Risk Insights Gained from Review of a Performance Assessment for Radioactive Waste Disposal – 9290

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ABSTRACT

The United States Department of Energy (US DOE) is currently decommissioning tanks that store liquid high-level radioactive waste generated from spent-fuel reprocessing at the Hanford site. DOE has prepared a performance assessment to determine the human health risks associated with residual waste expected to remain after completion of waste retrieval operations and stabilization activities for single-shell tanks. At the request of DOE, the US Nuclear Regulatory Commission (NRC) is currently reviewing DOE documents presenting the relative costs and benefits of additional remediation of single-shell tank 241-C-106 including the supporting single-shell tank performance assessment that provides a basis for the risk estimates associated with remaining residual waste in tank 241-C-106.

NRC's review of the safety of near-surface disposal of radioactive waste at the Hanford site was facilitated and focused by risk insights developed with independent analysis (e.g., consideration of independent sources of information, calculations, and probabilistic modeling). Key attributes of the disposal facility relied on for performance were identified to help risk-inform the review. Alternative conceptual models were tested and evaluated to determine the sensitivity of model results to conceptual model uncertainty (e.g., cementitious material degradation assumptions). Results from uncertainty analysis were used to identify important model sensitivities to focus the review on those aspects of the disposal facility expected to drive performance. The modeling approach and risk analysis discussed in this paper is expected to be applicable to other radioactive waste disposal reviews.

INTRODUCTION

DOE uses performance assessments (PAs) to demonstrate compliance with performance objectives for low-level waste disposal. PAs for radioactive waste disposal typically integrate several process models to consider various features, events, and processes that lead to the degradation of engineered barriers, releases of radioactivity into the environment, flow and transport of constituents in the natural environment, and resulting exposure of potential receptors. Simulations are often times conducted for tens of thousands of years to demonstrate compliance with performance objectives for radioactive waste disposal (e.g., comparison of peak dose against radiological criteria related to protection of the general population from releases of radioactivity from the disposal facility). DOE generally prepares PA models with a level of complexity dependent on the site characteristics and the level of credit needed to meet performance objectives. DOE prepared a PA model for single-shell tanks at Hanford taking credit for engineered and natural barrier performance (e.g., hydraulic barrier afforded by grouted tank limiting radionuclide release and natural attenuation of contaminants through sorption and dilution in the saturated zone) to estimate the risks associated with waste residuals expected to remain following single-shell tank retrieval operations [1].

At Hanford, DOE is responsible for determining which criteria are applicable to incidental waste determinations. DOE, the U.S. Environmental Protection Agency, and the State of Washington Department of Ecology entered into the Hanford Federal Facility Agreement and Consent Order (the Tri-Party Agreement) in 1989. Appendix H of the Tri-Party Agreement requires that DOE establish an interface with the NRC for those tanks for which DOE could not remove 99 percent of the waste by volume [2]. In addition, NRC provides technical advice and consultation in an advisory manner for waste determination reviews performed for the Hanford site, as requested.

DOE was not able to retrieve 99 percent of the waste by volume from single shell tank 241-C-106 (referred to as Tank C-106 hereafter) at the ninety-five percentile confidence level. Thus, DOE prepared a Basis for Exception that provides the rationale for concluding that there is no technical, risk reduction, or economic justification to support deployment of retrieval technologies to further retrieve waste from Tank C-106 [3]. Together the PA and Basis for Exception document DOE's evaluation that retrieval of waste from Tank C-106 is complete.

This paper provides an overview of the methods and tools used by the NRC, including development of an independent model, to provide risk insights to guide NRC review of the Basis for Exception and PA.

NRC REVIEW APPROACH

At the request of DOE, NRC provides technical advice and consultation in an advisory manner for certain waste-incidental-to-reprocessing analyses performed at the Hanford site. DOE requested that the NRC provide technical advice on the analysis, and NRC is currently reviewing the technical adequacy of DOE's Basis for Exception and PA for Tank C-106. NRC has conducted a preliminary review and generated requests for additional information to assist with its preparation of a technical evaluation report documenting NRC staff's conclusions with respect to DOE's ability to meet performance criteria. Information provided in this paper is based on NRC's preliminary review of DOE's PA and thus, no conclusions are drawn in this paper regarding the adequacy of DOE's approach.

Identification of Key Radionuclides

DOE commonly provides information on key radionuclides or those radionuclides expected to contribute most significantly to the risk to members of the public (including inadvertent intruders), workers, and the environment. NRC reviews the list of key radionuclides carefully to ensure that key risk drivers are identified. NRC uses knowledge gained from previous reviews to evaluate the list of key radionuclides. Table I lists key radionuclides identified based on DOE PA models for tank farm facilities located at the Idaho National Laboratory, Hanford, and Savannah River Site (SRS), as well as the saltstone facility at SRS.

