SPE 29712

Radiological Dose Assessment Related to Management of Naturally Occurring Radioactive Materials Generated by the Petroleum Industry

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ABSTRACT

A preliminary radiological dose assessment related to equipment decontamination, subsurface disposal, landspreading, equipment smelting, and equipment burial was conducted to address concerns regarding the presence of naturally occurring radioactive materials in production waste streams. The assessment evaluated the relative dose of these activities and included a sensitivity analysis of certain input parameters. Future studies and potential policy actions are recommended.

INTRODUCTION

The presence of naturally occurring radioactive materials (NORM) in oil and gas production and processing wastes has been recognized since the 1930s. However, concerns about the possible associated health risks did not arise until the mid-1980s, when the industry and regulators realized that NORM occurrence was more widespread than originally thought and that activity levels could be quite high. Although it is widely acknowledged that both workers and the general public may be at risk of radiation exposure resulting from NORM-contaminated waste streams, the magnitude of that risk and the resultant need to regulate NORM have been debated. This dose assessment adds new information to the debate surrounding NORM regulation by (1) estimating doses related to a set of management and disposal methods that includes several currently acceptable methods, a prospective method, and two past practices; (2) comparing the

estimated doses related to these different methods; and (3) conducting a sensitivity analysis of some of the key input parameters.

In the past few years, the petroleum industry has adopted methods for managing and disposing of NORM-contaminated wastes and equipment that are more restrictive than past practices and are likely to provide greater isolation of the radioactivity. State-level NORM regulations also have established standards for the management and disposal of NORM that favor more restrictive methods. Currently acceptable NORM management and disposal methods include (1) burial at licensed NORM or low-level radioactive waste disposal facilities, (2) dilution and burial at a licensed facility, (3) downhole encapsulation inside a plugged and abandoned well by license only, (4) underground injection into a subsurface formation by license only, and (5) regulated equipment decontamination and reuse. Another method, smelting contaminated equipment, also has been considered by the petroleum industry as a potentially viable disposal option.

The scope of this dose assessment includes six NORM management and disposal activities: equipment decontamination, downhole encapsulation, underground injection, landspreading with dilution, equipment smelting, and landfilling contaminated equipment. Disposal at licensed NORM or low-level radioactive waste disposal facilities was not included in this assessment on the assumption that the associated doses are acceptable by virtue of the licensed status of the facilities. Maximum individual dose equivalents associated with the selected activities were estimated and used as the basis for comparison between disposal options, as appropriate. Collective doses were considered to be beyond

References and illustrations at end of paper

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the scope of this study and were not calculated.

Input parameters were selected on the basis of reviews of previous, related risk assessments; relevant published data; and discussions with other risk assessment researchers and representatives of federal and state regulatory agencies, industry, and academia. Sensitivity analyses of some of the key input parameters were conducted to assess their impact on the predicted doses. Parameters chosen for the sensitivity analyses include those for which a set of definitive values could not be chosen because of variability in possible conditions (e.g., groundwater gradient, hydraulic conductivity) and those for which definitive data have not been collected but are thought to be quite variable (e.g., source term concentrations, the ratio of radium-226 [Ra-226] to radium-228 [Ra-228]).

REGULATORY FRAMEWORK

Currently, there are no federal regulations specifically addressing the handling and disposal of NORM. In the absence of federal regulations, individual states have developed their own regulatory programs. To date, five states have promulgated NORM programs and many other states have drafted NORM regulations. In addition, the Conference of Radiation Control Program Directors, Inc. (CRCPD) has drafted recommended NORM regulations, referred to as the Part N regulations, for use by states in developing their NORM regulatory programs.¹

The existing state regulatory programs establish standards for (1) the licensure of parties possessing, handling, or disposing of NORM; (2) the release of NORM-contaminated equipment and land; (3) worker protection; and (4) NORM disposal. In general, the effect of state-level NORM regulation has been to limit the number of disposal options available to the petroleum industry. Under these regulations, some of the previously acceptable waste disposal methods (e.g., landspreading, shallow burial) are no longer allowed when the waste stream is known to contain NORM in excess of a specified activity concentration level. Similarly, methods for cleaning contaminated equipment have been modified to reduce potential occupational exposures. The reuse of contaminated equipment also has been restricted to reduce the potential for both occupational and public exposures.

