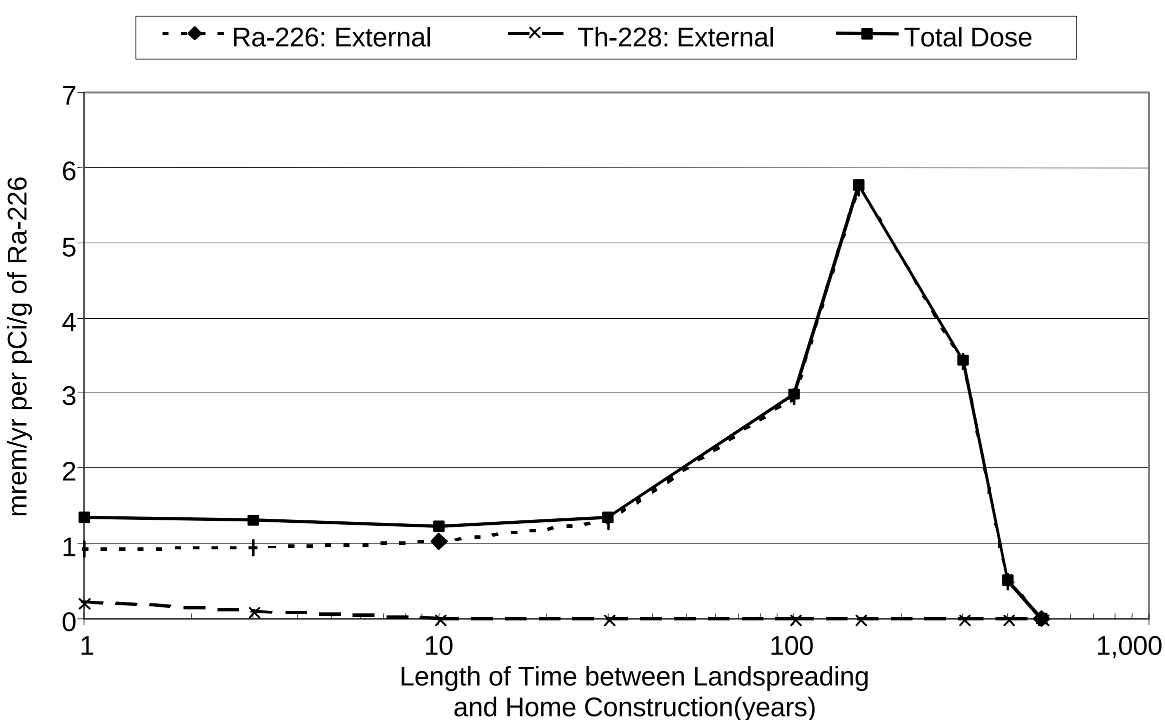

FIGURE 4 Potential Doses to a Resident of a Home with a Basement Excavated below the Contaminated Zone

dose over time was a result of the gradual erosion of the 0.5-ft thick layer of cover material before construction; the entire layer was assumed to have eroded away after 150 years.

The radon inhalation pathway was a significant contributor to dose only for residents living in a home constructed with a crawl space directly over the NORM layer; in this type of home, it was the dominant pathway for the first 100 years after landspreading. For the home constructed with a basement, the radon inhalation pathway was insignificant. This difference was due to the fact that excavation of the basement effectively removed all NORM waste from within the footprint of the home so that only a limited portion of the basement walls and none of the floor were in contact with the contaminated material. By comparison, the home with a crawl space was directly over the NORM waste. Radon emanating from the NORM waste present outside the home was assumed to be diluted to a negligible level by mixing with the ambient air. For residents living in a home with a crawl space built at any point during the first 150 years after landspreading, doses from radon inhalation were estimated at less than 7 mrem/yr per pCi/g of Ra-226.

For both types of construction, the total annual dose was highest for residents of homes that were not built until 150 years after the disposal action, by which time the cover material was assumed to have eroded away. For a resident living in a home with a crawl space, the total peak year dose was 12 mrem/yr per pCi/g of Ra-226, approximately half of which was from external radiation and half from inhalation of indoor Rn-222. For a resident living in a home with a basement, the total peak year dose was 5.8 mrem/yr per pCi/g of Ra-226.

The results presented here for the residential scenario do not consider the fact that additional clean cover material might be spread over a site before construction of a home, especially if the site has been unused for several years or more. This practice would increase attenuation of the gamma radiation, thereby resulting in lower estimated annual doses to the resident. The degree to which the dose would be lowered would depend largely upon the thickness of the new cover layer. However, assuming a new cover layer 0.5-ft thick was put in place before construction, the estimated doses would not be reduced much below those predicted for the first year after landspreading.