Many of the highly radioactive or key radionuclides are common from site to site (e.g., Tc-99 and I-129, because these radionuclides are long-lived and relatively non-reactive in most geochemical environments). Another long-lived radionuclide common to many sites is Pu-239; however, given its relative immobility in most natural systems, the peak dose from this constituent usually does not occur until tens of thousands of years after closure. While the activity (and risk) associated with relatively short-lived radionuclides such as Sr-90 and Cs-137 is very high in the first few hundred years, the activity and risk decrease rapidly with time. Therefore, short-lived radionuclides are not usually key risk drivers for the groundwater pathway in the engineered (grouted tank) systems that normally contain radionuclides for the first few hundred years following closure. However, Sr-90 was found to be a key radionuclide for the tank farm facility at Idaho National Laboratory given its presence in sandpads located outside of the stainless steel tanks within reinforced concrete vaults that were assumed to degrade after 100 years.

DOE identified Tc-99 as the only key radionuclide for the groundwater pathway for future releases from Tank C-106 in its PA. The peak dose associated with Tc-99 was estimated to be 1.18×10^{-03} mrem/yr at year 10,461 [1]. It is significant to note that due to the long travel times associated with transport through the thick vadose zone at Hanford, any constituent with a distribution coefficient (or K_d) greater than approximately 0.2 L/kg is not expected to arrive at the fenceline within the 10,000 year simulation period. Therefore, the simulation period is expected to be important to the identification of key radionuclides.

Table I. Summary List of Highly Radioactive Radionuclides for the Groundwater Pathway at DOE Facilities Based on DOE Performance Assessment Results

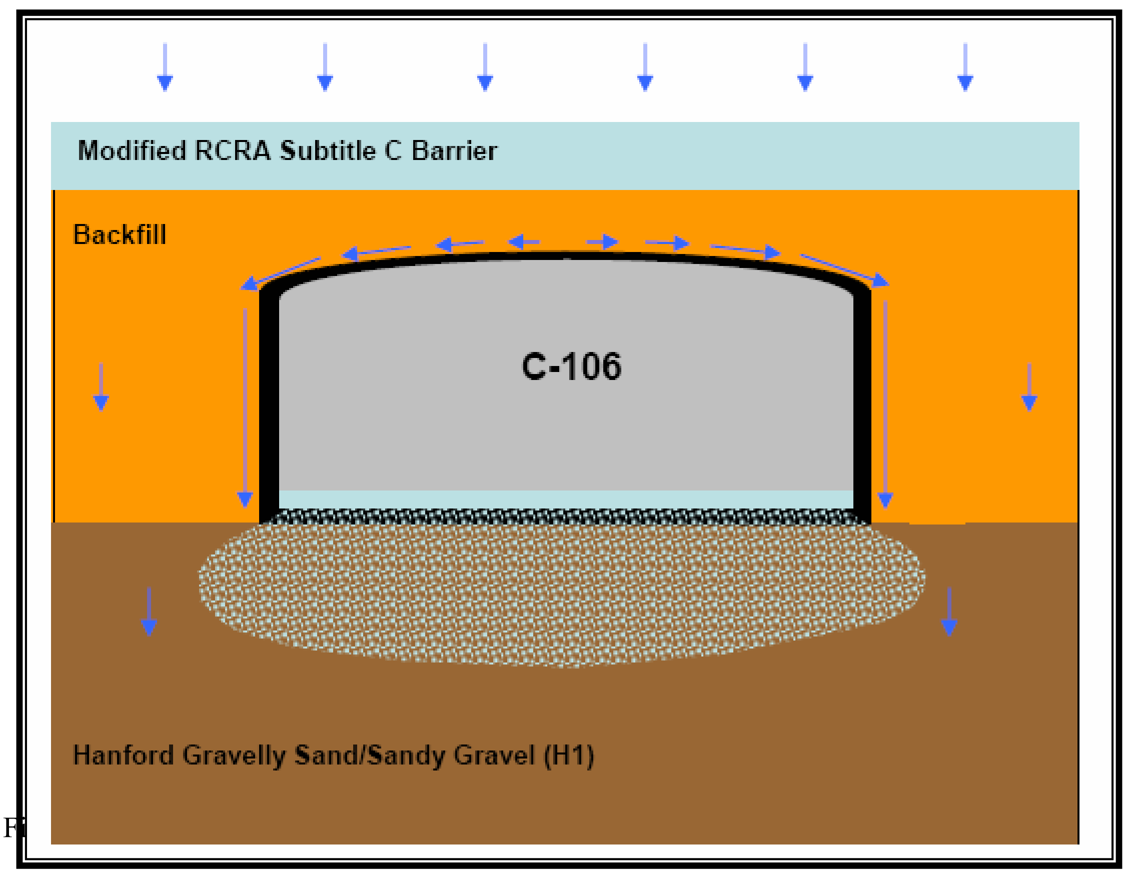
Radionuclide	INL	SRS (Saltstone)	SRS Tanks	Hanford
Tc-99	X	X	X	X
Sr-90	X			
I-129	X	X		
Se-79		X		
Np-237			X	
Pu-239			X	
Ra-226			X	