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.² This limit would apply to workers who handle NORM if they are 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 is 100 mrem/yr.³ However, the CRCPD has proposed

a limit of 25 mrem/yr¹ and the U.S. Environmental Protection Agency (EPA) has proposed a limit of 15 mrem/yr⁴ for public doses.

SOURCE TERM CHARACTERIZATION

The primary radionuclides of concern in oil and gas NORM are Ra-226 and Ra-228. These isotopes are members of the uranium-238 and thorium-232 decay series, respectively. The uranium and thorium isotopes, which are naturally present in the subsurface formations from which hydrocarbons are produced, are largely immobile and remain in the subsurface. The more soluble radium can become mobilized in the formation water and be transported to the surface in the produced water waste stream. The radium may remain in solution or precipitate in scale or sludge deposits depending on water salinity and on temperature and pressure phase changes. It has been estimated that 25,000 t of NORM-contaminated scale and 225,000 t of NORM-contaminated sludge are generated each year by the petroleum industry.⁵

Adequate characterization of the source term concentration has been a major limitation of most NORM risk assessments conducted to date. Available data indicate that the total radium concentrations in scale and sludge vary greatly from undetectable levels to extreme measurements of 410,000 pCi/g in scale⁵ and 700,000 pCi/g in sludge.⁶ Most data describing source term concentrations have been collected at the state and company levels and have not been aggregated to provide a comprehensive data set. The only national-level survey conducted to date,⁷ sponsored by the American Petroleum Institute (API), measured external gamma exposures from contaminated equipment and converted those readings to total radium concentrations by using 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 is heavily dependent 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 be contaminated with NORM due to previous survey results.⁷ Despite these limitations, the API survey data have been used in NORM risk assessments^{5,8} to calculate a median source term concentration because they are the most comprehensive data available. They were used in this assessment as well, for the same reason; however, this assessment attempted to place boundaries on the uncertainty related to the source term

concentrations by calculating doses with both a median and 75th-percentile composite concentration for many of the scenarios.

The source term concentrations used in this assessment were based on the scale and sludge composite concentrations used in a risk assessment conducted by the EPA and the state of Louisiana.⁸ In that study, median, 75th-percentile, and maximum concentrations in scale and sludge were derived from more than 3,000 external gamma measurements collected in Louisiana as part of the API survey. The median and 75th-percentile concentrations calculated for the Louisiana data, provided in Table 1, were used for this assessment because they represent the most complete set of data available; the median concentrations also were used by the EPA in its diffuse NORM waste study.⁵ On the basis of the Louisiana data, the median concentration for scale is 480 pCi/g total radium and the 75th-percentile concentration for scale is 2,700 pCi/g total radium. For sludge, the median concentration is 75 pCi/g total radium. (Because doses related to the 75th-percentile concentrations in sludge were not calculated in this assessment, these values are not provided in Table 1.)

Although definitive data describing the concentration ratio of Ra-226 to Ra-228 are not available, a ratio of 3:1 was assumed. In addition, to be conservative, secular equilibrium was assumed for the radium decay progeny. These assumptions regarding source term characterization are consistent with assumptions used in several other studies.^{5,8,9}

EQUIPMENT CLEANING FACILITIES

Estimated doses related to equipment cleaning facilities where scale and sludge are removed from pipe, vessels, and other equipment were calculated for three individuals: pipe cleaner, storage yard worker, and resident living adjacent to a storage yard. The intent of this assessment was to evaluate reasonable, maximum, annual doses to workers cleaning contaminated equipment at a licensed facility, operating in compliance with the Louisiana NORM regulations,¹⁰ and to an adjacent resident. Worker doses at unregulated facilities also are discussed. Median and 75th-percentile concentrations of total radium from Table 1 were used to place boundaries on the uncertainty associated with the source term concentration to the extent possible, given the available data.

