

Assessing the Disposal of Wastes Containing NORM in Nonhazardous Waste Landfills*

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ABSTRACT

In the past few years, many states have established specific regulations for the management of petroleum industry wastes containing naturally occurring radioactive material (NORM) above specified thresholds. These regulations have limited the number of disposal options available for NORM-containing wastes, thereby increasing the related waste management costs. In view of the increasing economic burden associated with NORM management, industry and regulators are interested in identifying cost-effective disposal alternatives that still provide adequate protection of human health and the environment. One such alternative being considered is the disposal of NORM-containing wastes in landfills permitted to accept only nonhazardous wastes.

The disposal of petroleum industry wastes containing radium-226 and lead-210 above regulated levels in nonhazardous landfills was modeled to evaluate the potential radiological doses and associated health risks to workers and the general public. A variety of scenarios were considered to evaluate the effects associated with the operational phase (i.e., during landfill operations) and future use of the landfill property. Doses were calculated for the maximally exposed receptor for each scenario. This paper presents the results of that study and some conclusions and recommendations drawn from it.

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INTRODUCTION

In the past few years, many states have established specific regulations for the management of petroleum industry wastes containing naturally occurring radioactive material (NORM) above specified thresholds. These regulations have limited the number of disposal options available for NORM-containing wastes, thereby increasing the related waste management costs. In view of the increasing economic burden associated with NORM management, industry and regulators are interested in identifying cost-effective disposal alternatives that still provide adequate protection of human health and the environment. One such alternative being considered is the disposal of NORM-containing wastes in landfills permitted to accept only nonhazardous wastes.[†]

The Michigan Department of Environmental Quality (MDEQ) has issued guidelines allowing the disposal of materials contaminated with radium-226 (Ra-226) in municipal nonhazardous landfills.(1) These guidelines are applicable to radium-bearing NORM wastes generated by the petroleum industry. Other states that have developed NORM regulations or guidelines, however, do not allow this type of disposal.

This paper presents the results of a study in which the disposal of radium-bearing NORM wastes in nonhazardous landfills was modeled to evaluate potential radiological doses and resultant health risks to workers and the general public.(2) In addition, that study included an evaluation of the potential doses and health risks associated with disposing of a different NORM waste stream generated by the petroleum industry — wastes containing lead-210 (Pb-210) and its progeny. The results of that evaluation also are presented in this paper. A more detailed presentation of the methodologies and assumptions used in the study, the results, and related analyses of regulatory constraints and disposal costs is contained in the original report by Smith et al.(2)

SOURCE AND NATURE OF PETROLEUM INDUSTRY NORM

As a result of oil and gas production and processing operations, NORM sometimes accumulates 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 Ra-226, of the U-238 decay series. Other radionuclides of concern include radon-222 (Rn-222), Pb-210, and polonium-210 (Po-210), which all form from the decay of Ra-226.

[†] In this study, nonhazardous landfills are defined as landfills permitted under Subtitle D of the Resource Conservation and Recovery Act (RCRA) to receive only those wastes that are defined by RCRA as nonhazardous. Under RCRA, nonhazardous solid waste includes any discarded, abandoned, recycled, or inherently waste-like material that is not listed as a hazardous waste, does not exhibit any of four hazardous characteristics (i.e., ignitability, corrosivity, reactivity, and toxicity), or is not otherwise exempted.

Radium-228 (Ra-228) of the Th-232 decay series also occurs in NORM wastes but is of less concern because of its shorter half-life and the fact that it usually is present in relatively low concentrations.

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. As the produced water is brought to the surface, some of the dissolved radium precipitates out in solid form. Most commonly, the radium co-precipitates with barium sulfate, a hard and relatively insoluble scale deposit. A variety of factors appear to affect the degree to which the radium in solution in produced water will precipitate out in solid form. These factors include, but may not be limited to, temperature and pressure phase changes, water salinity, and sulfate concentration.

Radium that remains in solution is disposed of along with the produced water stream. Most produced water is disposed of by subsurface injection; radium content in reinjected water is not regulated. Radium content in scales and sludges, however, is regulated, particularly in states that have enacted NORM regulatory programs. Periodically, the scales and sludges that accumulate inside pieces of oilfield equipment are removed. Scales and sludges can pose a waste management issue if radionuclide concentrations exceed specified exemption levels. Similarly, pieces of equipment containing residual quantities of NORM-bearing scales and sludges, and surface soils impacted by these wastes, can present a waste management problem for the petroleum industry.

To date, most of the focus regarding NORM has been on wastes containing radium isotopes and their decay products. A separate category of NORM wastes exists, however. That category includes wastes that do not contain any radium but instead contain Pb-210, a decay product of Ra-226, and its decay progeny. Typically, these lead-bearing wastes accumulate inside gas processing equipment from the decay of Rn-222. The Pb-210 may be present in elemental form, as a chemical precipitate, or as an integrated constituent of the equipment metal.

