

Development of Risk Insights for Regulatory Review of a Near-Surface Disposal Facility for Radioactive Waste

D.W. Esh, A.C. Ridge, M. Thaggard
U.S. Nuclear Regulatory Commission
Mail Stop T7J8, Washington, DC 20555
USA

ABSTRACT

Section 3116 of the Ronald W. Reagan National Defense Authorization Act for Fiscal Year 2005 (NDAA) requires the Department of Energy (DOE) to consult with the Nuclear Regulatory Commission (NRC) about non-High Level Waste (HLW) determinations. In its consultative role, NRC performs technical reviews of DOE's waste determinations but does not have regulatory authority over DOE's waste disposal activities. The safety of disposal is evaluated by comparing predicted disposal facility performance to the performance objectives specified in NRC regulations for the disposal of low-level waste (10 CFR Part 61 Subpart C). The performance objectives contain criteria for protection of the public, protection of inadvertent intruders, protection of workers, and stability of the disposal site after closure. The potential radiological dose to receptors typically is evaluated with a performance assessment (PA) model that simulates the release of radionuclides from the disposal site, transport of radionuclides through the environment, and exposure of potential receptors to residual contamination for thousands of years.

This paper describes NRC's development and use of independent performance assessment modeling to facilitate review of DOE's non-HLW determination for the Saltstone Disposal Facility (SDF) at the Savannah River Site. NRC's review of the safety of near-surface disposal of radioactive waste at the SDF was facilitated and focused by risk insights developed with an independent PA model. The main components of NRC's performance assessment model are presented. The development of risk insights that allow the staff to focus review efforts on those areas that are most important to satisfying the performance objectives is discussed. Uncertainty analysis was performed of the full stochastic model using genetic variable selection algorithms. The results of the uncertainty analysis were then used to guide the development of simulations of other scenarios to understand the key risk drivers and risk limiters of the SDF. Review emphasis was placed on those aspects of the disposal system that were expected to drive performance: the physical and chemical performance of the cementitious wastefrom and concrete vaults. Refinement of the modeling of the degradation and release from the cementitious wastefrom had a significant effect on the predicted dose to a member of the public.

INTRODUCTION

The Department of Energy performs non-HLW determinations to determine whether materials resulting from the reprocessing of spent nuclear fuel can be treated and disposed of safely in near-surface disposal facilities. Section 3116 of the Ronald W. Reagan National Defense

Authorization Act of Fiscal Year 2005 (the Act) requires DOE to consult with the Nuclear Regulatory Commission (NRC) about non-High Level Waste (HLW) determinations performed pursuant to the Act. In its consultative role, NRC performs technical reviews of DOE's waste determinations but does not have regulatory authority over DOE's waste disposal activities. The safety of disposal is evaluated by comparing predicted disposal facility performance to the performance objectives specified in NRC regulations for the disposal of low-level waste (10 CFR Part 61 Subpart C). The performance objectives contain criteria for protection of the public, protection of inadvertent intruders, protection of workers, and stability of the disposal site after closure. The potential radiological dose to receptors typically is evaluated with a performance assessment (PA) model that simulates the release of radionuclides from the disposal site, transport of radionuclides through the environment, and exposure of potential receptors to residual contamination for thousands of years.

PA models often are composed of a number of submodels, also called process models, which are used to simulate distinct processes, such as flow and transport in the vadose zone. The justification for input data, support for models, integration of submodels, and impact of uncertainty in data and models all must be provided to support estimates of the long term performance of the waste disposal system. Risk insights allow the staff to focus review efforts on those areas that are most important to satisfying the performance objectives. To develop risk insights, the NRC staff typically develops independent performance assessment models. NRC's models are internal review tools used solely to inform the review; conclusions about the appropriateness of DOE's waste determinations are based on DOE's analysis.

This paper provides an example of NRC's use of independent performance assessment modeling to support its review of a non-HLW determination. The subject of the example review is the treatment and disposal of salt waste from HLW storage tanks at the Savannah River Site [1]. DOE plans to dispose of the waste in a cementitious wastefrom, called saltstone. Approximately 5 million cubic meters of saltstone will be disposed of in concrete vaults. The vaults will be covered with a 4 meter thick composite cap designed to limit infiltration and prevent erosion. The example is limited to assessment of the potential long term radiological doses to the public and does not include parts of the model used to estimate doses to potential inadvertent intruders.

MODEL DEVELOPMENT

The PA model used to support the review of the Saltstone Disposal Facility (SDF) at the Savannah River Site was developed with the software package GoldSim [2]. The GoldSim software package is a visual model-building platform for performing dynamic, probabilistic simulations. The Radionuclide Transport module provides built-in elements that can simulate radioactive decay and ingrowth, advection, dispersion, adsorption, diffusion, and matrix diffusion for fractured flow. The PA model for the SDF is composed of more than 1150 GoldSim elements and contains abstracted submodels that represent degradation of the engineered cap and oxidation and physical degradation of the saltstone as a function of time. The model can be used to estimate radiological impacts to different types of receptors (e.g., resident, farmer, recreational user) through multiple exposure pathways. Parameter and model uncertainty were included in the model through the use of more than 300 stochastic elements.

The model is composed of three main parts: 1) source term and near-field release, 2) saturated zone and surface water flow, and 3) dose assessment. In addition, the model contains information about radionuclide decay and the physical properties of site soils, the saltstone wasteform, and vaults.