Description of DOE Performance Assessment Models Reviewed by NRC

The PA for the Hanford site [1] discusses the conceptual process models DOE used to analyze long-term human health impacts of residual wastes that will remain in the single-shell tanks (SSTs) after retrieval of the tank wastes. The SSTs in the Hanford Site are grouped into areas known as Waste Management Areas (WMAs). Tank C-106, is located within WMA C, which contains a total of sixteen (16) SSTs, and makes up a portion of the 200 East Area. The long-term impacts presented in DOE's PA [1] are from all the SSTs within the WMAs. Results for Tank C-106 alone were extracted from the PA [1] to support the risk estimates in the Basis for Exception [3]. The SST PA methodology begins with the current natural system, the future engineered systems, and the expected contaminant migration pathways that together form the major components of the conceptual models. Numerical models are developed using information from the conceptual models to estimate risk for each pathway based on deterministic calculations. The engineered barrier systems, intended to isolate or slow contaminant migration from residual waste remains in SSTs, will consist of an engineered surface cover, three different types of grout used to fill the tanks and encapsulate the contaminants, and the present-day tank itself to deflect infiltrating water away from the residual waste (see Fig. 1). The natural system has two major components: the unsaturated and saturated zones (see Fig. 2). The unsaturated zone, or vadose zone, underneath WMA C is composed of four major hydrogeological units while the saturated zone is composed of the stratigraphic layer called the Undifferentiated Cold Creek unit (CCu) in which the unconfined aquifer is present. All the units slow contaminant transport to some degree due to sorption of the radiological constituents to subsurface materials, although this affect is limited for key radionuclide Tc-99.

An important component of the engineered barrier system is the planned Modified Resource Conservation and Recovery Act, or RCRA, Subtitle C Barrier covering the WMA C as depicted in both Figs. 1 and 2. The primary feature of the surface barrier with respect to the groundwater pathway is to limit moisture infiltration into the WMA. The intended cover will consist of vegetation on top, and layers of silty loam, gravel, and asphalt. The silt loam layer provides for moisture storage and allows water removal by means of evapotranspiration. The silt loam together with the gravel layer form a capillary break and impedes moisture flow across the interface. If a substantial amount of moisture moves past this interface, the gravel would act as a lateral drainage layer and move water away from the tank surface. In addition, the 5 m [15 ft] thick surface cover is expected to deter inadvertent intrusion and to help stabilize the waste form. Inclusion of the engineered surface barrier in the numerical model leads to consideration of four long-term recharge estimates. The conceptual recharge estimates include rates from before construction of tank farms, during operation of the tank farms (infiltration-controlling soil removed), the period during which the fully functional surface barrier is in place, and the period which the cover is degraded.

Tank C-106 is 23 m [75 ft] in diameter, 10 m [32 ft] tall, 5 m [15 ft] deep, and has a 2000 m^3 [530,000 gal] operating capacity. Some residual waste will remain in Tank C-106 and be distributed mostly along the bottom of the tank. Carbon steel lines the bottom and sides of a reinforced concrete shell. Grout will be poured into the tank in order to enclose and encapsulate the residual waste and significantly slow the eventual release of contaminants. As seen in Fig. 1, DOE's conceptual model for waste release is diffusive release of contaminants from the grout-filled tank system. Structural details of the tank were neglected as was the process of advective release of contaminants by means of cracks in the grout that may develop in the future, although a sensitivity analysis was conducted to investigate the impact of advective releases from the tank. To calculate the diffusional flux from a contaminated zone, an effective diffusion coefficient for intact grout and mixing length were assumed. The mixing length accounts for the heterogeneous distribution of residual waste within the tank due to upwards diffusion into the tank grout, as well as transport of contaminants through the thick concrete structure (i.e., basemat) that together represent the source of releases from the engineered system.