REGULATORY CONSTRAINTS

The disposal of petroleum industry wastes containing NORM is, at this time, primarily a state-level regulatory issue because of two factors: (a) in every state with significant oil and gas production, the authority to regulate petroleum industry wastes has been delegated to the states, and (b) the presence of NORM in petroleum industry wastes currently is not addressed specifically in any federal regulations. In most states, regulatory oversight for the disposal of NORM in nonhazardous landfills will reside with more than one state agency. Agencies that probably will have some authority are those with oversight of (a) radioactive materials and wastes; (b) oil and gas activities, including waste management; and (c) all solid waste management facilities, including landfills.

A number of states have determined that their existing radiation control programs already contain adequate regulations applicable to NORM. Other states, however, have determined that specific regulatory programs for NORM are warranted. Table 1 lists the states with significant oil and gas production that have developed NORM regulations, the exemption levels that have been established to define regulated NORM in each of those states, and the regulatory citation for the NORM rules.

In most states, consistent with a determination made by the U.S. Environmental Protection Agency (EPA),(3) exploration and production (E&P) wastes are exempt from regulation as hazardous waste. However, many states consider E&P wastes to be distinct from other nonhazardous solid wastes, such as household waste.[‡] E&P wastes may be classified as "special wastes," "industrial wastes," "exempt E&P wastes," or "nonhazardous oilfield wastes." Under these various classification schemes, the disposal of E&P wastes in landfills may be restricted to specific types of landfills, or their disposal may be allowed only with the approval of the state's solid waste management agency.

State regulations governing nonhazardous landfills must be at least as stringent as the regulatory standards established by the EPA in Title 40, *Code of Federal Regulations (CFR)*, Parts 257 and 258. These standards address the location, design, construction, operation, monitoring, closure, and post closure care of all solid waste disposal facilities, including nonhazardous landfills. States typically establish classification schemes for nonhazardous landfills on the basis of the types of wastes they are permitted to receive, the volume of wastes they will receive, and their physical location. One specific type of nonhazardous landfill is the municipal solid waste (MSW) landfill.

An MSW landfill receives primarily household wastes but also may receive nonhazardous commercial and industrial wastes, nonhazardous sludges, and hazardous wastes generated by conditionally exempt small-quantity generators. In most states, MSW landfills are the most stringently regulated nonhazardous waste landfills. They typically are required to have composite liners, leachate collection systems, and groundwater monitoring systems. In addition, upon closure of an MSW landfill, the owner must record a notification on the deed to the landfill property (or some other instrument that normally would be examined during a title search) that (a) the property was used as a landfill and (b) future use is restricted to ensure that the integrity of the final cover, liner, containment system, and monitoring system will not be compromised. This deed restriction must be maintained in perpetuity.

In many states, nonhazardous landfills are not permitted to receive radioactive wastes. The State of Michigan, however, has issued guidelines allowing the disposal of wastes containing Ra-226, including petroleum industry NORM, in MSW landfills (which in Michigan are classified as Type II landfills).(1) Specifically, the MDEQ guidelines allow bulk wastes containing Ra-226 (e.g., contaminated soil or debris) to be disposed of in a Type II landfill, provided the Ra-226 concentration does not exceed 50 pCi/g averaged over any single shipment and the maximum Ra-226 concentration within any single shipment does not exceed 100 pCi/g.

[‡] Household wastes include garbage, trash, and sanitary wastes collected in septic tanks that are derived from homes, hotels, most other types of living quarters, and recreation areas, such as campgrounds and picnic grounds.

A survey of regulatory requirements in several of the other major oil and gas producing states found considerable variation from state to state.(2) In several of the states, landfill disposal of NORM was allowed for very specific waste streams, in a specific type of commercial nonhazardous landfill facility, or by special permission only. In the remaining states surveyed, there seems to be less latitude both in the state regulations and on the part of individual regulators.

RISK ASSESSMENT METHODOLOGY

Potential doses and health risks associated the disposal of NORM-impacted wastes in a municipal, nonhazardous landfill were calculated both for workers and the general public. Evaluations were performed for operational phase receptors (i.e., individuals who could be exposed as a result of the waste placement activities) and future use receptors (i.e., individuals who could be exposed as a result of future use of the property following closure of the landfill or consumption of groundwater impacted by landfill leachate). Doses were calculated for the maximally exposed receptor for each scenario. Collective doses were also estimated for the off-site population that could be exposed during waste placement operations. A variety of models were used to calculate potential radiological doses.(4-8) For this assessment, radiation doses were converted to carcinogenic risks by using risk factors recommended by the International Commission on Radiological Protection (ICRP).(9) The ICRP risk factor is 5×10^{-7} per mrem for the public and 4×10^{-7} per mrem for workers. Risks are expressed as the increased probability of fatal cancer over a lifetime. Health impacts associated with nonradiological constituents of the wastes placed in the landfill were not evaluated.