Source Term and Near-Field Release

The source term and near-field release submodel represents infiltration, cap degradation, source oxidation and degradation, and radionuclide transport through the unsaturated zone. The model includes 41 radionuclides, including decay chains. Table I provides the projected SDF inventory of radionuclides that contribute a peak dose greater than $1\text{E-}6$ mSv/yr in this analysis [3]. In the model, advective and diffusive releases from the waste can occur only after the concrete vault containing the waste has failed hydraulically. Advective flow is modeled as vertical flow through the waste while both vertical and lateral diffusive flux is modeled. Because releases from the waste are assumed to occur only after the vault has failed hydraulically, the model represents advective and diffusive fluxes as transmitting radionuclides from the wasteform into cells that represent both the degraded vault and adjacent soil as a material with the hydraulic properties of soil. Distribution coefficients are used to predict partitioning of radionuclides between the solid phases (e.g., saltstone, soil) and pore fluids. Solubility limits are applied to the pore fluids, and different solubility limits can be applied to different regions of the model to simulate different chemical environments. For example, pore fluid in the saltstone wasteform is expected to be highly alkaline, whereas the groundwater in the saturated zone is expected to be nearly neutral even when modified by fluids released from the facility.

The cementitious saltstone wasteform contains blast furnace slag to create reducing conditions in the wasteform. Reducing conditions are beneficial primarily because reduced forms of technetium typically are much less mobile than oxidized forms of technetium. Preliminary analyses performed with an early version of the model indicated that the assumption regarding whether the waste would maintain a reducing environment or become oxidizing would have a significant effect on the predicted dose to a member of the public. Because this assumption had a significant effect on dose, and because the assumption that the waste is either entirely reducing or entirely oxidizing is unrealistic, the model was refined to reflect the oxidation of waste as a function of time. In addition, the model was refined with a submodel that predicts physical degradation of the waste as a function of time.

Waste oxidation and degradation are modeled as proceeding from waste surfaces, including the surfaces of cracks, inward (Figure 1). Wasteform cracking may occur during curing, as a result of settlement, or as a result of other processes. The model does not predict the amount of cracking that will occur in the waste form. Instead, the potentially complex pattern of cracking in the wasteform is represented in the model as a series of planar cracks through the waste [Figure 1, item (3)]. The spacing of the cracks is represented with a stochastic variable that the user controls to represent different degrees of degradation of the waste. Whereas for a cementitious containment structure cracks may need to penetrate through the structure in order to affect performance (e.g., by diverting flow), degradation of a wasteform may only need to impact a surface layer in order to affect performance (e.g., by exposing more waste to oxidation). In the model, infiltrating water is routed around or through the wasteform based on the quantity of

water infiltrating to the top of the wastefrom and the hydraulic properties of the material [Fig. 1, item (1)]. At each fracture or exposed surface, an oxidation front and a degradation front are estimated to penetrate into the material. The oxidation and degradation fronts may

Table I. Projected Saltstone Disposal Facility Inventory of Radionuclides That Contribute a Peak Dose of More Than 1E-6 mSv/yr in This Analysis [3]

Radionuclide	Projected Inventory (Bq [Ci])	Radionuclide	Projected Inventory (Bq [Ci])
C-14	1.92 E+13 [520]	Ra-226	4.81 E+11 [13.0]
Se-79	3.31 E+12 [89.4]	Ac-227	7.07 E+05 [1.91E-5]
Tc-99	1.22 E+15 [33,100]	Pa-231	1.97 E+06 [5.32E-5]
Sn-126	1.67 E+13 [451]	Np-237	7.84 E+10 [2.12]
I-129	6.66 E+11 [18.0]	Pu-239	2.42 E+13 [655]
Pb-210	0.0 [0.0]	Pu-240	6.48 E+12 [175]

propagate at different rates, resulting in different thicknesses of material that are oxidized or degraded [Figure 1, item (2)]. DT(t) is the degraded thickness as a function of time from an empirical model for sulfate and magnesium attack [4,5],

(Eq. 1)

$$DT(t) = 0.55 C_c (C_m + C_s) t$$

where

- 0.55 = empirical constant (cm · L)/(moles · yr)
- C_c = weight percent of tricalcium aluminate in unhydrated cement
- C_m = concentration of magnesium in the bulk solution (moles/L)
- C_s = concentration of sulfate in the bulk solution (moles/L)
- t = time (yr)
- DT(t) = degraded thickness (cm)

OT(t) is the oxidized thickness as a function of time from a shrinking-core model [6],

$$OT(t) = \left(\frac{8D\theta\tau C_{O_2} t}{\Xi} \right)^{\frac{1}{2}} \quad (\text{Eq. 2})$$

where

- D = diffusion coefficient of oxygen in water (cm²/s)
- θ = volumetric water content
- τ = tortuosity/ geometry correction factor
- C_{O₂} = concentration of oxygen outside the waste form (moles/cm³)
- Ξ = equivalents of reduced material per unit volume of the waste form (equivalents/cm³)
- t = time (s)
- OT(t) = penetration depth of the redox front (cm)

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The process models for wasteform degradation and oxidation that have been implemented in the performance assessment model do not necessarily represent the dominant mechanisms of degradation and oxidation of saltstone waste. Rather, the models serve as tools to evaluate time-dependent degradation or oxidation of the waste, and can be replaced with different submodels if