4.2.2 Industrial Scenario

Results for the industrial scenario are shown in Figure 5. This scenario assumed that an industrial facility was constructed on a concrete slab directly over the land on which NORM had been landspread. As in the residential scenario, it was assumed that immediately following landspreading, a layer of clean soil 0.5-ft thick was spread over the contaminated zone to regrade the surface for future construction. The placement of additional clean cover material on the site before construction was not accounted for in this assessment.

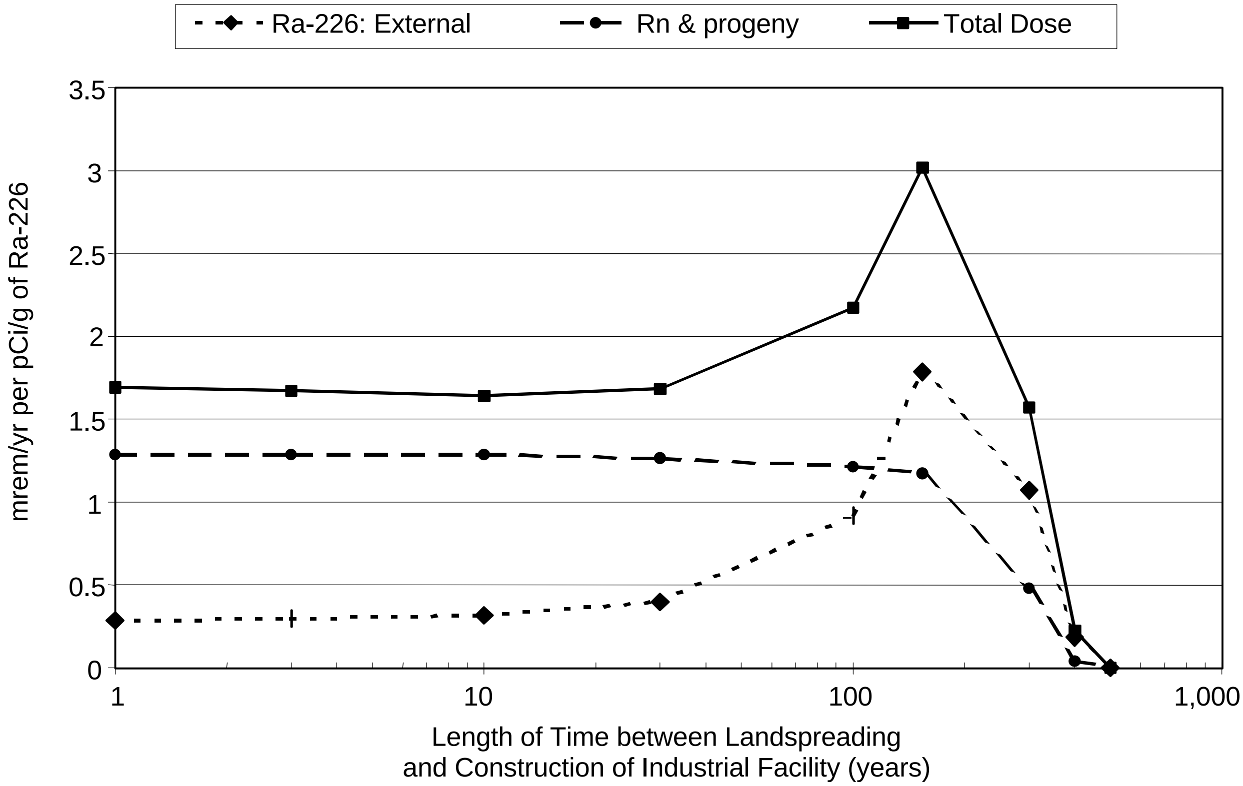

FIGURE 5 Potential Doses to an Industrial Worker

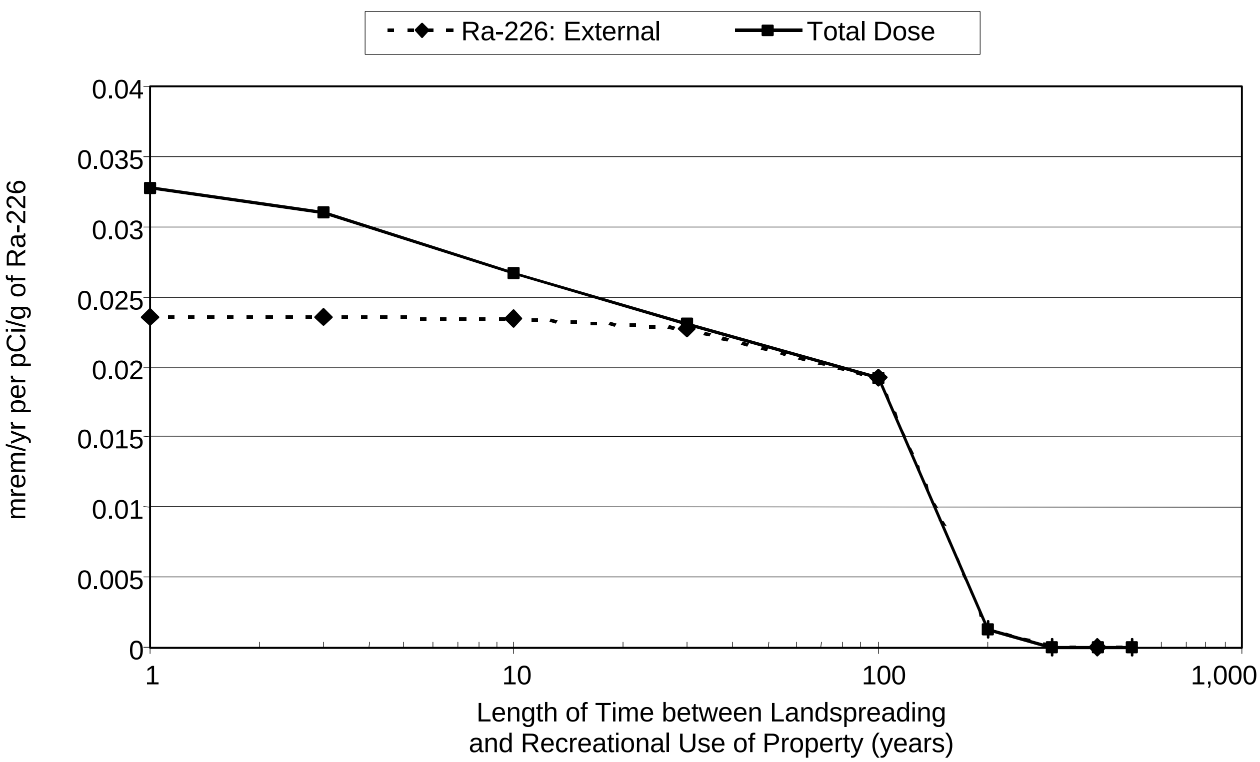

FIGURE 6 Potential Doses to a Member of the General Public Resulting from Occasional Recreational Use of the Property

The industrial worker was assumed to spend a total of 2,000 hours at the site, with 50% of the time spent indoors. An annual dose was estimated for each year following landspreading assuming that the industrial facility was built and became operational during that year. External radiation and radon inhalation were the two dominant pathways. All other pathways combined contributed less than 3% of the total dose for the industrial scenario.

For the industrial worker at a facility constructed at any time during the first 100 years after landspreading, the total annual dose from external radiation and radon inhalation combined was estimated at less than 2.5 mrem/yr per pCi/g of Ra-226. By 150 years after landspreading, the total annual dose peaked at approximately 3 mrem/yr per pCi/g. As in the residential scenario, the peak dose corresponded to a peak in the estimated external radiation dose, reflecting the assumption that all of the clean cover material had eroded away by that time.

