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PRELIMINARY PERFORMANCE ASSESSMENT OF A NEVADA TEST SITE WASTE DISPOSAL FACILITY[a]

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ABSTRACT

The performance of the Nevada Test Site Greater Confinement Disposal (GCD) site was assessed against the Environmental Protection Agency's (EPA) requirements for disposal of high-level waste, spent fuel and transuranic waste, 40 CFR Part 191. No new data were collected for this assessment. This preliminary assessment indicates that the GCD concept is a viable method of disposing of transuranic wastes. The results are being used to direct future site characterization activities.

I. INTRODUCTION

The Department of Energy (DOE) is responsible for disposing of a variety of radioactive wastes, which include high-level wastes (HLW), transuranic (TRU) wastes, and low-level waste (LLW). The last also includes greater-than-class-C (GTCC) waste. Some of these wastes do not comply with the Waste Acceptance Criteria for existing disposal sites (e.g., the Waste Isolation Pilot Project (WIPP) and Yucca Mountain) or, in the case of GTCC waste, are prohibited from shallow land burial. These wastes have been termed "orphan" wastes and require an alternative disposal method.

Since 1984, the DOE has been disposing of some of these orphan wastes at the Radioactive Waste Management Site (RWMS) in Area 5 of the Nevada Test Site (NTS). The method of disposal employed at this site is called Greater Confinement Disposal (GCD). This method consists of boreholes that are 36.6 meters (120 feet) deep and either 3 meters or 3.7 meters (10 or 12 feet) in diameter. The boreholes are filled with waste to a depth of 15.2 meters (50 feet) with the upper 21.4 meters (70 feet) backfilled with native material. The boreholes are within the unsaturated zone, approximately 200 meters (660 feet) above the water table. Currently, four GCD boreholes contain approximately 600 curies of TRU waste, most of which is ^{239}Pu. Two other boreholes contain approximately 500,000 curies of ^{90}Sr, 200,000 curies of ^{137}Cs, 100 curies of ^{226}Ra, and 10 curies of ^{227}Ac.

Sandia National Laboratories (SNL) staff are conducting a Preliminary Performance Assessment (PPA) of the GCD facilities as part of an ongoing project to evaluate the suitability of this site for orphan waste disposal. This evaluation is based on assessing the performance of the GCD site against the EPA's requirements for the disposal of HLW and TRU, 40 CFR Part 191.[1] Thus, the PPA includes HLW and TRU, but not LLW. The purpose of the PPA is threefold:

1. Determine the technical feasibility of the GCD disposal concept as a solution for the disposal of the DOE's orphan wastes by assessing compliance with the EPA's requirements for the disposal of HLW and TRU.

2. Examine the usefulness, in the context of performance assessment, of existing information and data for the RWMS in Area 5 of the NTS.

3. Determine the most significant uncertainties and set priorities for future site characterization efforts by performing sensitivity analyses on the PPA results.

The purpose of this paper is to present an overview of the preliminary performance assessment of the GCD site. In Section II, the performance assessment methodology employed is discussed. Section III contains a review of the conceptual models for ground water flow and radionuclide transport. The results of uncertainty and consequence analyses are presented in Section IV, while results of sensitivity analyses are presented in Section V. The conclusions of this study are presented in Section VI. Detailed information concerning the conceptual model, the parameters used, and the model implementation will be documented in a future report.

II. PERFORMANCE ASSESSMENT METHODOLOGY

The approach to assessing the suitability of the GCD site is based on the HLW Performance Assessment Methodology (PAM) previously developed at Sandia National Laboratories for the Nuclear Regulatory Commission.[2] The methodology includes scenario selection, process and pathway identification, consequence analysis, uncertainty analysis, and sensitivity analysis.

A. Scenario Selection

Scenarios are sets of feasible future states of the disposal system resulting from naturally occurring and human induced conditions that affect the release and transport of radionuclides. Four scenarios are selected for this study. These are base case, erosion, climate change, and human intrusion.

The base-case scenario represents a continuation of the current environmental conditions at the site for the next 10,000 years. A study of the erosion patterns at the GCD site indicates that 10 to 12 cm of alluvium will be deposited on top of the boreholes over the next few thousand years. Therefore, the consequences associated with the erosion scenario are identical to those of the base case and separate analyses for the erosion scenario are not performed.

In the human-intrusion scenario, it is assumed that future exploration activities result in a well 20 cm (8 inches) in diameter being drilled directly through one of the GCD boreholes. In the climate-change scenario, future climatic conditions are assumed to be wetter and cooler, thereby increasing the amount of recharge occurring at the site.

Probabilities of occurrence of each of these scenarios are not calculated; rather, it is assumed that each scenario occurs (i.e., a probability of one). Hence, the consequence of each scenario is calculated separately from the other scenarios, but these consequences are not consolidated into one probabilistic result for assessing compliance with the requirements. Instead, comparisons with the requirements are made for each scenario. The effect of including probabilities of occurrence is discussed in more detail in Section IV.

B. Identification of Processes and Pathways

For each of the four scenarios considered, the processes affecting radionuclide transport and their associated pathways are identified. For the base-case and climate-change

scenarios, the processes of radionuclide dissolution, liquid-phase and vapor-phase diffusion, hydrodynamic dispersion, convection, and retardation are considered. The transport pathways are either downward through the unsaturated zone and horizontally in the saturated zone (convective pathway), or upward to the ground surface (diffusive pathway). The liquid-diffusion pathway is considered here because of the relatively low recharge-flux estimates at the GCD site, and because of the relatively shallow depth of disposal (21.4 meters from the top of the waste to the land surface). For the human-intrusion scenario, the waste is intercepted directly as a result of drilling (hence, no transport processes) and the pathway is up through the well bore to the surface.