External doses for workers were calculated with the Microshield Version 4 computer code.¹¹ The inhalation and ingestion pathways were modeled only for workers who use dry pipe cleaning methods with the RESRAD-BUILD computer code,¹² consistent with a methodology developed by the U.S. Nuclear Regulatory Commission.¹³ All other workers at an equipment cleaning facility were assumed to be protected from inhalation

and ingestion because (1) wet pipe cleaning processes typically are conducted inside a closed system and (2) storage yard workers have minimal contact with dry, respirable, NORM-contaminated particles. In addition, at licensed facilities, workers who handle the NORM-contaminated wastes directly are required to wear respirators and protective clothing.

By using median source term concentrations, the total estimated dose for workers at equipment cleaning facilities ranges from 4 to 50 mrem/yr (Table 2). These estimated doses are considered to be very conservative due to the nature of the input parameters and the assumption that workers would be exposed only to equipment contaminated at median or higher source term concentrations. For the pipe cleaners, external doses are estimated at 4 mrem/yr. For the storage yard worker, who spends the most time around the equipment, the external dose is estimated at 40 mrem/yr. Pipe cleaners who use dry processes without respirators have the highest estimated total dose of 50 mrem/yr from all pathways (i.e., inhalation, ingestion, and external irradiation), assuming a conservative dust loading factor and secular equilibrium. For the resident living adjacent to a storage yard, the estimated dose is approximately 0.2 mrem/yr.

Sensitivity analyses were conducted on the Ra-226:Ra-228 ratio, pipe wall thickness, and distance between source and receptor. Changing the Ra-226:Ra-228 ratio from 3:1 to 1:0, a more conservative value, increased the estimated doses by approximately 10%. Varying the thickness of the pipe wall from 0.5 to 2 cm decreased the dose by approximately 60%. For the pipe cleaning scenario, the distance between the source and receptor was varied from 0.3 to 1 m, which resulted in a 25% decrease in dose. For the storage yard worker scenario, the distance from the source to the receptor was varied from 1 to 6 m, which decreased the dose by a factor of 10. If the 75th-percentile source term concentration for scale is used, estimated doses increase by a factor of approximately 5.6.

SUBSURFACE DISPOSAL

Subsurface disposal options include underground injection and downhole encapsulation. Underground injection is accomplished by injecting a slurry of NORM-contaminated wastes into a deep, subsurface formation. Downhole encapsulation entails placing NORM-contaminated scale, sludge, tubing, and other small pieces of equipment (e.g., valves, filters, screens) inside the casing of a well that is to be plugged and abandoned. After the material is in place, the wellbore is sealed with cement or grout to isolate the contaminated material. It was assumed that the depth of encapsulation is similar to the depth of injection and that one or more confining units isolate that depth from the groundwater aquifer. Transport of the radionuclides was simulated for a 100,000-year period. Conservative assumptions were made in

running the models, thereby resulting in higher estimated doses at the receptor locations than would be expected under more realistic conditions.

Doses resulting from the underground injection and downhole encapsulation of NORM-contaminated wastes were estimated at several different receptor locations. In addition, a number of possible scenarios were simulated that represent casing failures in each geologic layer. Both downhole encapsulation and underground injection activities were modeled with the same assumptions and settings. A three-dimensional model, SWIFT II,¹⁴ was employed to model casing failures that might occur at different depths and the subsequent transport of radionuclides to downgradient receptor locations. The model stratigraphy consisted of a top sandstone layer (550 m thick) considered to be the source of groundwater at the receptor locations, underlain by alternating shale and sandstone layers, each 490 m thick. The total stratigraphic sequence consisted of three sandstone and three shale layers.