Scenarios and Exposure Assumptions

Table 2 lists the receptors that were evaluated in this study and, for each receptor, identifies the exposure pathways that were evaluated and the models that were used. A complete listing of assumptions used for each receptor is contained in the full report by Smith et al.(2)

Operational Phase Scenarios. The operational phase receptors that were evaluated included (a) a driver working at the landfill, (b) a waste-placement operator working at the landfill, (c) a landfill worker involved in pumping and disposing of landfill leachate, and (d) off-site residents living adjacent to the landfill or within a 50-mi radius of the landfill. For each of the landfill workers, the primary exposure pathway was assumed to be external irradiation. Inhalation of contaminated particulates also was considered to be a potential pathway for the waste-placement operator for cases in which the wastes were not disposed of in containers. For the off-site residents, the primary pathway of exposure was inhalation of contaminated particulates. External irradiation, incidental ingestion of contaminated particulates, and ingestion of contaminated foodstuff were also evaluated for completeness.

Future Use Scenarios. The future use receptors evaluated in this study included (a) an on-site resident, (b) an on-site industrial worker, (c) a recreational visitor, and (d) an off-site resident consuming groundwater impacted by leachate from the landfill. The on-site resident scenario was the most conservative scenario evaluated in this study (i.e., the scenario expected to result in the greatest risk). For this scenario, it was assumed that an individual lived on the site and produced most of his or her food on site, including vegetables, milk, meat, and fish. The primary exposure pathways for the on-site resident were assumed to be external irradiation and inhalation of indoor and outdoor radon. Although unlikely, given that the integrity of the landfill cap would be maintained, other pathways were also evaluated — inhalation of contaminated particulates; inadvertent ingestion of contaminated soil; and ingestion of crops, milk, and meat grown on the contaminated property. It was assumed the resident's water supply was from an unaffected off-site source, such as a municipal drinking water system. This scenario may not represent a realistic future use of a landfill; however, it was evaluated to represent a maximally exposed individual. These residential land use assumptions are commonly used by risk assessors for this purpose.

For the on-site industrial worker and recreational visitor, the primary pathways of exposure were assumed to be external irradiation and inhalation of radon. Inhalation of contaminated particulates and inadvertent ingestion of soil were also evaluated for completeness, although they are considered unlikely pathways assuming the integrity of the landfill cap would be maintained. For both of these scenarios, it was assumed the receptors would use water only from an unaffected, off-site supply.

The off-site residential scenario evaluated potential doses to an off-site resident from consumption of groundwater impacted by leachate from the landfill. The only exposure pathway to this receptor was assumed to be ingestion of groundwater.

Landfill Construction and Operation

The landfill modeled in the study was assumed to contain nine disposal cells of varying size with a total disposal capacity of approximately 9.6 million yd³. It was assumed that the cell that would receive the NORM wastes had a capacity of 513,000 ft³ and that when the landfill was full it would be about 80 ft thick. The landfill was assumed to be constructed with a liner system consisting of a 3-ft-thick layer of compacted clay at the base, overlain successively by a 0.39-in.-thick high-density polyethylene (HDPE) liner, a 0.24-in.-thick drainage net, a 0.24-in.-thick bentonite layer, a second HDPE liner, and a 3-ft-thick gravel drainage layer. The municipal wastes would be placed directly over the gravel drainage layer. Upon closure of the cell, the municipal wastes would be covered by a cap composed of, from the bottom up, a 2-ft-thick layer of compacted clay, 1.5-ft-thick gravel layer, and a 1.5-ft-thick layer of topsoil.

In the base case it was assumed that the NORM wastes were placed in a single cell within the landfill in a layer 8 ft thick (Figure 1). As part of normal landfill operations requiring placement of cover material at the end of each day of operations, the NORM waste layer was overlain by a 1-ft-thick layer of clean soil. This layer was then overlain by 8 ft of municipal wastes and a 6-ft-thick cap.

Source Concentrations

The study evaluated two separate waste streams — radium-bearing NORM wastes and waste containing Pb-210. Because the origins of these waste streams would be different and because these wastes would thus be managed and disposed of separately, they were treated independently in this analysis. Dose calculations were performed for each waste stream for the principal radionuclides in the decay series.[§] The chain of decay products of a principal radionuclide (i.e., the associated radionuclides) extending to (but not including) the next principal radionuclide was assumed to be in secular equilibrium** with the principal radionuclide. Secular equilibrium also was assumed between Ra-226 and Th-232. For most of the receptors and exposure pathways, the source concentration was defined by the case study assumptions. For those receptors exposed to either leachate or groundwater, leachate and groundwater transport calculations (below) were made to define the source concentrations.