As in the residential scenario, the results presented here for the industrial scenario do not consider the fact that additional clean cover material might be spread over a site before construction. However, assuming a new cover layer 0.5-ft thick was put in place before construction, the estimated doses would not be reduced much below those predicted for the first year after landspreading.

4.2.3 Recreational Scenario

Results for the recreational scenario are shown in Figure 6. This scenario assumed that members of the general public would visit the property for recreational uses following landspreading. Annual doses were estimated for an exposure time of only 20 hours per year. Unlike the residential and industrial scenarios, in this scenario it was assumed that clean soil was not placed over the contaminated zone following landspreading. As a result, the estimated dose peaked in the first year after landspreading. For the recreational users, the total dose from all pathways was estimated to be 0.024 mrem/yr per pCi/g of Ra-226, almost entirely from external radiation. The contribution from Ra-228 and Th-228 increased the dose to 0.034 mrem/yr per pCi/g during the first five years following disposal. After this time, a significant amount of Ra-228 had decayed, and the dose was primarily from Ra-226. Radon inhalation was not a significant pathway because the concentration of radon in outdoor air is very low.

4.2.4 Agricultural Scenario

Doses to an off-site receptor from ingestion of produce and meat grown on land used for disposal of NORM waste are shown in Figures 7 and 8, respectively. The receptors were assumed to receive 25% of their total meat and produce from the site. As