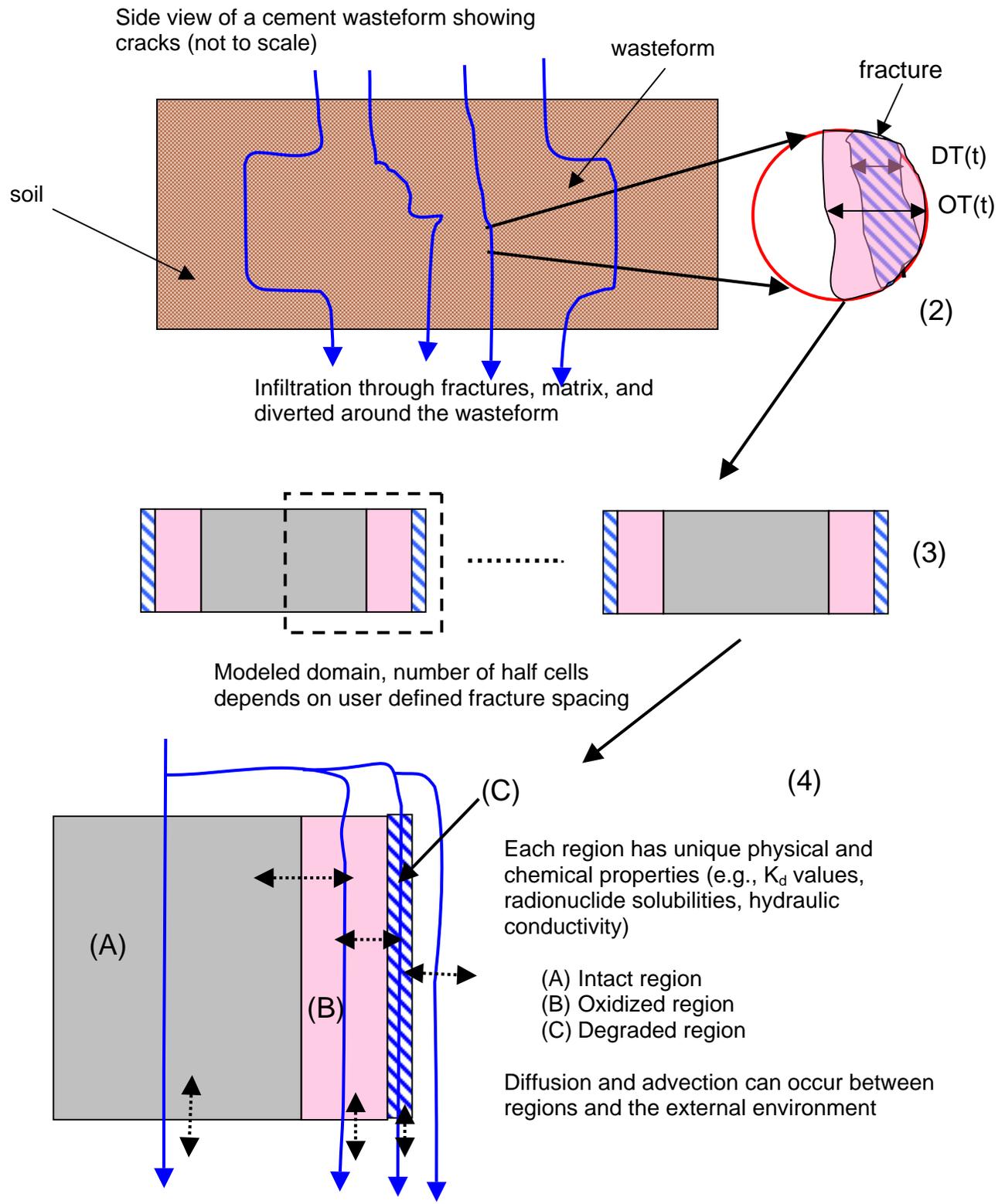


Fig. 1. Conceptual model for degradation of the cementitious wasteform
 additional site-specific information about the mechanisms or rates of degradation becomes available

In the conceptual model, there are three regions in the wasteform: intact, oxidized, and degraded. The predicted release of radionuclides from each region of waste is affected by the modeled physical and chemical properties of the waste in each region. The actual degraded wasteform may have an extremely complicated collection of units of intact material with variable volumes and shapes. Consistent with the use of the PA model as a review tool, the potentially complicated geometry was simplified into three connected cells in the length dimension of the facility, one for each of the intact, oxidized, and degraded regions. The wasteform was assumed to be broken into a series of blocks by fractures extending through the wasteform. Therefore the results from the three cells were scaled up to represent the total number of blocks in the system based on the total length of the facility and the assigned fracture spacing. Infiltrating water is assumed to flow through the fractures, thereby resulting in a zero concentration boundary condition at the exposed side of the wasteform. The dimensions of the blocks in the model were determined by the physical dimensions of the system (7.5 m high by 30 m thick) and the user-defined stochastic fracture spacing distribution. Half of a degrading block was represented in the model and the results were extrapolated to the whole block by invoking a symmetry argument from the midpoint of a block [Figure 1, item (3)]. Diffusive transport between the three regions of the wasteform and from the wasteform to the surrounding soil was represented in the model.