Separate model runs were made, assuming that casing failure caused the entire volume of NORM-contaminated waste to be released into each geologic layer, including the drinking water aquifer. It was assumed that 100,000 barrels of a slurry contaminated with 2,000 pCi/l total radium were injected over a period of four days. Radionuclide concentrations were calculated at receptor points located at a depth of approximately 90 m in the drinking water aquifer at distances ranging from 0 to 32 km downgradient of the disposal site. Additional calculations were made for the three closest receptors, assuming that two municipal wells pumping simultaneously at a rate of 0.6 l/s were installed at 0.3 and 0.8 km from the disposal site. Annual doses from ingestion of the groundwater were calculated using exposure parameters recommended by the EPA for reasonable maximum residential exposures.¹⁵ An individual was assumed to drink two liters of water each day, 350 days per year.

Table 3 presents the estimated doses at the three closest receptors for the six most conservative scenarios modeled. Predictably, the highest concentrations of Ra-226 calculated at the receptor points correspond to injection of the slurry directly into the drinking water aquifer, at depths ranging from approximately 90 to 275 m. At the receptor located 0.3 km from the disposal site, the maximum calculated Ra-226 concentration was approximately 1 pCi/l, which occurred 700 years after failure. This concentration equates to an estimated dose of 1 mrem/yr. All values calculated for injection into geologic units below the aquifer were at least five orders of magnitude smaller. Calculated radon-222 (Rn-222) concentrations were insignificant, at least four orders of magnitude below those calculated for Ra-226.

Raising the hydraulic conductivities for the sandstones and shales by one order of magnitude increased the predicted Ra-226 concentrations slightly and lowered the arrival times of the maximum concentrations at the receptor points. Increasing the groundwater gradient by one order of magnitude had a similar effect. Reducing the distance to the receptors by a factor of two had a negligible effect on the predicted results. Doubling the radium concentration level in the slurry effectively doubled the observed maximum concentrations at the receptors and had small effects on arrival times. The installation of two pumping wells (1) increased the vertical component of the contaminant migration, resulting in an increased concentration at the receptor located directly above the failure point; (2) increased dispersion of the contaminant plume, resulting in decreased values at the downgradient receptors; and (3) decreased arrival times of the maximum concentration values at all receptors.

The estimates used to model underground injection were extremely conservative for most parameters. The results suggest that deep underground injection of slurries with total volumes less than 100,000 barrels cause very low-level concentrations in the groundwater and corresponding low estimated doses. Even injection directly into the drinking water aquifer does not result in appreciable concentrations of Ra-226 or Rn-222 at receptor locations 0.3 km or farther away.

The model runs for underground injection effectively model downhole encapsulation as well, if instantaneous radium dissolution is assumed to be the leaching model. If more realistic leaching times are assumed, it can be predicted that radionuclide concentrations resulting from casing failure during downhole encapsulation will be lower at all receptor locations than those calculated for underground injection of the slurry. Casing failures during encapsulation were assumed to be identical to casing failures during injection.

LANDSPREADING WITH DILUTION

Landspreading with dilution, in which NORM-contaminated wastes are spread over the surface of a parcel of land and mixed into the upper layer of soil, was modeled with the RESRAD computer code.¹⁶ Although this practice is no longer permitted in states that have NORM regulations, it was included in this assessment because some individuals in the industry regard it as a valid option and because it may still be employed in states that do not have a NORM regulatory program.

The scenario evaluated for this assessment considered a parcel of land that has been used repeatedly for landspreading. As a baseline case, an area of 1 acre (4,047 m²) with a contaminated zone 20 cm thick was assumed. In the baseline case, it was

assumed that the soil had a concentration of 240 pCi/g total radium, based on the median source term concentration for scale (Table 1) and a 100% dilution factor. A range of resultant soil concentrations was modeled to represent various levels of dilution. Resulting soil concentrations of 30 and 5 pCi/g total radium were assumed because these values bracket the limits established by existing state-level NORM regulations and the CRCPD Part N regulations for land being released for unrestricted use. It was assumed that the land was released for unrestricted use, at which time a family began living on the property. The pathways analyzed include external irradiation; inhalation of resuspended dust and radon; ingestion of crops, milk, and meat grown on the property; ingestion of fish from a nearby pond; ingestion of contaminated soil; and ingestion of surface water or groundwater. For the radon pathway, an emanation coefficient factor of 0.05 was used.^{5,8,9} RESRAD default values were assumed for all other input parameters because they represent a generic facility and are intended to be conservative.