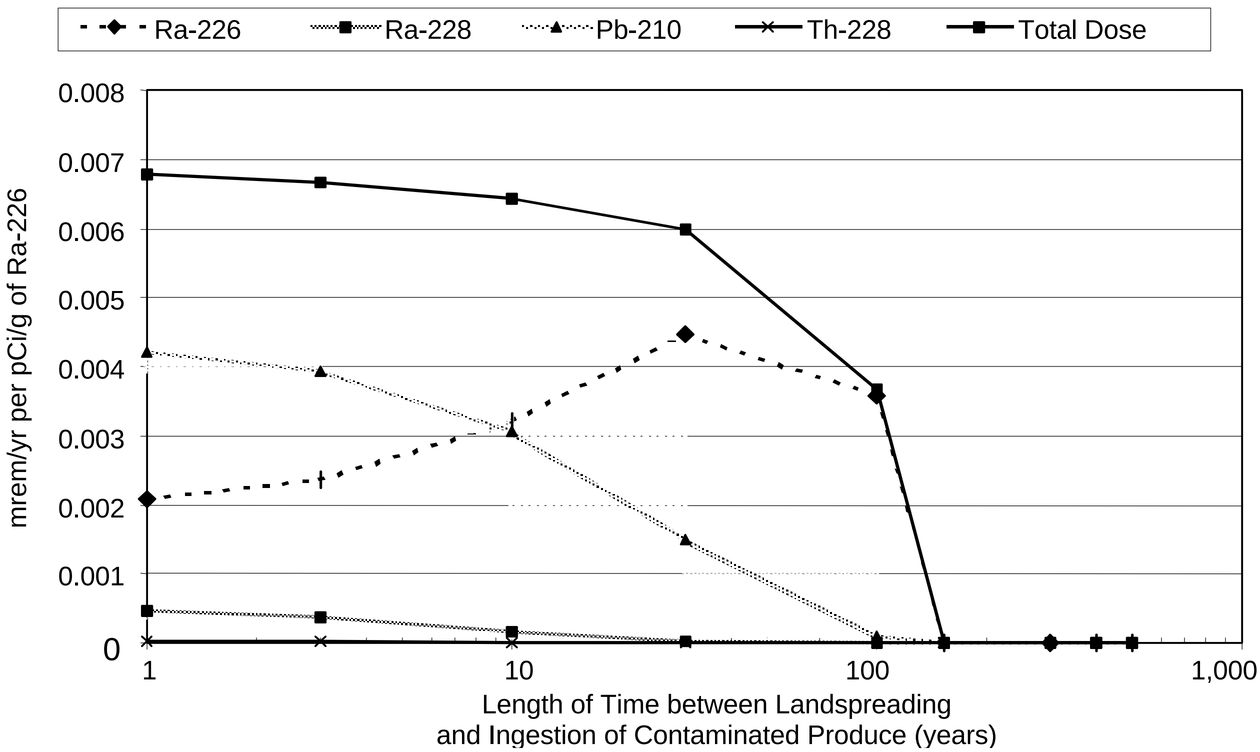

FIGURE 7 Potential Doses to an Individual from Ingestion of Contaminated Produce

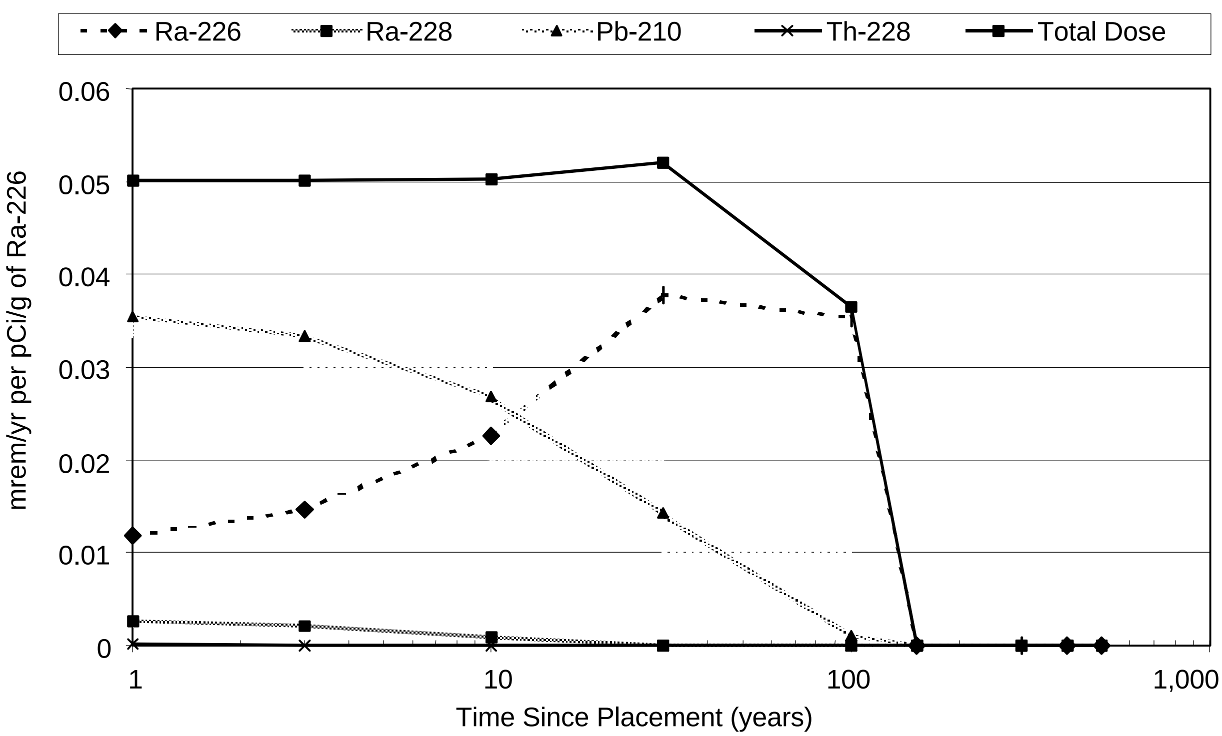

FIGURE 8 Potential Doses to an Individual from Ingestion of Contaminated Meat

in the recreational scenario, in this scenario, it was assumed that clean soil was not placed over the contaminated zone following landspreading The maximum annual dose from ingestion of contaminated produce was estimated to be less than 0.007 mrem/yr per pCi/g of Ra-226 and the maximum dose from ingestion of contaminated meat was estimated to be 0.052 mrem/yr per pCi/g. The major contributors to the dose were from ingestion of Pb-210 and Ra-226.

4.3 COMPARISON OF ESTIMATED DOSES AND RELATED RISK

The estimated annual doses relative to increasing concentrations of Ra-226 in soil are shown in Figure 9 for each scenario considered in this study: landspreading worker, resident in a home with a crawl space (i.e., the worst-case residential scenario), industrial worker, recreational user, and food consumer (i.e., agricultural scenario). Estimated risks of fatal cancer relative to increasing Ra-226 concentrations are presented in Figure 10 for each scenario. The doses and risks reported in the graphs were based on the peak year dose for each scenario. Similar relationships among dose and concentration can be generated for other years on the basis of the information provided in Figures 3 through 8. The radium concentrations presented represent the concentration of radium in soil after landspreading, not the concentration in the waste.

4.4 SENSITIVITY ANALYSES