In the conceptual model, water flows through the degraded fraction of the waste only if water flowing into the intact fraction exceeds the capacity of that fraction to transmit water. Similarly, water flows through the degraded fraction of the waste only if water flowing into the intact and oxidized fractions of the waste exceeds the capacity of those fractions to transmit water. In the PA model, first the volume of infiltration to region (A) is calculated. If this volume exceeds the saturated hydraulic conductivity of the material, the excess infiltration is available to region (B) in addition to the moisture that would be captured based on the cross sectional area of region (B) (extending into the page in Figure 1) [Figure 1, item (4)]. The potential flow through region (C) is calculated in a similar manner. Any additional flow is made available to the planar fracture that bound the side of the cell network next to the degraded region of the wasteform. In summary, advective flow through the intact, oxidized, and degraded fractions is based on the assumption that water will flow through the waste vertically. The amount of flow predicted to occur through each type of waste is calculated based on the horizontal surface area of the type of waste (i.e., intact, oxidized, or degraded) and the hydraulic conductivity for the type of waste.

Oxidized waste is waste in which oxygen from groundwater diffuses into the waste and consumes the reducing capacity of the saltstone. In the oxidized fraction of the waste, the distribution coefficient of technetium is much lower (i.e., 1 mL/g) than it is in the reducing fraction of the waste (i.e., 1000 mL/g). As previously discussed, oxidation is modeled based on a shrinking core model [6,7]. In addition, the hydraulic conductivity of the waste in the oxidized fraction is assumed to be greater than the hydraulic conductivity of the intact waste but less than the hydraulic conductivity of the degraded waste. Oxidation is modeled to occur from each exposed surface of the waste, including the surfaces of fractures. The depth to which the waste is predicted to oxidize is limited by the diffusion of oxygen through water into the wasteform. In the degraded fraction of the waste, the hydraulic properties of the waste are compromised by small-scale cracking. In the model, the degraded fraction of the waste has a hydraulic conductivity that is a factor of 30 to 300 times greater than the extreme values of the range of values used to represent hydraulic conductivity of the intact waste. As previously discussed,

physical degradation of the waste is represented by sulfate and magnesium attack.

Radionuclides released from the source term are modeled as being transported vertically through the unsaturated zone. Unsaturated zone transport is represented with a pipe element. In GoldSim, a pipe element is a basic contaminant transport element designed to represent a feature that behaves as a fluid conduit. Pipe pathways use a Laplace transform approach to provide analytical solutions to a broad range of advectively-dominated transport problems involving one-dimensional advection, longitudinal dispersion, retardation, decay and ingrowth, and matrix diffusion (if needed). The length of the pipe element is represented by a stochastic variable, the values of which are based on site-specific information. The flow rate from the cell element to the pipe element and through the pipe element is equal to the sum of the rate of water infiltration through the waste and the rate of water flow through the lateral cells that represent the soil surrounding the saltstone vaults that radionuclides can diffuse into.

Long term Infiltration Cap Submodel

Infiltration into the wastefrom is limited by both the hydraulic properties of the saltstone itself, as described above, and by a closure cap. The closure cap is composed of an erosion barrier, an upper drainage unit, and a lower drainage unit. In the PA model, the effects of the closure cap are modeled as a factor applied to the infiltration rate that allows infiltration through the cap to increase linearly during the degradation period. The period over which the performance of the cap degrades is represented stochastically as a time period defined by the user. The period of cap degradation, modeled as lasting between 300 and 400 years, was based on consideration of erosion, pine root penetration, and clogging of a drainage layer with clay colloids. Because the flow-limiting upper and lower drainage units are protected beneath the erosion barrier and overlying backfill, and because monitoring and maintenance could be performed while institutional controls are in place to limit deterioration of the engineered cap, the model uses a static parameter to represent a delay before which cap degradation starts. Prior to the onset of cap degradation, it is assumed that no water is transmitted to the top of the waste form. The degree to which the cap limits infiltration once it has degraded is defined by the user. In uncertainty analyses performed to generate risk insights for the saltstone review, the long term performance of the cap (i.e., infiltration through the cap after the cap has degraded) was varied to represent infiltration ranging from a fraction of a percent of natural infiltration to the natural infiltration rate (i.e., the amount of infiltration expected in the absence of a cap).

Far-Field Transport

Radionuclide transport is represented as vertical transport through the unsaturated zone and horizontal transport through the aquifer and to surface water. Contaminated water entering the saturated zone from the unsaturated zone under the SDF is diluted by clean water flowing through the aquifer. The PA model does not calculate water flow based on information about the hydraulic gradients at the site, and does not calculate gradients based on modeled precipitation or infiltration. Instead, information about groundwater movement is based on site-specific information about the speed of groundwater flow in the area, DOE's predicted depth of mixing of contamination in the saturated zone, site-specific information about precipitation, and variable performance of the engineered cap. Water is assumed to flow from the area under the waste

through a stream tube in the saturated zone toward a surface stream.