C. Consequence Analysis

Consequence analysis involves the use of several different models and associated computer codes. A simple Darcy flow model is used to predict the ground-water velocity field in both the unsaturated and saturated zones. Radionuclide transport is simulated with the computer code NEFTRAN which considers one-dimensional convective transport for multiple radioactive decay chains with multiple members.[3] Analytical solutions are used for one-dimensional liquid phase diffusive transport to simulate the upward diffusion of radionuclides, and for one-dimensional gas phase diffusive transport of radon (a daughter product).

Three performance measures are evaluated in the PPA. These measures are derived from requirements in 40 CFR Part 191 concerning individual protection, ground water protection, and containment of radionuclides within the accessible environment.[1] The first performance measure limits the maximum annual dose to any member of the public in 1,000 years, the second limits the maximum concentrations of radionuclides in significant sources of water averaged over a given year for 1,000 years, and the third limits the cumulative release, in terms of curies, of specific radionuclides to the accessible environment for 10,000 years. For the purposes of the PPA, the accessible environment is defined to include both the ground surface and any point in the geosphere that is five kilometers away from the disposal site. The cumulative release for each radionuclide is normalized by the release limits listed in 40 CFR Part 191 which are based on the amount of waste disposed of. The normalized release estimates are summed over all radionuclides to produce what is referred to as the "EPA sum."

D. Uncertainty Analysis

Knowledge of the values of the parameters governing ground-water flow and transport is uncertain; therefore, these parameters are treated as random variables, each with a specified probability density function (pdf). The Monte Carlo simulation technique is used to propagate this uncertainty through the models. Ranges and pdf's for the parameters are shown in Table 1. Some parameters have no uncertainty associated with them and values for all the parameters were taken from information already available in the literature. As a result, significant uncertainty exists for some of parameters, as evidenced by the very large ranges in their values.

Table 1. Parameter Values Used in the Analyses

Parameter	Value	Distribution Type
Recharge (Hydraulic conductivity in unsaturated zone)	2.5×10^{-8} - 9.0×10^{-14} cm/s (Base case) 5×10^{-7} - 1.8×10^{-12} cm/s (Climate change)	based on empirical data
Moisture content in unsaturated zone	0.06 - 0.17	lognormal
Hydraulic conductivity in saturated zone	2.2×10^{-4} - 2.4×10^{-3} cm/s	uniform
Porosity in saturated zone	0.248 - 0.475	uniform
Dispersivity in unsaturated zone	0.1 - 1.0 cm	uniform
Dispersivity in saturated zone	250 - 750 meters	uniform
Pressure gradient in saturated zone	1×10^{-5} - 2.4×10^{-4}	lognormal
Rock bulk density	1.59 g/cm^3	constant
K_D for plutonium (all isotopes)	1.0×10^{-3} - 1000 cm^3/g	lognormal
K_D for uranium (all isotopes)	1.0×10^{-3} - 5.75 cm^3/g	lognormal
K_D for ^{231}Pa, ^{227}Ac, ^{229}Th, ^{230}Th, ^{232}Th, ^{241}Am, ^{237}Np, ^{226}Ra, and ^{210}Pb	1.0×10^{-3} - 5.0 cm^3/g	lognormal
K_D for ^{90}Sr	1.0×10^{-3} - 166 cm^3/g	lognormal
K_D for ^{137}Cs	1.0×10^{-3} - 6500 cm^3/g	lognormal
Plutonium solubility (all isotopes)	2×10^{-5} - 6×10^{-5} g/g	uniform
Uranium solubility (all isotopes)	1×10^{-11} - 1×10^{-6} g/g	loguniform
^{231}Pa, ^{227}Ac, and ^{137}Cs solubility	1 - 10 g/g	uniform
Thorium solubility (all isotopes)	1×10^{-7} - 3×10^{-7} g/g	uniform
^{241}Am solubility	1×10^{-9} - 5×10^{-7} g/g	loguniform
^{237}Np solubility	2×10^{-5} - 3×10^{-4} g/g	uniform
^{226}Ra solubility	2.5×10^{-8} - 3×10^{-8} g/g	uniform
^{210}Pb solubility	3×10^{-9} - 5×10^{-7} g/g	loguniform
^{90}Sr solubility	9×10^{-9} - 9×10^{-5} g/g	lognormal
Enriched uranium inventory	3969 - 47169 grams	uniform
Medium enriched uranium inventory	34,000 grams	constant
Depleted uranium inventory	611,130 - 620,510 grams	uniform
Plutonium inventory	4283 - 6011 grams	uniform
^{90}Sr inventory	3620.2 grams	constant
^{137}Cs inventory	250.95 grams	constant
^{226}Ra inventory	100 grams	constant
^{227}Ac inventory	0.1377 grams	constant
Tortuosity	1 - 110	uniform
Rise in water table with increased recharge	0 - 50 meters	uniform

The pdf's for uncertain parameters are sampled using the Latin Hypercube Sampling (LHS) technique.[4] This sampling method results in a set of input vectors, each vector consisting of a specific numerical value for each of the uncertain parameters. For the purposes of the PPA, the sample vectors are constructed in a manner that preserves independence (i.e., no correlation) among the variables. Each vector is then used as the input to the consequence analysis models and a value of the performance measure (i.e., EPA sum) is obtained for each of the sample vectors. The resulting set of values of the EPA sum is transformed into a complementary cumulative distribution function (CCDF) using the probability of each sample vector (probability = 1/total number of vectors). The CCDF presents the results in terms of the probability of exceeding given values of the EPA sum. The number of vectors required to define the CCDF curve is determined through experimentation. For the base-case and the climate-change scenarios, 4000 vectors are used, while 1000 vectors are used for the human-intrusion scenario.