For the case study evaluation of radium-bearing wastes, it was assumed that 2,000 m³ of NORM waste with a Ra-226 concentration of 50 pCi/g was disposed of in the nonhazardous landfill. Ra-228 was assumed to be present in the waste at a ratio of 3:1 Ra-226 to Ra-228 (i.e., 50 pCi/g Ra-226 in addition to 12.5 pCi/g Ra-228). Ingrowth of Pb-210 was assumed for 10 years at the start of analysis.

For the case study evaluation of Pb-210 wastes, it was assumed that the wastes would be disposed of in 55-gal drums and that disposal in any single landfill would be limited to one truckload per year. One truckload was assumed to contain 96 55-gal drums, equal to 20 m³. This analysis evaluated disposal in drums, but, to be conservative, the disposal of this waste stream in bulk was also evaluated. Estimates provided in this report are based on a barrel-weighted average activity concentration of 260 pCi/g of Pb-210. Lead-210 is the only principal radionuclide of interest for this waste stream. Radioactive decay of Pb-210 results in bismuth-210 (Bi-210), which has a half-life of about 5 days. The Bi-210 decays by beta emission to Po-210, which has a half-life of approximately 140 days. The Po-210 decays by alpha particle emission to stable lead-206 (Pb-206).

Groundwater and Leachate Transport Modeling

Very conservative assumptions were used to define the solubility of the radionuclides of concern and, hence, their concentrations in the landfill leachate and groundwater. In petroleum industry NORM, Ra-226 typically is present in the form of

[§] The term "principal" refers to those radionuclides in the decay series with half-lives of more than one year; these include Ra-226, Pb-210, Ra-228, and thorium-232 (Th-232) for the radium-bearing NORM wastes, and Pb-210 for the wastes containing lead.

** Secular equilibrium refers to the relationship established 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 (disregarding the mobility of the radon gas) such that the activity of each element is equal.

radium/barium sulfate, a relatively insoluble material with a solubility limit of 2×10^{-6} g/L. To be conservative, it was assumed that as the radium was exposed to leachate moving through the landfill, it would dissolve instantly to its solubility limit. Most of the Pb-210 is present in elemental state and, therefore, is insoluble. However, to evaluate a worst-case scenario, it was assumed that the lead was in the form of lead sulfate, the most soluble form of lead that might occur in a landfill, with a solubility of 4.25×10^{-3} g/L.(10) In addition, although the majority of Pb-210 is found on the interior surfaces of equipment, it was assumed that the Pb-210 bearing wastes were exposed to the leachate and that the leachate instantaneously dissolved the lead to its solubility limit. These conservative assumptions resulted in an overprediction of the amount of radium and lead that would be present in the landfill leachate.

Three separate models were used individually and in tandem to evaluate leachate and groundwater transport (Figure 2). The Hydrologic Evaluation of Landfill Performance (HELP) model (6) was used to calculate the amount of fluid that could percolate through the surface cover of the landfill and the amount of leachate that could leak through the landfill containment system (e.g., the base liner). An analytical model developed by Tomasko (7) was used to estimate the movement of dissolved Ra-226 and Pb-210 from the original position of the NORM waste in the landfill to the impermeable liner at the bottom of the landfill cell. A dilution calculation was used to estimate the Ra-226 and Pb-210 concentrations in leachate at the base of the cell and at the base of the entire landfill. The SWIFT II model (8) was used to calculate groundwater transport of Ra-226 and its decay product, Rn-222, from beneath the landfill to various groundwater receptor locations. The SWIFT II model was not used for Pb-210 because calculations of Pb-210 movement within the landfill indicated that lead did not reach the liner in appreciable concentrations.

Sensitivity Analyses

Sensitivity analyses were conducted for several input parameters that were considered likely to have an effect on potential doses. For the on-site resident and industrial worker scenarios, sensitivity analyses were conducted to determine the effects on potential doses, of the depth of the NORM waste layer from the surface of the landfill, radon emanation coefficient, thickness of the NORM waste layer, and the source concentration. In addition, the effect of breaching the landfill cover during home construction (i.e., building a home with a basement) also was investigated for the on-site resident scenario. For the recreational visitor, a sensitivity analysis was conducted only for the depth of the NORM waste layer. For the groundwater receptor scenario, sensitivity analyses were conducted within the leachate and groundwater transport models. Parameters examined in these analyses included depth of the NORM waste layer, thickness and areal extent of the waste layer, percolation velocity, distance to the groundwater receptor, and depth of the groundwater receptor below the water table.