Sensitivity analyses indicated that the parameters with the most significant impact on dose were the radon emanation fraction, building air exchange rate, thickness of the contaminated zone, and thickness of the clean cover material. Other parameters investigated in the sensitivity analysis had little impact on the resultant estimated doses.

The most critical parameters for scenarios having an indoor radon pathway were the Rn-222 emanation fraction and the building air exchange rate. In the base case, a Rn-222 emanation fraction of 0.04 (the average fraction measured for petroleum scale, [Rood and Kendrick 1996]) was used. Variability of this parameter by a factor of two resulted in a 30% increase or decrease in dose for the most conservative residential scenario. When the Rn-222 emanation fraction was increased to a value of 0.2, which was assumed for sludge in Baird et al. (1990), EPA (1993), and Smith et al. (1996), the resultant dose increased by a factor of two. Similarly, if the building air exchange rate was increased by a factor of two for the home constructed with a crawl space, the dose from radon decreased by a factor of 2.6, and the total dose decreased by a factor of 1.5. Variation of the building air exchange rate parameter did not significantly affect the total dose estimated for the home constructed with the basement.

The thickness of the contaminated zone also had a significant impact on the dose estimates for all scenarios. A 50% increase in thickness resulted in a 10% increase in the resultant dose. For this assessment, a thickness of 8 in. (20 cm) was used. In reality, it is