E. Sensitivity Analysis

The results of the consequence analyses are used to perform sensitivity analyses that identify the most important parameters associated with the model predictions (i.e., those parameters which have the greatest influence on the performance measures). The results of a sensitivity analysis can be used to set priorities for data acquisition activities and optimize expenditure of available resources.

In the first stage of the analysis, scatter plots are used to examine the relationship between the performance measure and each of the model parameters. To facilitate the comparison of these relationships among parameters whose values vary over vastly different magnitudes and ranges, the scatter plots are generated using rank-transformed data (i.e., rank values rather than absolute values). Usually, the more important variables can be identified by visual inspection. The rank-transformed data are also used in a stepwise regression analysis that provides quantitative measures of relative importance among the independent variables.[5]

Often, definitive relationships between dependent and independent variables are difficult to discern because of the complexity of the system of models and degree of uncertainty in the parameter values. That is, scatter plots and regression relationships may not indicate clearly the variables or combinations of variables to which the model is most sensitive. In this case, detailed inspection of input and output data may be performed to develop an understanding of how the predictions are affected by changes in model inputs.

III. CONCEPTUAL MODELS

The RWMS in Area 5 is located near the eastern edge of the NTS and is in the southern part of the Basin and Range geologic province. The Basin and Range geologic province is characterized by north-to-northwest trending mountains separated by basins. The RWMS is located in the Frenchman Flat basin. This basin is believed to be filled with alluvium to a depth of approximately 457 meters (1500 feet); the vadose zone is approximately 235 meters (770 feet) thick and the remaining 222 meters (730 feet) is

saturated. These estimates of the depth of the alluvium, saturated zone, and unsaturated zone are based on published data obtained from a few boreholes.

The assumptions that comprise the conceptual models for ground-water flow, radionuclide transport, and radon transport and resulting dose are shown in Table 2.

Radon is the only radionuclide included in the PPA that exists in the vapor phase. All of the radionuclides except for ^{90}Sr and ^{137}Cs that are initially disposed of at the GCD generate radon as a decay product, although ^{226}Ra (the immediate parent of ^{222}Rn) produces 90% of the radon present at the GCD site.

Five of the boreholes included in the radon transport analyses do not contain any heat-generating wastes. However, one borehole contains the heat-generating radionuclides ^{90}Sr and ^{137}Cs, as well as 100 curies of ^{226}Ra. The resulting temperature gradient complicates the analysis of radon diffusion because the diffusion coefficient is a function of temperature, and the temperature is changing both temporally and spatially. It is beyond the scope of this PPA to develop a model that couples the transient temperature gradient with the diffusion coefficient. Therefore, it is assumed that the temperature in this particular borehole is constant everywhere, but is much higher than ambient to account in part for the heat-generating waste.

IV. RESULTS OF CONSEQUENCE AND UNCERTAINTY ANALYSES

Most of the analysis efforts are directed toward assessing compliance with the containment requirements in 40 CFR Part 191. These requirements are probabilistic in nature, requiring the EPA sum to have a likelihood of less than one in 10 of exceeding an allowable value. The EPA sum must also have a likelihood of less than one in 1000 of exceeding 10 times this allowable value. The allowable value is determined on the basis of the EPA's radionuclide-specific release limits and the initial inventory of radionuclides.

One of the considerations in doing the analysis is whether the non-TRU waste (i.e., ^{90}Sr, ^{137}Cs, ^{226}Ra, and ^{227}Ac) should be included in the initial GCD inventory. The EPA has defined HLW to include highly radioactive material that requires permanent isolation, even if the material is not spent fuel or is not from the reprocessing of spent fuel. Thus, the EPA has specified release limits for these non-TRU isotopes in 40 CFR Part 191. However, these wastes could also be categorized as LLW, so the inclusion of the non-TRU waste in the initial inventory is debatable. The TRU inventory consists of approximately 600 curies, while the non-TRU inventory comprises about 500,000 curies. Including the non-TRU waste in the analysis increases both the initial inventory and the curies that are allowed to be released to the accessible environment (i.e., the allowable quantity) according to 40 CFR Part 191. The analyses are performed with (1) only TRU waste as the initial inventory and (2) both TRU and non-TRU waste included in the initial inventory.

The results of the PPA analyses are presented in the form of CCDF's of the EPA sum. The base-case scenario is discussed first, followed by the climate-change scenario, and finishing with the human-intrusion scenario.