For the baseline concentration level (i.e., 240 pCi/g total radium), the estimated total dose was on the order of 3,000 mrem/yr at the time the property was released. The major contributor to dose was external gamma radiation, which accounted for more than 80% of the total dose. Ingestion of crops contaminated by uptake of lead-210 accounted for approximately 15% of the total dose, and inhalation of Rn-222 contributed about 1%. When the resultant soil concentration was lowered to 30 and 5 pCi/g, the estimated total dose from all pathways decreased to approximately 340 and 60 mrem/yr, respectively.

The exposure pathway of greatest concern related to landspreading of NORM-contaminated scales and sludges is external irradiation. Arguments that the radium is virtually immobile in natural soils cannot be used to justify landspreading as a safe disposal method for NORM-contaminated wastes. Although the relative immobility of radium in soils may be protective of groundwater, the other exposure pathways result in a very high total dose. The addition of cover material over the waste would attenuate gamma radiation.

EQUIPMENT SMELTING

A large volume of NORM-contaminated scrap metal is generated by the petroleum industry each year. Although smelting currently is not employed by the industry to dispose of contaminated equipment, it was included in this study to assess its feasibility as a disposal option. A number of scenarios were modeled to estimate potential doses to commercial metal workers, the general public, and petroleum industry workers related to the smelting of NORM-contaminated equipment. The methodology used to model these scenarios was adopted from a

methodology used by Argonne National Laboratory to assess the radiological impacts to workers and the general public related to the recycling of radioactive scrap metal generated by the U.S. Department of Energy.¹⁷ Consistent with this methodology, potential doses were evaluated for several steps of the recycling process, including the transportation of contaminated scrap metal, smelting process, manufacture of industrial products, and fabrication and distribution of end-use products. In addition, potential radiological doses from the use of products made from the recycled steel and slag were evaluated. Radiological doses were analyzed with the RESRAD-BUILD computer code.¹² The pathways evaluated include external irradiation, inhalation of contaminated particulates, and incidental ingestion. Potential doses to the public from any emissions released during the smelting process were analyzed with the CAP88-PC computer code.¹⁸

The radiological impacts of recycling contaminated metal were evaluated on the basis of maximum individual dose equivalents. Radiological impacts from recycling are dependent upon many factors, including the annual throughput, amount and concentration of specific radionuclide contaminants, dilution factor, radionuclide partition factors, and distribution of contaminated scrap in the steel industry. Because this information is not available, several conservative assumptions were made, based upon available data. In light of this, the results of this assessment should be viewed as preliminary.

The median source term concentration of total radium in scale (Table 1) and a Ra-226:Ra-228 ratio of 3:1 were assumed. The contaminated equipment was assumed to be melted in 100-t batches. The amount of scale was estimated to be 5% of the total mass, assuming no initial decontamination of the equipment other than removal of sludge from vessels. An estimate of 50,000 t was used to conservatively represent throughput at a regional level. The partition factors, which describe the fraction of the original radionuclide concentration that ends up in each by-product of smelting, were derived from available literature and bench-scale testing for the radionuclides of interest.¹⁹⁻²¹ For the steel ingots, off gas, and slag, the partition factors were conservatively assumed to be 0.1, 0.005, and 1, respectively. A dilution factor of 1:10 also was assumed to be realistic.

Table 4 summarizes the estimated doses related to smelting contaminated equipment. Preliminary dose estimates indicate that potential doses to commercial workers at a smelting facility would be highest for the worker who handles the slag product. On the basis of conservative exposure parameters, the estimated annual dose to the slag worker is approximately 14 mrem; more than 95% of the dose is from external radiation. Increasing the radionuclide concentrations from the median to 75th-percentile values, increased the dose to approximately 80 mrem/yr. A sensitivity analysis was conducted on the activity concentration

and amount of scale contained in the initial charge. The amount of scale in the initial charge was varied from 1 to 10% by weight, for both the median and 75th-percentile radionuclide concentrations; the resultant doses to the slag worker varied from 3 to 160 mrem/yr.