Water flow through the saturated zone is modeled conceptually as flow through underground stream tubes that are represented in the GoldSim PA model with pipe elements. The flow of water through the tubes is represented by the flow velocity (a stochastic parameter based on flow measurements) multiplied by the lateral area of the stream tube, where the lateral area of the stream tube is represented by the characteristic length of the waste on the surface multiplied by the estimated depth over which contaminants will be mixed in the aquifer. In the PA model, the mixing depth is fixed at 10 m. The characteristic length of the waste on the surface is equal to the square root of the foot print of the waste on the surface (i.e., the square root of the width of the waste multiplied by the length of the waste). Transport through the saturated zone is modeled with a set of two transport pipes. A set of two pipes is used so that the output of the first pipe can be used to represent groundwater use by a receptor, with the remaining flow continuing to the second pipe and, ultimately, to a surface water stream. The location of the receptor can be varied by changing the lengths of the pipes while keeping the sum of the lengths constant to maintain the modeled transport distance from the aquifer to the surface water system.

As noted previously, the discharge from the saturated zone stream tube is input into a pipe representing a surface water stream. Contaminated water from the saturated zone is diluted by clean water flowing in the stream. The amount of water flowing in the stream is represented by a stochastic variable with values based on site-specific data.

Dose Modeling

As discussed in the introduction, the PA model can be used to predict doses for members of the public and inadvertent intruders. The user can choose to represent one of two different land use scenarios: a residential scenario and an agricultural land-use scenario. For the residential receptor, there are five main exposure pathways: drinking contaminated groundwater, consuming plants grown in a garden using contaminated irrigation water, inadvertent soil ingestion, consumption of fish caught in a stream, and direct radiation exposure to garden soil. In addition to these pathways, the farmer receptor is exposed by consumption of milk, eggs, and beef produced by animals exposed to contaminated water and fodder. In the original model development process, an air pathway was included. However, subsequent analyses indicated that the contribution from the air pathway was likely to be small and it was removed from further consideration. The dose analysis is based on the concentrations of contaminants in the ground water or surface water multiplied by the appropriate dose conversion factors that relate environmental concentrations to receptor doses for each pathway. The dose conversion factors used in the model are from Federal Guidance Report 11 and 12 [8,9]. The environmental concentrations of radionuclides in the model were calculated using the submodels previously described. The GoldSim submodel that used environmental concentrations to calculate receptor dose due to specific uptake pathways borrowed extensively from a model created by John Tauxe of Neptune and Company [10].

ANALYSIS APPROACH

An iterative approach was used to develop risk insights. First, a base case model file was

developed that represented uncertainty in parameters stochastically. Individual realizations of the base case model file were examined in detail to ensure the results were reasonable, physically consistent, and consistent with the conceptual model. The GoldSim software package is a visual simulation environment in which intermediate outputs of time series and distributional results can be saved and plotted, thereby facilitating model review. The model output was reviewed to ensure there was limited sensitivity to the time-stepping defined in the model (ranging from 25 to 100 years) or to the number of realizations used to sample the uncertain distributions in the probabilistic calculations (ranging from 100 to 500). All simulations evaluated the system performance for 10,000 years unless otherwise indicated. Identification of uncertainties most likely to influence risk to a member of the public was facilitated by representing uncertainties in key parameters with broad probabilistic distributions. Broad uncertainty distributions typically can not be used in an analysis of a compliance case because the projected time of occurrence of risks may be spread arbitrarily, thereby reducing the calculated risk to an individual. However, broad distributions are useful in this type of probabilistic analysis because they ensure that the parameter uncertainty space is fully covered by the ranges of parameters selected.

Uncertainty analysis of the base case model output was performed using neural network software developed by Neuralware [11]. Neuralworks Predict® is an add-in to Microsoft Excel that can be used to build neural networks. The approach used in this analysis was to export the sampled stochastic input variables along with the pertinent output variable (e.g., peak total dose, dose at a particular time, dose for a particular radionuclide at a particular time) from the PA model to Excel and then to build a neural network using Neuralworks Predict. The neural network was not used in the analysis; instead, the variable selection algorithms were used to select the most important input variables needed to develop a neural network to predict the output. The Input Variable Selection component of Neuralworks Predict uses a genetic algorithm to search for synergistic sets of input variables which are good predictors of the output. The software also can perform a preselection of variables using a cascaded genetic algorithm approach. This method gives more consistent variable sets by pruning out variables which are consistently rejected by different invocations of the genetic algorithm. NRC experience with applying this technique for uncertainty analysis suggests it is quite powerful at identifying key input variables while eliminating spurious correlations, a common problem with large data sets of many input variables.

Genetic algorithm variable selection was performed for many cases, with three pertinent examples presented in the section that follows. The base case output was first analyzed. Next, the list of more than 250 input variables was reduced to a list of approximately 100 input variables to eliminate those variables which may not have been used in the model calculation or were pertinent to radionuclides that did not contribute more than $1\text{E-}5$ mSv/yr ($1\text{E-}3$ mrem/yr) peak mean dose. For example, because the PA model is set up to predict the dose to different types of receptors, parameters pertaining to receptors that have not been selected by the user are not used during the calculation, but they are still sampled. These types of parameters can be eliminated from consideration by the genetic variable selection algorithms without risking eliminating a variable that could influence the output. The neural network was then rebuilt with the shortened list of input variables. This was done because the ability of the algorithms to identify the variables driving the output is enhanced when the input variable list is shorter (i.e., noise is reduced).