Table 2. Conceptual Models Used in the Analyses

Model	Assumptions
Ground water flow	The alluvium, which includes both the saturated zone and the unsaturated zone, is a homogeneous isotropic porous media. In the unsaturated zone, flow is vertical, one-dimensional, steady-state, and isothermal. Flow through the saturated zone is also one-dimensional, steady-state, and isothermal, but horizontal.
Radionuclide Transport	Longitudinal dispersion in the unsaturated zone is small (1 - 10 cm) and the coefficient of dispersion does not vary with the length of the flow path. Dispersion in the saturated zone is higher than in the vadose zone and the coefficient of dispersion varies between 5% and 15% of the length of the flow path. Retardation occurs and is caused by radionuclide adsorption onto the porous medium. The release of radionuclides into the geosphere is limited by the solubility of radionuclides in ground water. Radionuclides are immediately available for transport from the waste source. Radioactive decay and production occurs. The diffusive flux for transport is negligible except when the convective transport flux is minimal. The diffusion coefficient is the same for all radionuclides. Vapor phase transport of radionuclides (except radon) is negligible because the radionuclides are not volatile.
Radon transport and resulting dose	The dominant transport process is Fickian diffusion. Advection is minimal, and the effects of barometric pumping are negligible over the time scale of interest (one year). Radon does not partition into either the liquid phase or the solid phase. The pathway for radon exposure is inhalation. The concentration of radon one meter above the ground surface is 0.15 times the concentration in the soil gas just below the ground surface. The exposed person breathes the contaminated air one meter above the ground surface continually for one year. The dose from breathing air containing 1 picocurie/liter of radon for an entire year is 162 millirem[6]. There is no temperature gradient in the borehole.

A. Base-Case Scenario

The results of assessing compliance with the *containment requirements* for the base-case scenario with only TRU as initial inventory are shown in Figure 1, where R is defined as the EPA sum. The curve does not pass through the cross-hatched area, indicating that the base case scenario does not lead to a violation of the containment requirements. Most of the release is attributed to ^{239}Pu and ^{240}Pu. This is expected because most of the TRU inventory (in terms of curies) consists of plutonium.

Also shown in Figure 1 is the CCDF for the base-case scenario with the non-TRU waste included in the initial inventory along with the TRU waste. Note that the curve does not pass through the cross-hatched area and falls generally to the left of the TRU-only curve, and that the two curves have the same shape. Thus, for a given probability, the TRU-only case has a higher EPA sum than the case where the non-TRU waste is also included in the initial inventory. This appears to be counterintuitive at first, because it would seem that including more waste would be more conservative, leading to a higher EPA sum for a given probability. Adding the non-TRU waste to the inventory results in an increase in the curies that are allowed to be released. However, most of the non-TRU waste decays before it can be released to the accessible environment. Therefore, including the non-TRU waste in the initial inventory increases the allowable release limit without increasing the actual release of radionuclides. This leads to EPA sums that are lower than those that result when only the TRU waste is included in the initial inventory.

Of the 4,000 samples generated using LHS, approximately 3,910 result in no radionuclide release to the accessible environment. Thus, only 90 of the samples give non-zero EPA sums. This implies that, assuming the models and parameters employed are adequate for estimating radionuclide releases, the probability of any one of the radionuclides governed by the EPA's containment requirements reaching the accessible environment in 10,000 years is only 0.02.

Liquid phase diffusion to the ground surface is the dominating transport mechanism in 47 of the 4,000 samples. That is, for those particular sample values, the flux of ground water toward the water table is less than the diffusive flux of radionuclides toward the ground surface. Of these 47 samples, 16 result in non-zero answers. Thus, of all the non-zero answers, approximately 18% are the consequence of diffusion in the liquid phase and 82% are the consequence of convection.

Assessing compliance with the *individual protection requirements* is straightforward, except for the consideration of radon transport in the vapor phase. For analyzing the transport of radionuclides in the liquid phase, the strategy employed in assessing compliance with the probabilistic containment requirements is also employed in assessing compliance with the nonprobabilistic individual protection requirements. The analyses indicate that, over 1,000 years, no radionuclides reach the water table and that in less than 1% of the simulations, minute quantities of radionuclides reach the ground surface via diffusion in the liquid phase combined with plant uptake. These quantities range from 4×10^{-19} pc/m^3 to 6×10^{-6} pc/m^3 in the ground water and result in an annual effective dose equivalent of about of 5.5×10^{-4}