RESULTS

Leachate and Groundwater Transport Calculations

The HELP model (6) was used to evaluate landfill performance in terms of the volume of leachate that potentially could leak from the base of the landfill each year. A series of runs were made to determine how this volume was affected by the quality of both the clay cap and the liner system at the base of the landfill. Predictably, the results indicated that potential leakage through the bottom of the landfill increased with increasing hydraulic conductivity of the clay cap and decreasing quality or absence of the geomembrane liners.

An analytical model (7) was used to calculate the vertical transport of radionuclides through the municipal waste layer. Ra-226 concentrations in the leachate were estimated for three different waste layer thicknesses at three different locations within the landfill: (a) at the liner immediately below the NORM waste layer; (b) at the base of the cell containing the NORM; and (c) within the entire landfill, assuming leachate from all of the landfill cells is mixed. Table 3 presents the maximum Ra-226 concentrations in the leachate at each of these locations for the different waste thicknesses. Predictably, the Ra-226 concentration below the NORM waste layer increased with increasing thickness of the waste layer and decreased as the leachate was mixed with leachate generated from larger areas within the landfill. Similar calculations indicated that Pb-210 concentrations at the landfill liner would be essentially zero because of the high retardation and the very short half-life (22 years) of Pb-210.

The SWIFT II model (8) was used to evaluate groundwater transport of Ra-226 and its progeny, Rn-222, from the point of release below the landfill liner to a receptor located 1,000 ft downgradient of the landfill at a depth of 5 ft below the base of the landfill. A series of runs were made to estimate the Ra-226 and Rn-222 concentrations under different conditions. The results of these runs are presented in Table 4. The base-case run of the SWIFT II model used very conservative values for some of the input parameters. In the base case, it was assumed that there were no geomembrane liners present at the base of the landfill and that the groundwater was in immediate contact with the base of the landfill. These assumptions result in an overprediction of the concentration of radionuclides in the subsurface; even so, the estimated concentrations were very low: 3.3×10^{-4} for Ra-226 and 3.9×10^{-8} for Rn-222. When a separate run was made assuming the presence of poor-quality geomembrane liners, the estimated Ra-226 concentration was reduced by about five orders of magnitude to 5.7×10^{-9} . Similarly, when the depth of the groundwater was assumed to be 10 to 30 ft below the base of the landfill, the Ra-226 concentrations were reduced by an additional three orders of magnitude.

The SWIFT II model was not used to calculate Pb-210 concentrations in the groundwater because the analytical model results indicated that essentially no Pb-210 would be present in the leachate leaking from the landfill.

Calculated Doses and Health Risks

Table 5 presents the estimated doses and resultant health risks for each receptor evaluated in this study. These doses and risks are related to the disposal of either (a) 2,000 m³ of NORM wastes containing an average Ra-226 concentration of 50 pCi/g, or (b) 20 m³ of wastes containing an average Pb-210 concentration of 260 pCi/g. To place the estimated doses in perspective, the currently accepted public dose limit recommended by the ICRP is 100 mrem/yr from all sources.(9) Unless workers involved in the disposal of NORM are classified as radiation workers, this dose limit is applicable to them, as well.

For the operational phase worker scenarios, the results indicated that the waste-placement operator would receive the highest potential dose; however, this value was very low, less than 2 mrem/yr. Potential doses to the other workers and to the general public were all negligible.

For the future use scenarios, the results indicated that the on-site residential receptor would receive the highest potential dose; however, this value also was low, at only 7.4 mrem/yr. The potential doses to other future users of the site were negligible.

Sensitivity Analyses

Sensitivity analyses for disposal of radium-bearing NORM wastes were conducted on several input parameters for the on-site resident, on-site industrial worker, and recreational visitor scenarios. Only those parameters related to the radon pathway were analyzed because this was the only pathway that would contribute significantly to dose. These parameters included depth of the NORM waste layer below the landfill surface, radon emanation coefficient, area and thickness of the NORM waste layer, and source concentration. In addition, breach of the landfill cap in home construction was analyzed for the residential scenario. Sensitivity analyses for disposal of wastes containing Pb-210 were not performed, with the exception of the parameter defining the depth of the waste.

The results of the sensitivity analyses indicated that all of the parameters evaluated except the areal extent of the NORM waste layer had an impact on estimated doses. The two parameters potentially having the greatest impact on doses to the on-site residential receptor were depth of the NORM waste layer and integrity of the landfill cap. In the case of waste layer depth, the sensitivity analyses indicated that potential doses could be unacceptably high (125 mrem/yr) if the waste layer was shallower than about 10 ft. Similarly, if the landfill cap were breached during home construction, potential doses could also be unacceptably high (63 mrem/yr).