Doses to the general public from reuse of the recycled steel and slag by-products were estimated assuming that the steel was recycled into an automobile and the slag was recycled in construction of a parking lot. The estimated individual annual dose associated with use of the recycled steel and slag was approximately 0.02 mrem. Doses related to smelter emissions were estimated for the maximally exposed individual who lived 500 m from the stack at 4×10^{-4} mrem/yr.

For comparison purposes, doses related to landfilling the same quantity of contaminated equipment were calculated with the RESRAD code.¹⁶ It was assumed that a pile of scrap metal with a volume of 5,700 m³ was mixed with an equal volume of clean soil and then covered with a 0.5-m thick layer of clean soil. The estimated dose to an individual living on the site of this landfill was 80 mrem/yr. This dose is approximately two orders of magnitude greater than any estimated general public dose related to smelting or product use.

Because of the large degree of uncertainty related to the radionuclide source term concentrations, annual throughput, and amount of scale contamination contained in the initial throughput, the estimated doses related to equipment smelting must be interpreted in a relative manner only. If smelting were to be implemented by the industry, it could be controlled to keep doses as low as possible. For example, by limiting the contamination level of the initial throughput, the resultant slag concentrations could be controlled to a specified activity concentration. Because smelting concentrates almost all of the radionuclides of concern in the slag, controlling the activity levels in the slag might relieve some of the factors that determine the feasibility of smelting as a disposal option. Controlling the activity levels in the slag would reduce exposures for workers who handle the slag. It also could provide greater flexibility in disposing of the slag and potentially relieve the industry of having to dispose of the slag at a regulated disposal facility. By minimizing the slag disposal costs, the industry could optimize the savings realized by recycling the steel. Other aspects that need to be explored to determine the feasibility of recycling NORM-contaminated equipment include the political, economic, sociological, and nonradiological impacts. In addition, the willingness of the scrap metal recycling industry to handle radioactive scrap metal needs further investigation.

COMPARISON OF ESTIMATED DOSE

The scope of this assessment is quite broad in that it addresses a variety of NORM management and disposal options that the industry may pursue. These methods are not entirely comparable because they do not apply to exactly the same set of NORM-contaminated wastes. Absolute health risks cannot be determined with the estimated doses from this assessment because of (1) the uncertainty of the source term characterization and (2) the conservative nature of many of the input assumptions. However, it is possible to compare the estimated doses related to some of these methods as a preliminary indication of the relative risks associated with each management and disposal method. Better characterization of the source term is needed to adequately assess the radiological impacts associated with various NORM management and disposal alternatives. The following comparisons of estimated dose related to NORM management and disposal options can be made on the basis of the conclusions drawn in this assessment:

- External exposures are roughly equivalent for workers at licensed and unregulated equipment cleaning facilities. However, the potential dose to workers from inhalation or ingestion of NORM particulates may be greater for workers at unregulated facilities where respirators and protective clothing are not used during dry pipe cleaning operations. Additional information about the dry pipe cleaning processes (e.g., dust loading factors, worker practices) and the source term are needed to fully quantify the doses related to the inhalation and ingestion pathways.
- The estimated doses to the general public associated with casing failures during underground injection of NORM-contaminated wastes are higher than those associated with casing failures during downhole encapsulation. However, the estimated doses associated with either subsurface disposal method appear to be so low that risk to the general public from either method is negligible.
- Assuming residential land-use, landspreading with dilution presents the highest potential dose to the general public of all of the methods assessed in this study.
- Estimated doses to the general public from both smelter stack emissions and use of products made from recycled steel and slag are lower than estimated doses related to landfilling the same quantity of NORM-contaminated equipment by at least two orders of magnitude.