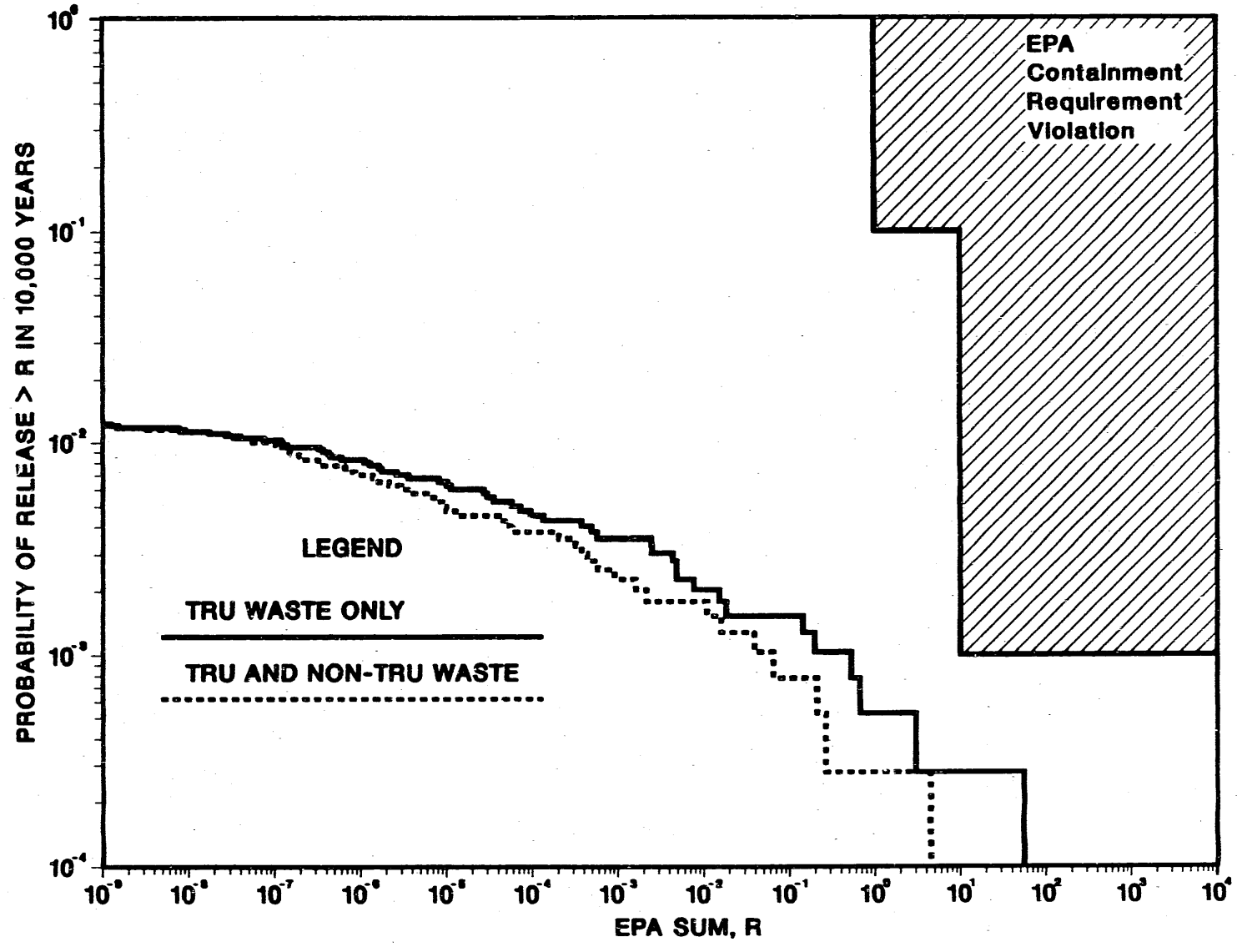

Figure 1. Results of Analyses for the Base Case Scenario

millirems. The pathways included in this analysis are external exposure, inhalation uptake, and animal product ingestion. The individual protection requirements limit the annual dose equivalent to 75 millirems to any critical organ and 25 millirems to the whole body, well above the annual effective dose equivalent calculated above.

For the boreholes that contain only TRU waste (i.e., no heat-generating waste), the analyses indicate that the diffusion of radon upward to and above the ground surface does not result in annual effective doses that exceed the quantities set by the individual protection requirements. For the borehole that contains heat-generating wastes, these preliminary analyses indicate that at the present time, a person continually inhaling radon at the site receives an annual dose equivalent of approximately 500 millirems to the epithelium of the lungs, which is significantly more than allowed by the individual protection requirements. However, in 100 years, that dose decreases to approximately 4 millirems. The dose decreases because the heat source has diminished to 10% of its original strength, causing the diffusion coefficient to diminish by a factor of four. Because the individual protection requirements apply only to a "member of the public," and because NTS personnel are not "members of the public," it is not clear whether the individual protection requirements are currently applicable. Assuming that the individual protection requirements are applicable only after 100 years of institutional control, the dose resulting from the diffusion of radon (4 millirems) does not violate these requirements.

Assessing compliance with the *ground water protection requirements* is very straightforward because no radionuclides reach the water table within 1,000 years. Thus, the ground water protection requirements are not violated.

B. Climate-Change Scenario

For the climate change scenario, it is assumed that the climate becomes cooler and wetter, similar to the conditions thought to be present during the last glacial period. In this scenario, precipitation doubles, resulting in an increase in the downward flux of water in the unsaturated zone (recharge) and a rise in the elevation of the water table. The assumptions are that recharge increases by a factor of 20 and the water table rises between 0 and 50 meters.

For both the climate-change scenario and the human-intrusion scenario, the *containment requirements* are the *only* requirements with which compliance is assessed. The individual protection and ground water protection requirements apply only to undisturbed conditions (i.e., base case scenario).

The CCDF for the climate-change scenario with only TRU waste in the initial inventory is shown in Figure 2. The curve does pass through the cross-hatched area, indicating a potential violation if the probability of the climate-change scenario were one. The curve would be shifted downward and to the left if the probability of occurrence had been incorporated into the CCDF, possibly moving out of the cross-hatched region.

The highest EPA sum in this scenario is about 6600, corresponding to a cumulative release of 272 curies, of which 271 are ^{239}Pu and ^{240}Pu. As with the base case, this is not