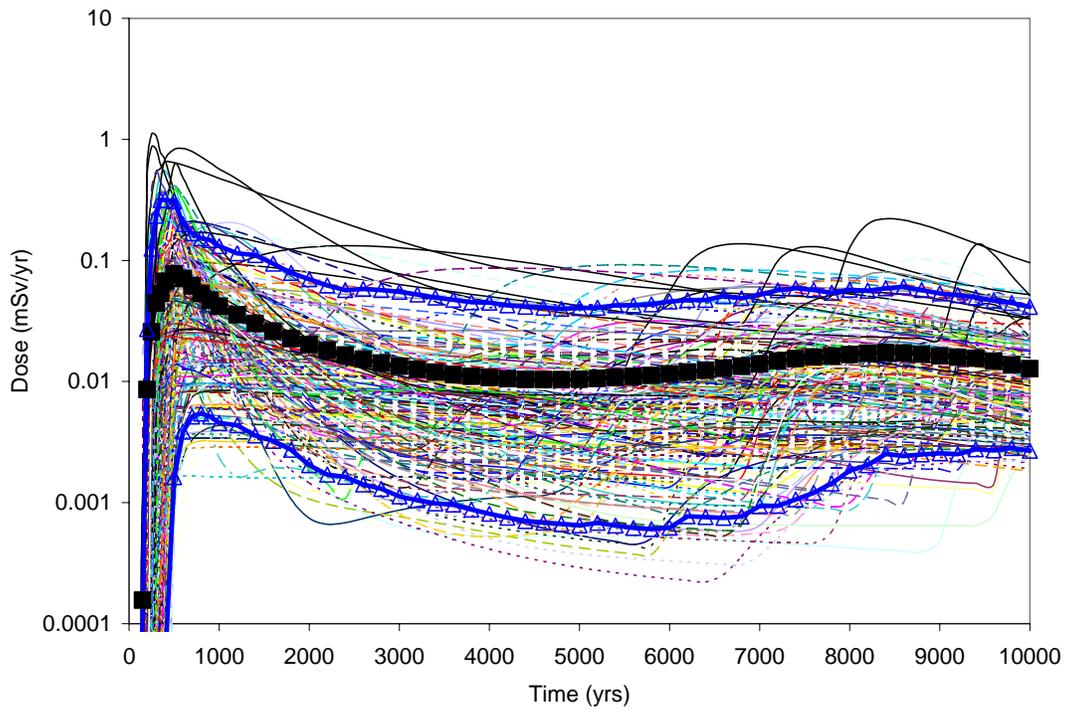
The results of the uncertainty analysis were used to develop scenarios to define the performance of the system over more narrow ranges of performance, and to evaluate special cases. For example, the third example that is presented in the results section was generated using the peak output for the dose from Pu-239. The peak mean Pu-239 dose for this calculation was only $2\text{E-}4$ mSv/yr (0.02 mrem/yr), whereas the total peak mean dose was 0.077 mSv/yr (7.7 mrem/yr). The total peak mean dose was dominated by Tc-99 and I-129, radionuclides that are long-lived, highly soluble, and expected to be weakly sorbing in this system. Therefore, the third example was performed to evaluate the key input variables for a radionuclide that may be rather insoluble and more strongly sorbing.

RESULTS

Fig. 2 provides the results of the base case. Fig. 2a is the horsetail plot showing the individual realizations. Superimposed is the mean, 5th, and 95th percentile results. Fig. 2b provides the mean result showing the contribution from individual radionuclides. Although the model contains 41 species including decay chains, only those radionuclides that contribute more than $1\text{E-}6$ mSv/yr ($1\text{E-}4$ mrem/yr) at their peak value are shown in Fig. 2b. The peak mean result for the base case was 0.077 mSv/yr (7.7 mrem/yr) and was dominated by Tc-99 and I-129, which account for more than 99% of the total peak dose, with a minor contribution from Np-237. As a result of sorption by the cementitious wastefrom and the geologic system, most radionuclides are likely to be retained by the system and pose minimal risk to the public receptor through the groundwater pathway.

Results from the uncertainty analysis of the base case file with all stochastic input variables selected is presented in Table II. The variable name, its description, and the frequency at which it was selected to build the neural network, called the Importance Factor, are provided. The variables with a high degree of selection are more likely to be a variable that truly drives the output and not be a spurious result. The top three variables all pertain to the degradation of the wastefrom. It is less clear whether variables other than the top three have a significant effect on the model output. For example, the doses are dominated by ingestion of contaminated water and to a minor extent consumption of contaminated plants grown in a garden. Therefore, *TransFactor_indoor*, which is related to shielding of radiation when an individual is inside a residence, is likely to be a spurious result. Likewise, the Eu isotopes are not estimated to cause any dose due to their short half lives and retention in the system, therefore *Kd_waste_Eu*, which represents sorption of Eu in the waste form, also is likely to be a spurious result. Similar arguments can be made for other variables at the bottom of the table. Table III provides the results from performing an identical variable selection calculation with a shortened list of variables. The shortened list of variables removed those pertaining to parts of the model that were not activated in the calculation, or for radionuclides that contributed a very small fraction to the total dose. The variable selection algorithm identified 6 variables, all with a high frequency.