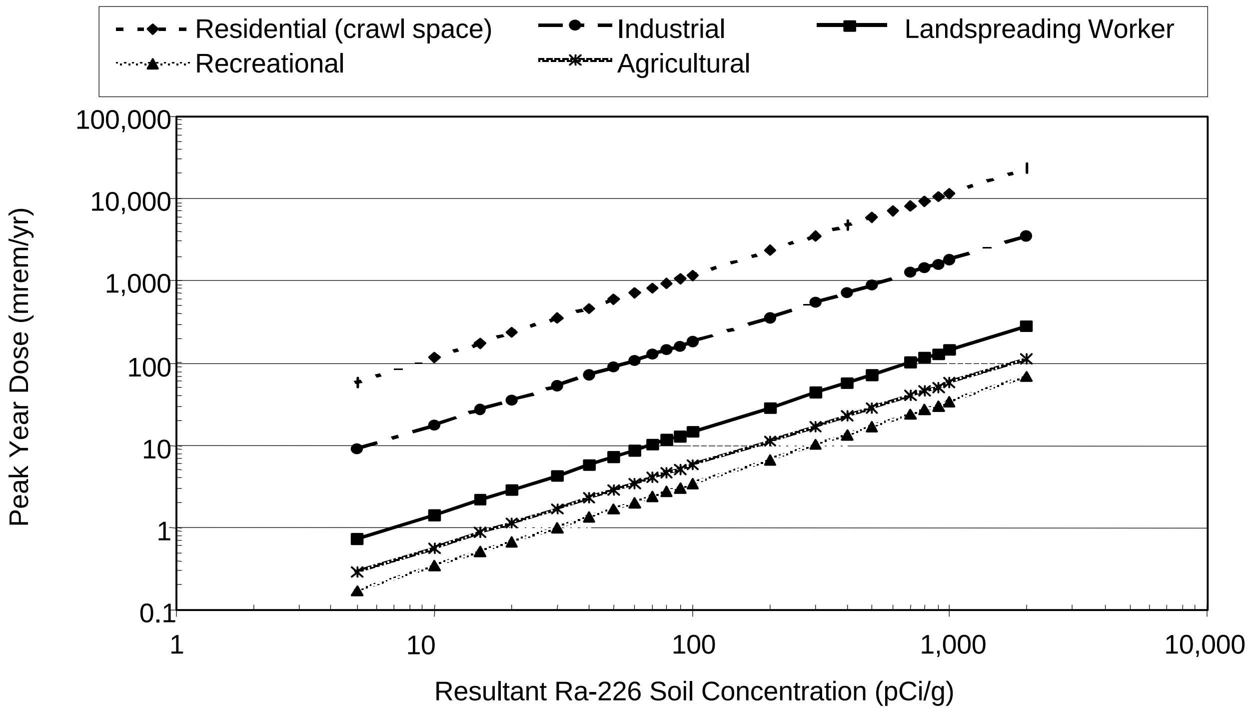

FIGURE 9 Correlation of Peak Year Dose to NORM Concentration

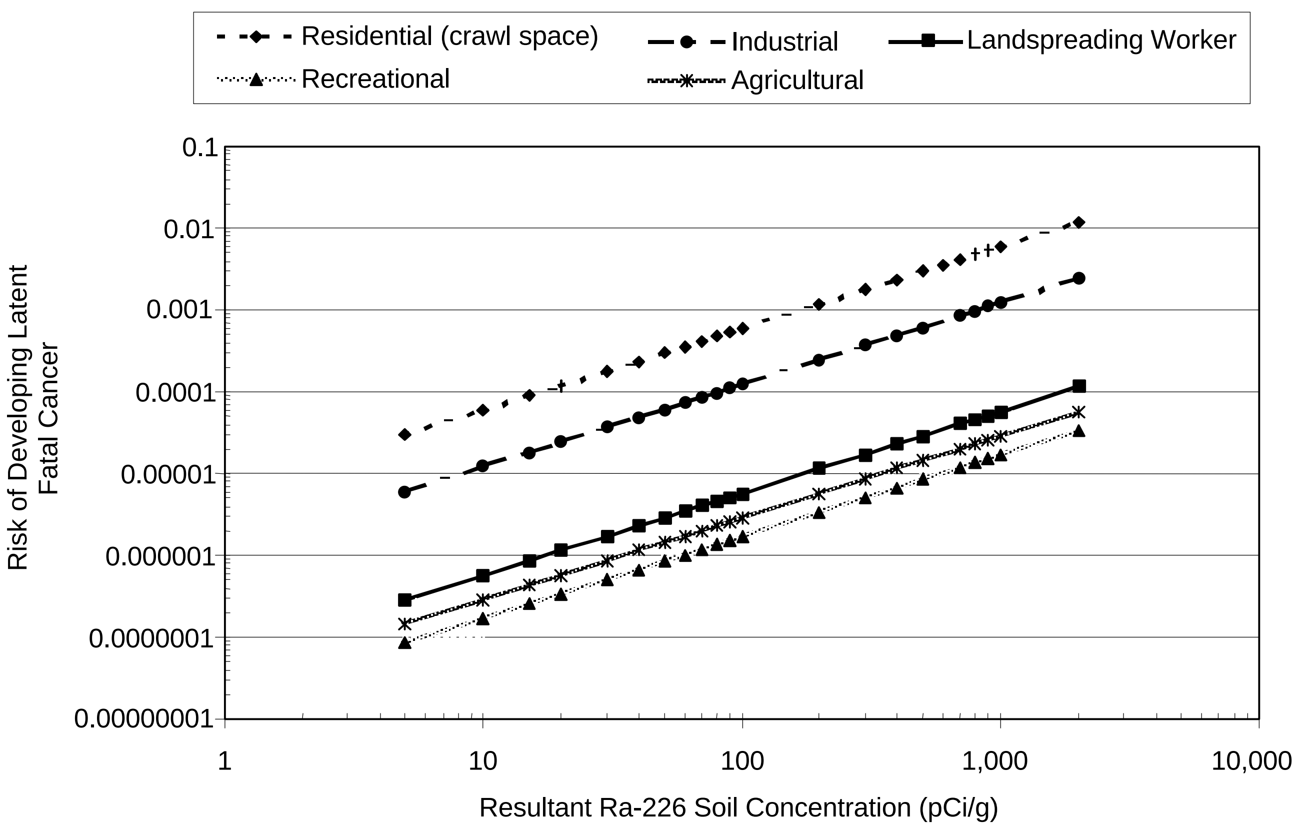

FIGURE 10 Correlation of Individual Risk of Developing Latent Fatal Cancer to NORM Concentration

unlikely that the thickness would extend beyond 1 ft because of the limited supply of oxygen, which is a requirement for the breakdown of hydrocarbons.