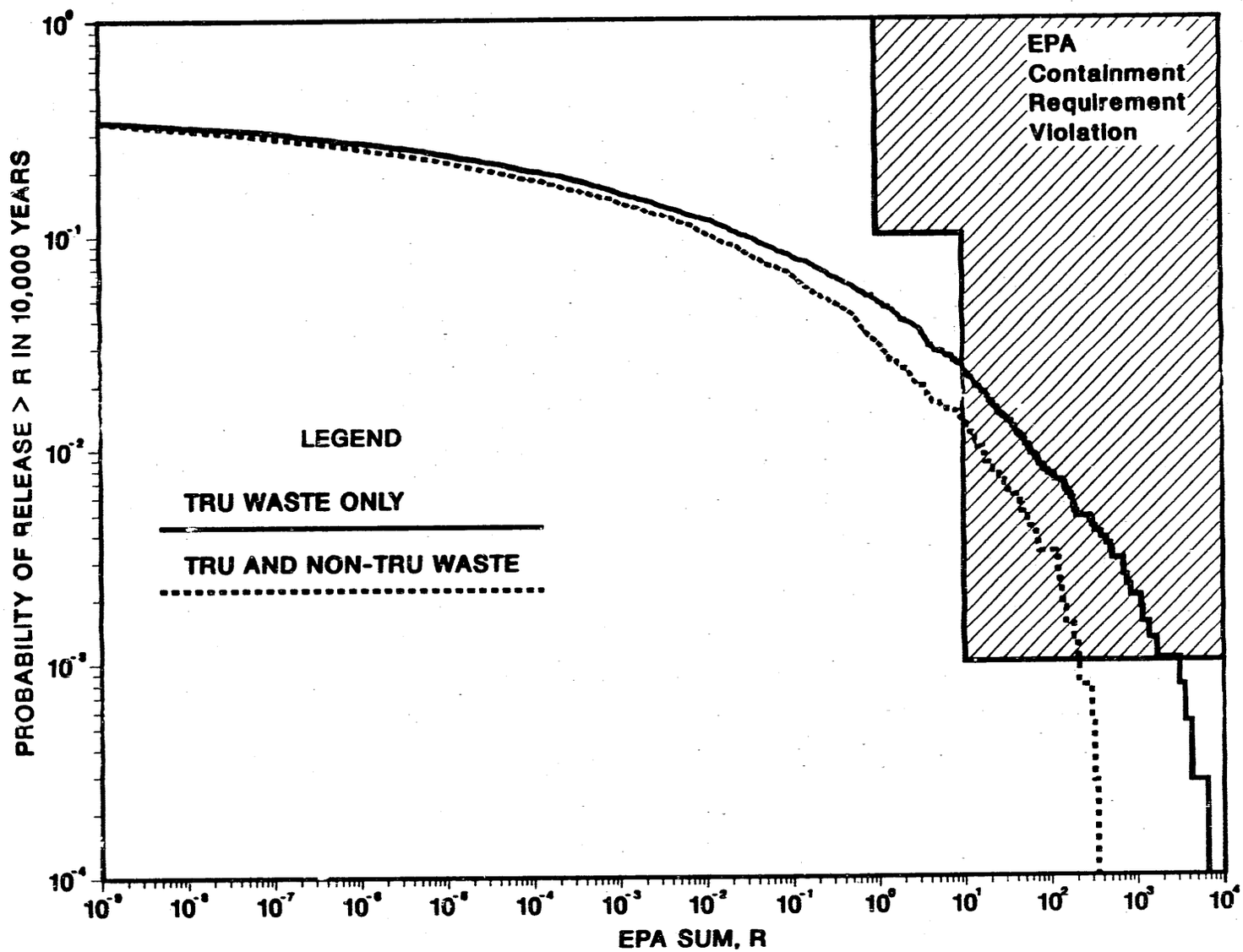

Figure 2. Results of Analyses for the Climate Change Scenario

surprising because the initial inventory (in terms of curies) consists primarily of plutonium.

Also shown in Figure 2 is the CCDF for the climate-change scenario with both the TRU waste and the non-TRU waste included in the initial inventory. The curve lies to the left of the TRU-only curve, similar to the results of the base case and for the same reason as in the base case.

Out of the 4,000 samples, almost half result in non-zero cumulative releases of radionuclides to the accessible environment. This is significantly more than in the base case, where only 2% of the samples result in non-zero releases to the accessible environment.

Liquid-phase diffusion dominates convection in only 13 of the 4,000 samples, about 25% as often as in the base case. This is expected, because the increased downward flux of water tends to make liquid-phase diffusion a less significant pathway for radionuclide migration. Of these 13 samples, none result in significant releases to the accessible environment.

C. Human-Intrusion Scenario

To model the human intrusion scenario, it is assumed that, 100 years after closure, an eight-inch diameter hole is drilled through the center of one of the GCD boreholes. The release of radionuclides consists of those radionuclides that are entrained in the drilling fluid and brought to the ground surface. The waste is assumed to be distributed uniformly within the borehole and to be immobile (i.e., no transport). It is also assumed that each borehole has the same chance of being drilled into. In contrast to the base case and climate change scenario, the only uncertain (i.e., sampled) variables are the radionuclide inventories in each of the boreholes.

The CCDF for the human-intrusion scenario with only TRU waste in the initial inventory is shown in Figure 3. Note that the entire curve falls within the cross-hatched area and EPA sums range from one to 20; there are no samples that yield a zero release. The variability of the CCDF is much less than that of either the base-case CCDF or the climate-change CCDF due to less variability in the uncertain parameters for the human-intrusion scenario.

The highest EPA sum is about 20, resulting primarily from the release of 0.60 curies of ^{239}Pu and 0.14 curies of ^{240}Pu from borehole 4, which contains more plutonium than the other boreholes. The shape of the curve and the highest EPA sum do not change appreciably if the intrusion occurs 1,000 years after closure instead of 100 years. This is because the TRU waste is very long-lived, so that the inventory does not change substantially in 900 years.