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

On the basis of the results presented in Table 5, the following conclusions can be drawn regarding the potential doses and risks associated with disposing of 2,000 m³ of waste containing an average Ra-226 concentration of 50 pCi/g:

- Potential radiological doses and resultant health risks for workers actively involved in landfill operations would be negligible.
- Potential doses to an individual living adjacent to the landfill during the NORM disposal action and to the general population living within a 50-mi radius would be negligible.
- Potential doses to future industrial and recreational users of the landfill property would be negligible.
- Potential doses to hypothetical future residential users of the landfill property are most sensitive to depth of the NORM waste layer and integrity of the landfill cap. These doses would be negligible on the basis of the assumption that (a) the NORM wastes would be placed at a depth greater than approximately 10 ft below the cap and (b) the landfill cap would not be breached during construction of the home.
- Provided the NORM wastes are placed deeper than approximately 10 ft below the landfill cap, the Michigan policy allowing wastes containing up to 50 pCi/g to be disposed of in Type II landfills is protective of human health.

As noted, these conclusions relate to a disposal volume of 2,000 m³. Increasing the total volume would increase the worker doses linearly and could increase the potential doses to the off-site resident via the groundwater pathway. However, it is estimated that doses for these receptors would be negligible, and increasing the volume probably would not change this overall conclusion. Radiological doses to the future-use receptors would not be affected by increasing the total volume; doses to these receptors would be affected primarily by changes in the location of the NORM waste within the landfill.

Regarding the disposal of lead-bearing NORM wastes, the results of this study indicate that potential doses and associated health risks to workers and the general public would be negligible for disposal of 20 m³ of wastes containing an average Pb-210 concentration of 260 pCi/g.

Recommendations

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

- It may be feasible for other states besides Michigan to consider issuing regulations allowing the disposal of NORM wastes containing up to 50 pCi/g of Ra-226 in municipal, nonhazardous landfills. In approving of this type of disposal, regulators should consider the total volume of radium-bearing wastes that are disposed of in a single landfill and cell, as well as the depth of the NORM waste layer within the landfill. Property records denoting that a landfill was in operation at that location should also note that radium-bearing wastes were disposed of therein.
- Regulators should consider allowing the disposal of NORM wastes containing radium in concentrations greater than 50 pCi/g on a case-by-case basis.
- States should also consider regulations governing the disposal of wastes containing Pb-210 in municipal, nonhazardous landfills. As they should for radium-bearing wastes, the regulations should consider the allowable concentrations of Pb-210 and the total volume that can be disposed of in a single landfill.
- States may want to consider allowing NORM wastes to be disposed of in other categories of nonhazardous landfills, provided the requirements for deed restrictions and protection of the landfill cap are equivalent to those for municipal landfills.

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Table 1. Summary of Exemption Levels Defining Regulated NORM Established by Existing State-Level Regulations

State	Exemption Levels		Regulatory Citation
	Radium	Other Radionuclides (including Pb-210)	
Arkansas	<5 pCi/g Ra-226 and/or Ra-228	<150 pCi/g of any other NORM radionuclide	<i>Rules and Regulations for Control of Sources of Ionizing Radiation</i> , Section 7, "Naturally Occurring Radioactive Material (NORM)."
Louisiana	≤5 pCi/g Ra-226 or Ra-228 above background	≤150 pCi/g of any other NORM radionuclide	Title 33, <i>Louisiana Administrative Code</i> , Part XV, Chapter 14, "Regulation and Licensing of Naturally Occurring Radioactive Materials (NORM)."
Mississippi	<5 pCi/g Ra-226 or Ra-228 above background; or <30 pCi/g Ra-226 or Ra-228, averaged over any 100 m ² , if the radon emanation rate is ≤20 pCi/m ² /s	≤150 pCi/g of any other NORM radionuclide	<i>Regulations for Control of Radiation in Mississippi</i> , Part 801, Section N, "Licensing of Naturally Occurring Radioactive Materials (NORM)."
New Mexico	≤30 pCi/g Ra-226 above background	≤150 pCi/g of any other NORM radionuclide above background	Title 20, <i>New Mexico Administrative Code</i> , Chapter 3.1.14 "Naturally Occurring Radioactive Materials (NORM) in the Oil and Gas Industry."
Texas	≤30 pCi/g Ra-226 or Ra-228	≤150 pCi/g of any other NORM radionuclide	Title 25, <i>Texas Administrative Code</i> , Chapter 289, Subchapter F, "Licensing of NORM."