A sensitivity analysis performed on cover material thickness indicated that if the cover layer was doubled to a thickness of 1 ft, potential external radiation doses to residents of either type of home would be reduced by approximately 85%. A similar reduction in the external dose to a worker at an industrial facility would occur. For a resident of a home with a crawl space and a worker at an industrial facility, total dose reductions would not be as great as 85% because the cover thickness would not affect the radon dose level significantly. For both of these receptors, the total dose would be reduced by a varying amount, ranging from 10-20% if the home was built in the first 60 years after landspreading and going up to 40% if the home was built 150 years after landspreading. In addition, the peak year dose for residents and industrial workers would be shifted from 150 years to approximately 300 years after landspreading, primarily because it would take longer for the cover to erode away completely. As a result, the peak year dose would be reduced by approximately 10% due to the incremental radioactive decay that would occur over the additional 150 years.

A sensitivity analysis also was performed to investigate the effect on potential doses associated with the size of the landspreading area, on the basis of the assumption that landspreading might be performed on smaller tracts of land. If the tract of land was only 0.2 acre, the potential dose was reduced by only approximately 5%.

The effect of increasing the plant-to-soil transfer ratio by a factor of 10 also was examined in the sensitivity analyses. For the residential scenario, increasing the plant-to-soil ratio did not increase the dose, since the ingestion pathway was a minor component of the total dose. However, for the agricultural scenario, increasing the plant-to-soil ratio by a factor of 10 resulted in a 10-fold increase in the receptor's dose from plant ingestion.

4.5 DOSES ASSOCIATED WITH ESTABLISHED STATE EXEMPTION LEVELS

As stated in Section 1.2.2, established state exemption levels for radium in soils, which determine when property may be released for unrestricted use, typically have been set between 5 and 30 pCi/g above the background level. In Texas, landspreading of NORM wastes is allowed only when the resultant total radium concentrations in soil are ≤5 pCi/g above background. In New Mexico, the equivalent landspreading standard is ≤30 pCi/g of Ra-226 above the background level. Other states considering landspreading of NORM as a viable disposal alternative may use the Texas or New Mexico limits or their own state exemption levels for soil.

The potential peak year doses associated with landspreading of NORM wastes to the radium concentrations discussed above are presented in Table 2 for each scenario modeled. As shown, the results of this study indicate that for a radium concentration of 5 pCi/g, the resulting dose for the residential scenario was 30 to 59 mrem/yr, depending

TABLE 2 Potential Peak Year Doses That Correspond with Various Radium-226 Concentrations after Landspreading

Ra-226 Concentration after Landspreading (pCi/g)	Receptor Dose (mrem/yr) by Scenario				
	Worker	Residential[a]	Industrial	Recreational	Agricultural
5	0.72	30–59	15	0.17	0.28
10	1.4	60–120	30	0.34	0.57
15	2.2	90–180	45	0.5	0.84
30	4.3	180–350	91	1.0	1.7

[a] The range presented for the residential scenarios represents the doses estimated for the two types of home construction. The lower dose corresponds to the resident living in a home constructed with a basement and the higher dose corresponds to the resident living in a home constructed with a crawl space.

on type of home construction, and the dose for the industrial scenario was 15 mrem/yr. Doses for the recreational and agricultural scenarios were estimated to be less than 1 mrem/yr. The estimated health risks corresponding to these doses ranged from 7×10^{-8} for the recreational scenario to 3×10^{-5} for the most limiting residential scenario (i.e., a home with a crawl space directly on top of the landspread NORM). A soil concentration limit of 15 pCi/g resulted in an estimated dose of 90 to 180 mrem/yr for the residential scenario, 45 mrem/yr for the industrial scenario, and less than 1 mrem/yr for the recreational and agricultural scenarios. The estimated health risks corresponding to these doses ranged from 2×10^{-7} to 9×10^{-5}. A soil concentration limit of 30 pCi/g resulted in an estimated dose of 180 to 350 mrem/yr for the residential scenario, 91 mrem/yr for the industrial scenario, 1.7 mrem/yr for the agricultural scenario, and 1 mrem/yr for the recreational scenario. Corresponding health risks ranged from 4×10^{-7} to 2×10^{-4}.

As noted in Section 1.2.3, the current acceptable dose limit for members of the general public is 100 mrem/yr. On the basis of the analyses presented in this study, the equivalent Ra-226 concentrations in soil corresponding to this dose limit were 8.5 to 17 pCi/g for the residential scenario, 33 pCi/g for the industrial scenario, 3,700 pCi/g for the recreational scenario, 1,900 pCi/g for the agricultural scenario, and 1,000 pCi/g for the worker scenario.