The CCDF for the human-intrusion scenario with both TRU waste and non-TRU waste included in the initial inventory is also shown in Figure 3. This curve has slightly more variability than the curve for the TRU-only inventory and does not fall entirely within the cross-hatched area. For this curve, the highest EPA sum is about 40, corresponding to the release of approximately 200 curies of ^{90}Sr and 9 curies of ^{137}Cs. This highest EPA sum

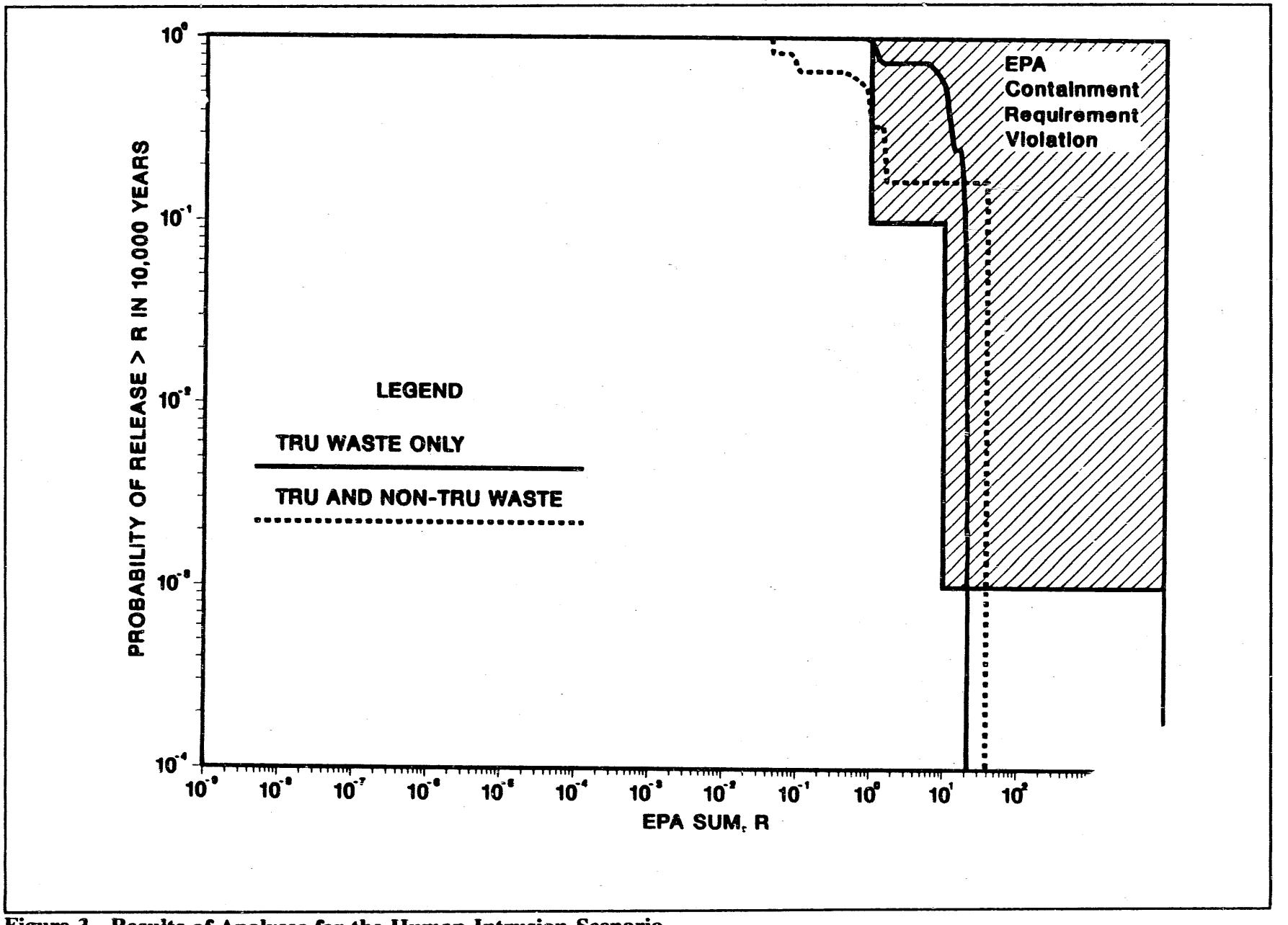

Figure 3. Results of Analyses for the Human Intrusion Scenario

changes if the intrusion occurs at 1,000 years after closure instead of 100 years because the inventories of ^{90}Sr and ^{137}Cs are approximately 1×10^{-10} times their original values after 1,000 years.

Recall that there is no probability of occurrence associated with the CCDF's in Figure 3. This is important because including the probability of occurrence results in shifting the curve downward and to the left, possibly out of the "violation zone."

V. RESULTS OF SENSITIVITY ANALYSES

Sensitivity analyses are performed on the results of the containment requirement analyses for the base-case and climate-change scenarios. The sensitivity analyses consider only the convection pathway and not the liquid diffusion pathway. Sensitivity analyses are not performed for the human intrusion scenario because the only uncertain parameters are the waste inventory (by borehole) and these parameters are much less uncertain than the parameters that control ground water flow and radionuclide transport.