RECOMMENDATIONS

The following studies and potential policy actions are recommended:

- NORM wastes generated by the petroleum industry should be further characterized to improve efforts to assess potential doses to workers and the general public. Further characterization of the source term concentration is particularly important. Existing data collected at the state and company levels should be aggregated to improve efforts to calculate statistically representative source term concentrations.
- NORM regulatory programs should be encouraged at the state level to provide uniform and comprehensive control of NORM. In particular, these programs should establish standards for worker health and safety at equipment cleaning facilities to reduce the potential doses to workers engaged in cleaning processes, particularly dry processes.
- State regulatory agencies should be encouraged to permit subsurface disposal projects more readily because they constitute realistically safe methods for disposing of NORM-contaminated wastes. Underground injection projects should not be considered to pose a significantly greater risk to the general public than downhole encapsulation projects. Regulators should strive to educate the public to the realistic risks related to subsurface disposal so that unfounded fears do not complicate the permitting process.
- Judging from the magnitude of the estimated doses related to landspreading with dilution, restrictions on this practice should be implemented in all states to limit potential radiological doses to the general public.
- The potential inconsistency within the CRCPD Part N NORM regulations regarding the 5 pCi/g limit for land release and the 25 mrem/yr public dose limit should be addressed.
- Political, economic, sociological, and nonradiological issues related to smelting NORM-contaminated equipment generated by the petroleum industry should be explored to further define the feasibility of this disposal option.

cm ³	cubic centimeter(s)
g	gram(s)
km	kilometer(s)
l	liter(s)
m	meter(s)
m ²	square meter(s)
m ³	cubic meter(s)
mrem	millirem
pCi	picocurie(s)
rem	Roentgen Equivalent Man
s	second(s)
t	metric ton(s)
yr	year(s)

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NOMENCLATURE

cm centimeter(s)

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Table 1: Source Term Concentrations for Scale and Sludge⁵

Radionuclide	Concentration (pCi/g)		
	Median Scale	75th-Percentile Scale	Median Sludge
Radium-226	360	2,025	56
Lead-210	360	2,025	56
Radium-228	120	675	19
Thorium-228	120	675	19
Total radium	480	2,700	75

Table 2: Summary of Doses Associated with Equipment Cleaning Facilities

Scenario	Pathway	Annual Doses (mrem) ^a	
		Median	75th-Percentile
Pipe cleaner (Wet processes)	External gamma	4	25
Pipe cleaner (Dry processes)	External gamma	4	25
	Ingestion	35 ^b	— ^c
	Inhalation	11 ^b	— ^c
	Total	50	—
Storage yard worker	External gamma	40	22
Adjacent resident	External gamma	0.2	1

^a All doses are based on a 2,000-hour exposure time.

^b Dose calculations include ingrowth and decay over a 1-year period.

^c Doses were not calculated for the 75th-percentile concentration.

Table 3: Summary of Doses Associated with Subsurface Disposal at the Three Closest Receptors

Scenario (failure depth)	Annual Dose (mrem) at Receptor Location Relative to Disposal Site		
	0.0 km	0.3 km	0.8 km
Top aquifer (90 m)	— ^a	1	0.2
Top aquifer (185 m)	0.2	0.1	0.04
Top aquifer (275 m)	0.01	0.01	0.008
High conductivity (275 m)	0.04	0.04	0.04
High gradient (275 m)	0.03	0.03	0.03
Pumping wells (275 m)	0.04	0.002	0.009

^a This receptor is coincident with the failure point; therefore, the concentration is equal to the source concentration and potential doses from groundwater ingestion were not calculated.

Table 4: Summary of Doses Associated with Smelting NORM-Contaminated Equipment

Scenario/Receptor	Annual Doses (mrem)	
	Median	75th-Percentile
Smelter worker/slag worker ^a	14	80
Product end-use/general public ^b	0.02	0.1
Smelter emissions/general public	4×10^{-4}	2×10^{-3}

^a Doses are presented for the constraining worker scenario (i.e., slag worker), for a 2,000-hr exposure time.

^b Doses are presented for reuse of the recycled steel into an automobile or reuse of slag into construction of a parking lot.

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