2(a)



2(b)

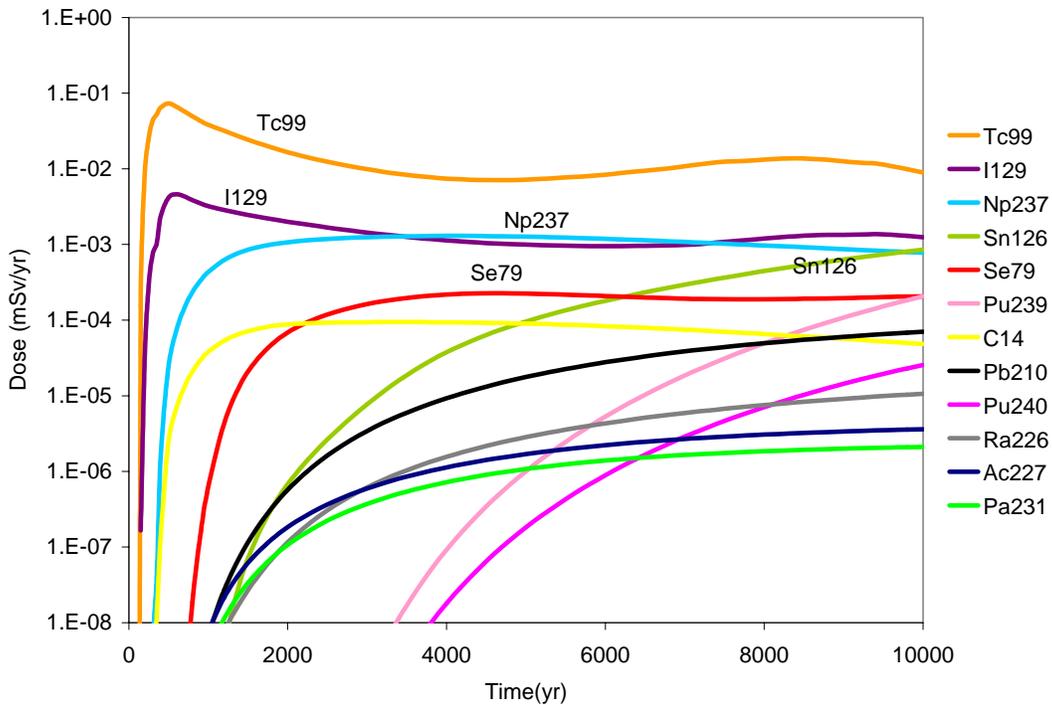


Fig. 2. 2a) The horsetail plot showing the individual realizations. Superimposed with thicker lines is the mean, 5th, and 95th percentile results. 2b) Provides the mean result showing the contribution from individual radionuclides that contributed more than 1E-6 mSv/yr at their peak (the model contains 41 species including decay chains).

Table II. Results of an Uncertainty Analysis with Genetic Algorithms for the Base Case

Variable Name	Description	Importance Factor
Grout_deg_start	The time at which degradation of the wasteform can begin. Used to represent the protection of the wasteform by a vault that fails because of rebar corrosion or another form of degradation.	0.98
Nm	MacMullin number. The effective diffusion coefficient is a product of Nm and the molecular diffusion coefficient. Influences the extent of degradation in the analysis.	0.93
Degraded_grout_Kh	The hydraulic conductivity for the degraded region of the wasteform.	0.36
TransFactor_indoor	Factor to account for shielding of radiation when an individual is inside a residence.	0.29
Se_solubility	The solubility of Se in the pore fluid of the wasteform.	0.21
Kd_waste_Sr_ox	The distribution coefficient for Sr in the oxidized region of the wasteform.	0.11
Vent_light_activity	Breathing rate for an individual during light activity.	0.11
SZ_dispersivity_factor	Used with the transport length in the saturated zone to develop the saturated zone dispersivity.	0.10
Kd_Waste_Eu	The distribution coefficient for Eu in the intact portion of the wasteform.	0.08
Sn_solubility	The solubility of Sn in the pore fluid of the wasteform.	0.02

Table III. Results of an Uncertainty Analysis with Genetic Algorithms for the Base Case, Using a Shortened Variable List

Variable Name	Description	Importance Factor
GW_flow	The average darcy velocity of fluid in the saturated zone transport pipe. Influences dilution and transport times.	0.98
Fracture_spacing	The average spacing of fractures in the wasteform. Influences the amount of oxidation and degradation during the simulation period and the diffusive path length of contaminants to the fractures.	0.97
Water_intake	The consumption rate of drinking water. Directly influences the drinking water dose.	0.96
Bound_waste_deg_rate	The rate at which contaminants are available for release and transport. Conceptually represents dissolution of the wasteform.	0.93
Mg_conc	The concentration of Mg in the fluids contacting the wasteform. Influences the amount of degradation predicted to occur during the simulation period.	0.86
Infiltration_rate	The rate of infiltration of water into the subsurface. Influences the release and transport of contaminants from the wasteform.	0.71

The variables pertain to the degradation of the wasteform, the quantity of radionuclides directly consumed in drinking water, or the dilution of contaminants in the saturated zone during transport and the transport time. From a physical standpoint, the variables selected are in strong agreement with the analysts' conceptual understanding of the performance of the disposal system. Thus, the results in Table III demonstrate the importance of developing an adequate understanding of the performance of the model.