Initially, scatter plots of the nonzero values of EPA sum versus each of the rank-transformed parameter values are generated for each uncertain variable. Most of these plots do not show a strong functional relationship between input and output; however, the plots do yield useful information. For example, the scatter plot of the EPA sum versus recharge indicates that the lowest 2600 values (of 4000) of recharge give an EPA sum of zero for the base case. Thus, only the upper 1400 values of recharge can, but do not necessarily, result in a non-zero EPA sum. This indicates that there is some threshold value of recharge below which the EPA sum is always zero. For the climate-change scenario, the lowest 1000 values of recharge result in an EPA sum of zero. The rank of the threshold value of recharge is lower for the climate-change scenario than for the base case because the values of recharge for the former are 20 times those for the latter. The actual threshold value is probably about the same for both the base-case and the climate-change scenarios. In addition, a dependence of the EPA sum on the saturated pressure gradient is evident. The lack of an apparent functionality between the EPA sum and the remaining independent variables is a result of the large number of input variables, the large degree of uncertainty associated with the input variables, and the complex interactions among these variables in this system of coupled flow and transport models.

The data used to generate the scatter plots are also used in a stepwise regression analysis which is helpful in filtering out the noise in the scatter plots. The regression model coefficient of determination (R^2) measures the percent of the total variation explained by the regression model. The R^2 value is 0.50 for the base case; one reason the regression model fit is so poor is that there are very few nonzero EPA sum values with which to construct the regression model. For the climate-change scenario, the stepwise regression was performed using only nonzero values ($R^2 = 0.82$) *and* using all values (including zeros, $R^2 = 0.62$) of the EPA sum. Therefore, the regression models do not explain the relationship between input and output very well.

For both scenarios, the regression model coefficients indicate that the saturated ground water-flow model parameters are more important than the radionuclide transport

parameters. It was anticipated that recharge would be identified as the most important variable. Recharge is important in that a minimum value is needed to transport radionuclides through the vadose zone in less than 10,000 years. Once this is achieved, the effect of the saturated flow and transport parameters becomes important. However, identifying which parameters are most important is difficult because the variable interactions are complex.

To gain further insight into which combinations of variables produce the highest EPA sums, a detailed inspection of a portion of the input and output data is performed. The ranks of the parameter values are examined to assess whether a particular parameter value is consistently at the high or low end of its range for those runs resulting in the eight largest values of the EPA sum. In most of the eight cases, the recharge, the hydraulic conductivity in the saturated zone, and the pressure gradient in the saturated zone, are at the upper end of their respective ranges while the porosity and the Pu retardation factor are at the low end of their respective ranges. Thus, the extreme high values of the EPA sum occur only for sample vectors having this combination of extreme input values. No other input parameters values are consistently at the high or low end of their ranges for the highest EPA sums.

Identification of the radionuclides which are the primary contributors to the release at the accessible environment (for the high EPA sum values) helps to narrow the number of radionuclide-specific transport parameters that may be important. In general, the highest EPA sums result primarily from the release of ^{239}Pu and ^{240}Pu, with the release of ^{239}Pu being about ten times the release of ^{240}Pu. For example, for an EPA sum of 55, 49 is from the release of ^{239}Pu and 5 is from the release of ^{240}Pu. Thus ^{239}Pu and ^{240}Pu are responsible for 98% of the EPA sum. In terms of curies of specific isotopes, the ^{239}Pu isotope is the most abundant plutonium isotope in the initial inventory, which is why the highest releases of radionuclides to the accessible environment consist mostly of ^{239}Pu. The secondary contributors to the EPA sum are generally ^{237}Np, ^{234}U and ^{230}Th. These isotopes dominate the EPA sum when the sorption coefficient for plutonium is high (i.e., Pu retardation is enhanced). Neptunium is a secondary contributor because ^{237}Np is a daughter product of ^{241}Am, an isotope which is included in the initial inventory and which decays rapidly ($t_{1/2}$ = 433 years). ^{234}U is the most abundant uranium isotope in the initial inventory, in terms of curies, and ^{230}Th is a daughter product of ^{234}U.

VI. CONCLUSIONS

One of the conclusions of this study is that the GCD disposal concept is a technically feasible method of disposing of the DOE's orphan wastes. This conclusion is based on the curves shown in Figure 1 which indicate that, under undisturbed conditions, the GCD site complies with the containment requirements of 40 CFR Part 191. The results of the analyses also indicate that the site complies with both the ground water protection requirements and the individual protection requirements with the possible exception of the diffusion of radon from a borehole that contains heat-generating wastes. The models and parameters used in the PPA analyses are first approximations and will likely be revised as more information is obtained. However they are adequate for the purpose of determining the feasibility of compliance with 40 CFR Part 191.

Recall that the analyses described above were performed using data and information already in existence; no new information was collected. Therefore, a second conclusion of this study is that available data and information are sufficient for performing a preliminary performance assessment. However, available data and information are probably not suitable for a performance assessment that forms part of the basis for licensing the GCD site. This is because much of the data and information used are not site-specific or were not collected under acceptable quality assurance standards. Furthermore, there are significant uncertainties associated with the physicochemical properties of both the radionuclides and the transport medium. Thus, future work is focusing on refining the models that are used and on collecting site-specific data under acceptable quality assurance standards in order to reduce parameter uncertainty.

The sensitivity analyses indicate that the ground-water flow parameters are the most important parameters controlling releases of radionuclides to the accessible environment. Of these variables, the recharge, the saturated-zone pressure gradient, the hydraulic conductivity in the saturated zone, and the porosity are the most important variables. Of the radionuclide-specific parameters, the sorption coefficient of plutonium appears to be the most important variable. Analysis of the results is made difficult by the complex interactions of many different isotopes, each having different decay rates, sorption coefficients, solubility limits and positions within different decay chains. The combination of the wide range of uncertainty associated with the input parameters and the complex interactions tends to obfuscate the results of sensitivity analysis. Nevertheless, the insights gained from this preliminary analysis provide a useful tool to guide future site characterization efforts.

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