4.6 UNCERTAINTIES

The results presented in this report are based on best estimates for each of the input parameters that were made be using available data and reasonable but conservative exposure parameters. As discussed in the section on sensitivity analysis (Section 4.4), there is a large variation in dose with changes in the radon emanation fraction and the building exchange rate parameters. The emanation fraction used in this study, 0.04, was based on data presented for actual measurements taken from NORM scale. Emanation rates lower than 0.04 would result in lower doses (and corresponding higher dose-equivalent concentrations) for the residential and industrial scenarios. Increased ventilation in a building also would significantly decrease the resulting dose from radon. Soil concentrations levels estimated for the residential and industrial scenarios may be too conservative because simplified assumptions regarding construction practices were used. Construction practices would most likely involve excavation and mixing of soil and addition of new soil for regrading and landscaping. The full impact of these practices may not be represented in the dose estimates and corresponding soil concentrations.

The evaluation of risk to human health presented by low-level exposure to radiation is subject to a large degree of uncertainty. The risks presented in this report were estimated on the basis of the linear no-threshold model, which assumes that there is a linear relationship between radiation dose and health risk, and that there is not a threshold level of exposure below which there are no health impacts. Extrapolation assumes that the impacts are identical at any dose, which may not be a valid assumption. There may, in fact, be a threshold below which there are no risks from exposure to radiation, given that there is no scientific evidence to substantiate health impacts from low-level radiation exposure. Risks presented in this report should be viewed in light of the large degree of uncertainty associated with the limitations in methodology.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The results of this assessment provide estimates of annual doses and resultant health risks to workers and the general public for a variety of potential land use scenarios. On the basis of these results, the following conclusions can be drawn:

- Potential radiological doses and resultant health risks to workers actively involved in landspreading NORM wastes are below accepted public dose limits when Ra-226 concentrations in soil after landspreading are below 1,000 pCi/g, because landspreading does not require excessive handling of the waste and typical exposure times are limited.

- Potential radiological doses to the general public for all land use scenarios evaluated are reasonably low (i.e., below 60 mrem/yr considering all pathways) when the concentration of Ra-226 in soil after landspreading is 5 pCi/g or less above the background level.

- Potential doses to residents and industrial workers can vary greatly depending on a variety of factors such as type of building construction (e.g., crawl space, basement, slab), construction practices employed (e.g., the degree of excavation and/or regrading, use of clean cover material), and natural processes (e.g., erosion rate).

- Concentrations of Ra-226 in soil after landspreading that are above approximately 10-16 pCi/g for the residential receptor (depending on construction type) and 35 pCi/g for the industrial receptor result in potential radiological doses exceeding 100 mrem/yr, assuming the layer of clean cover material has been allowed to erode away.

- For the residential receptor living in a home with a crawl space, when the cover layer is maintained at a thickness of 0.5 ft, a Ra-226 concentration in soil after landspreading greater than 12 pCi/g may result in doses exceeding 100 mrem/yr, of which 80% is attributed to inhalation of radon. Doubling the cover layer thickness does not appreciably affect the upper limit on Ra-226 concentration.

- For the resident of a home with a basement, when the cover layer is maintained at a thickness of 0.5 ft, doses would not exceed 100 mrem/yr until the Ra-226 concentration in soil exceeded approximately 65 pCi/g. If the cover layer thickness is doubled, this dose limit would not be exceeded until the Ra-226 concentration exceeded several hundred pCi/g. This conclusion would apply to any case in which the NORM waste has been totally excavated from within the footprint of the building.

- Potential radiological doses to the general public associated with a future agricultural land use scenario are negligible except when concentrations of Ra-226 in soil after landspreading exceed several hundred pCi/g (e.g., 200 pCi/g corresponds to 10 mrem/yr.)

5.2 RECOMMENDATIONS

On the basis of the above conclusions, the following recommendations are suggested:

- Landspreading activities that result in Ra-226 concentrations of ≥10 pCi/g in soil should be evaluated on a case by case basis to estimate potential future risk to the general public. Future land use scenarios in which individuals are exposed over long periods to a soil Ra-226 concentration level of 10 pCi/g or more (e.g., the residential scenario), may result in unacceptably high doses depending on a variety of factors. These factors include the type of building construction (e.g., crawl space, basement, slab), construction practices employed (e.g., the degree of excavation and/or regrading, use of clean cover material), and natural processes (e.g., erosion rate).
- States that decide to allow landspreading of NORM that results in Ra-226 concentrations greater than 5 pCi/g above background should consider establishing policies that will restrict future land use or, at a minimum, ensure that future land owners are advised of the landspreading activities and the potential associated health risks. Such a policy is especially important because Ra-226 has such a long half-life.

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