In addition to the variables that drive the peak total dose, the dose due to Pu-239 was analyzed to examine the performance of the disposal system with respect to a contaminant that may respond differently in the disposal system than the highly-soluble, highly-mobile contaminants Tc-99 and I-129. In addition to many of the parameters found in Tables II and III, this analysis identified uncertainty in variables defining the sorption of plutonium and the unsaturated zone, plutonium solubility, waste saturation, unsaturated zone saturation, and parameters relating to the concentration of plutonium in the garden environment (after applying contaminated irrigation water) as important to estimating the dose from Pu-239.

Based on the results of the uncertainty analysis of the base case, a set of additional scenarios were developed to further understand the performance of the disposal system. Key aspects analyzed included long-term engineered cap performance (i.e., the infiltration available to the wasteform) and long-term performance of the wasteform (i.e., the hydraulic properties and the extent of degradation/oxidation of the wasteform). Table IV provides a description of the scenarios analyzed, the parameter values or associated submodel result for each scenario, and the overall dose result for the scenario. For a low-level waste facility, NRC's performance objective for protection of the public is 0.25 mSv/yr (25 mrem/yr) [12]. Various degrees of degradation of the engineered cap and wasteform are assigned in the analyses provided in Table IV. Ideally, the amount of degradation expected for the wasteform and engineered cap would be supported with a technical basis that reflects the risk significance of the degradation of the engineered barriers. The acceptable amount of support provided for model results would be dependent on both how much credit is being taken for the performance of the system to limit risks and the uncertainty in the predictions of performance. For example, model predictions of engineered cap performance for periods of time well in excess of current experience should be supported by multiple lines of evidence such as field tests, laboratory studies, natural analogs, and expert elicitation. The range in performance of the system and the degrees of degradation represented in this set of analyses represent hypothetical future states of the system. The calculations were performed primarily to facilitate understanding of the system; the calculated doses can be used to compare various scenarios but do not necessarily represent expected doses from the system.

The results of cases 1 and 2 demonstrate that, if the wasteform remains relatively intact, diffusive releases are likely to be low and the system would not be extremely sensitive to degradation of the engineered cap. The results of cases 3 and 4 demonstrate that a small fraction of the wasteform degrading at exposed surfaces over 10,000 years would significantly increase the risk, though not to unacceptable levels. The results of case 6 demonstrate that a high degree of degradation of the wasteform and engineered cap results in a large increase in the risk from the disposal facility. Cases 5 and 7 are nearly identical scenarios designed to demonstrate the significance of the timing of degradation in addition to the degree of degradation. In case 5, the engineered cap is assumed to be completely effective for 300 to 400 years, and then to limit the

Table IV. Alternate Scenarios for Engineered Cap and Wasteform Performance

Case-Description ¹	Infil (cm/yr) ²	Waste deg./ox. % ³	Kh_deg (cm/s) ⁴	Result (mSv/yr [mrem/yr])
1-Minimal long-term engineered cap or wasteform degradation	0.4	<0.1 / 0.1	1E-9	1.8E-4 [0.018]
2-Minor engineered cap degradation	4.0	<0.1 / 0.1	1E-9	2.3e-4 [0.023]
3-Minor wasteform degradation	0.4	1 / 2.6	1E-8	0.012 [1.2]
4-Minor engineered cap and wasteform degradation	4	1 / 2.6	1E-8	0.016 [1.6]
5-Minor engineered cap degradation/moderate wasteform degradation	4	5 / 1.3	1E-7	0.054 [5.4]
6-Engineered cap and wasteform significantly deteriorated	40	27 / 20	1E-6	0.62 [62]
7-Discrete failure of the engineered cap at 5000 years, moderate wasteform degradation	4	5 / 1.3	1E-7	0.25 [25]

¹ The description for the amount of degradation is a term (e.g., minor) used to compare the various analyses. Ideally, various forms of model support would be developed to define the degree of degradation in a more absolute sense.

² Infil (cm/yr) is the amount of infiltration that flows through the engineered cap in the long-term. Precipitation for the site analyzed is on the order of 120 cm/yr, therefore a value of 40 cm/yr would be reasonably close to the natural recharge rate given the local soil properties.

³ Waste deg./ox. % is the volume percent of the wasteform that physically and chemically degrades or is oxidized over the 10,000 year analysis period. Because the processes that cause degradation (loss of both physical and chemical retention capabilities) may proceed at different rates than the processes that cause oxidation of the waste, ratio of the amount of waste that is degraded to the amount of waste that is oxidized varies.

⁴ Kh_deg (cm/s) is the saturated hydraulic conductivity of the degraded region of the wasteform in cm/s.

amount of long-term infiltration to the wasteform to 4 cm/yr. In case 7, the analysis is identical except the infiltration cap is effective for 5000 years, then fails rapidly due to a hypothetical event such as a large flood. Case 7 results in a dose that is 5 times larger than case 5, even though there is longer performance for the engineered cap. The result demonstrates that various alternatives to failure modes and rates need to be evaluated for engineered systems in order to determine the limiting scenario for overall system performance. A key outcome of the alternate scenarios and the uncertainty analyses is that the rate of degradation of the wasteform is a key determinant of the risk from the disposal facility.

CONCLUSIONS

NRC's review of the safety of near-surface disposal of radioactive waste at the SDF was facilitated and focused by risk insights developed with an independent PA model. Review emphasis was placed on those aspects of the disposal system that were expected to drive performance: the physical and chemical performance of the cementitious wasteform and concrete vaults. The risk insights developed from the analysis were used to risk-inform the review of DOE's performance assessment.

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