Table 2. Methodologies Used to Model NORM Disposal in a Nonhazardous Landfill for Various Scenarios

Scenario/Receptor	Exposure Pathway	Model
<i>Operational Phase Scenarios</i>		
Driver	External irradiation	TSD-DOSE ^a
Waste-placement operator	External irradiation	TSD-DOSE
	Inhalation of particulates	TSD-DOSE
Leachate worker	External irradiation	TSD-DOSE
Off-site residents	External irradiation	TSD-DOSE
	Inhalation of particulates	TSD-DOSE
	Ingestion of soil and food	TSD-DOSE
<i>Future Use Scenarios</i>		
On-site resident	External irradiation	RESRAD ^b
	Inhalation of particulates and radon	RESRAD
	Ingestion of soil and food	RESRAD
On-site industrial worker	External irradiation	RESRAD
	Inhalation of particulates and radon	RESRAD
Recreational visitor	External irradiation	RESRAD
	Inhalation of radon	RESRAD
Off-site resident	Groundwater ingestion	HELP model ^c
		leachate model ^d
		SWIFT II ^e

- a Reference 4
- b Reference 5
- c Reference 6
- d Reference 7
- e Reference 8

Table 3. Results of Leachate Transport Modeling for Ra-226

NORM Waste Layer Thickness	Maximum Ra-226 Concentration (pCi/L)		
	Below NORM Waste Layer	In Leachate from NORM Cell	In Leachate from Entire Landfill
1 ft	92	2.1×10^{-1}	2.8×10^{-2}
4 ft	360	2.2×10^{-1}	2.9×10^{-2}
8 ft	740	2.2×10^{-1}	3.0×10^{-2}

Table 4. Maximum NORM Concentrations Predicted by Groundwater Transport Analysis

SWIFT II Run	Maximum Ra-226 Concentration (pCi/L)	Maximum Rn-222 Concentration (pCi/L)	Time to Maximum Concentration (yr)
SWIFT II base case	3.3×10^{-4}	3.9×10^{-8}	109
High conductivity	3.9×10^{-5}	4.5×10^{-9}	100
Low conductivity	2.9×10^{-4}	1.2×10^{-8}	394
High gradient	7.5×10^{-5}	9.0×10^{-9}	100
Low gradient	3.3×10^{-4}	4.2×10^{-8}	427
Increased recharge	1.1×10^{-4}	1.4×10^{-8}	125

Table 5. Estimated Peak-Year Dose and Carcinogenic Risks for Disposal of NORM-Impacted Wastes in a Nonhazardous Landfill

Receptor	Radium-Bearing NORM ^a		Lead-210 NORM ^b	
	Dose (mrem/yr)	Risk	Dose (mrem/yr)	Risk
<i>Operational phase scenarios</i>				
Driver	0.3	1×10^{-7}	0	0
Waste-placement operator	1.7	7×10^{-7}	2.4×10^{-6}	9×10^{-13}
Leachate worker	2×10^{-4}	8×10^{-11}	0	0
Off-site resident	6.6×10^{-4}	3×10^{-10}	3.3×10^{-6}	2×10^{-12}
General population ^c (50-mi radius)	2.7×10^{-5}	1×10^{-8}	1.3×10^{-7}	7×10^{-11}
<i>Future use scenarios</i>				
On-site resident	7.4	4×10^{-6}	0	0
On-site industrial worker	2.2	1×10^{-6}	0	0
Recreational visitor	1.2×10^{-7}	6×10^{-14}	0	0
Off-site resident	3.2×10^{-4}	2×10^{-10}	0	0

^a Doses are for bulk disposal of 2,000 m³ of radium-bearing wastes having an average Ra-226 concentration of 50 pCi/g.

^b Doses are for bulk disposal of one truckload (20 m³) of lead-bearing wastes having an average Pb-210 concentration of 260 pCi/g.

^c Dose for the general population is in person-rem.

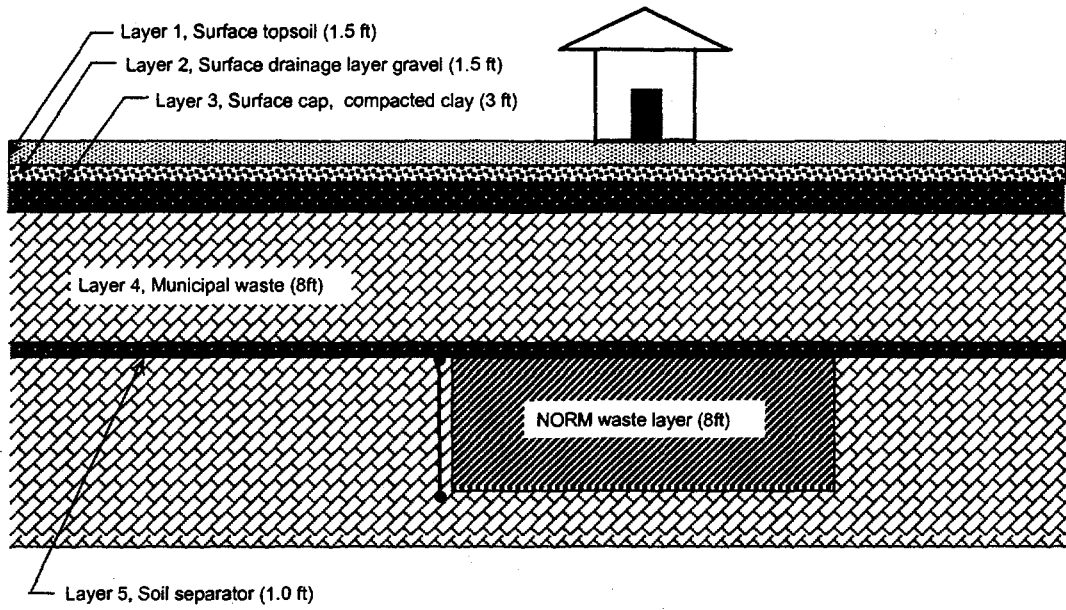


Figure 1. Schematic diagram of base-case assumptions regarding placement of NORM waste within the landfill

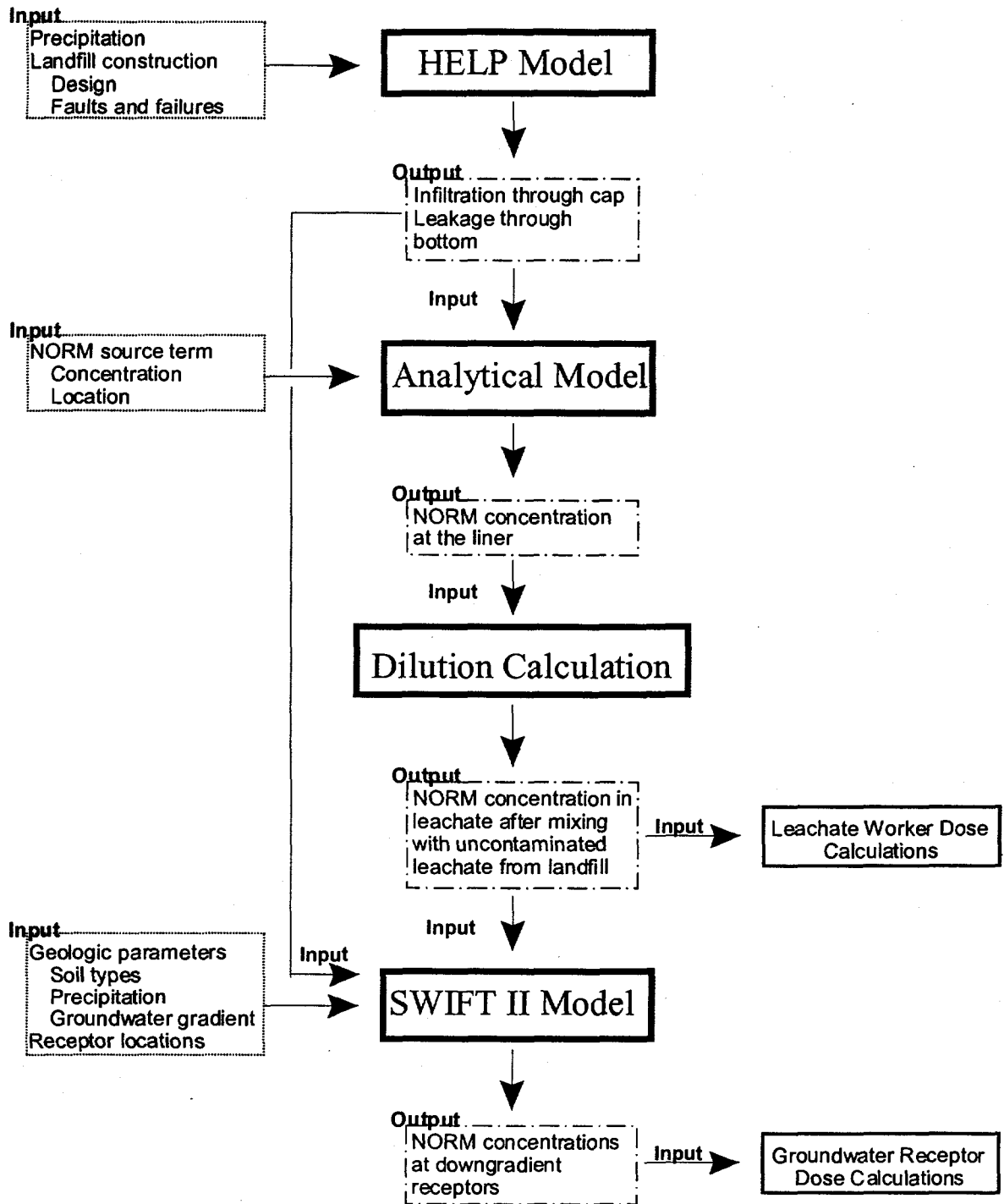


Figure 2. Diagram of models used to calculate leachate and groundwater transport