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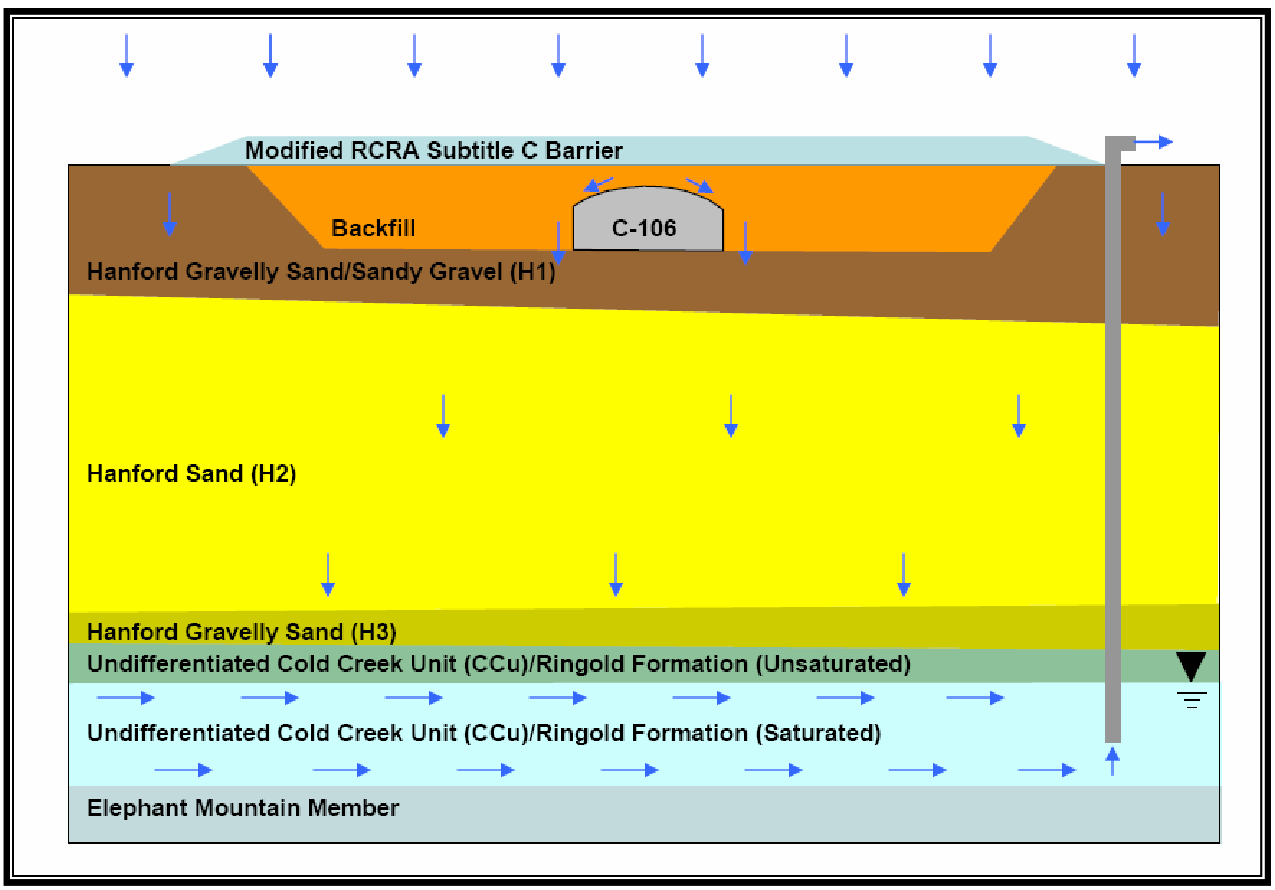
The four stratigraphic units underlying Tank C-106, shown in Fig. 2, consist primarily of sandy to gravelly sequences. Based on DOE's conceptual model, the relatively low recharge rates due to the surface cover, the diversionary effect of the top of the grouted tank, the thickness of the unsaturated zone, and soil-contaminant interactions (or sorption) prevent all but the least reactive contaminants from reaching the saturated zone for thousands years. Vertical clastic dikes are present in the 200 East Area and can intersect the horizontal layers and penetrate many meters deep; however, these dikes are not assumed to act as fast vertical pathways for contaminants. Each heterogeneous geologic unit within the vadose zone is replaced by a homogeneous equivalent in the numerical model, although the heterogeneity within the units is assumed to dampen the effect of discrete infiltration events so that episodic precipitation events can be replaced by an average annual recharge rate. For each horizontal stratigraphic unit, the laboratory measurements were upscaled to obtain equivalent unsaturated hydraulic conductivities as a function of mean tension. A range of distribution coefficients (or K_ds) is used to represent sediment-contaminant chemical interactions or sorption.

A two-dimensional flow and transport numerical model along a row of tanks was used for the integrated unsaturated-saturated vertical cross-section. Contaminants moving from the unsaturated zone into the saturated zone within the CCu formation mix with the groundwater and dilute the contaminant concentrations. The two-dimensional numerical model for WMA C assumes groundwater flow beneath the WMA is parallel to existing east-west tank rows. Tank C-106 is in alignment with three other tanks in an east-west direction. This flow direction is assumed to be consistent with the unconfined aquifer hydraulic gradient at WMA C before operations began at the Hanford Site. The contaminants move with the flow of groundwater to various calculation points, including the WMA C fence line where human receptors may potentially become exposed through various groundwater-dependent pathways. Exposure scenarios are then applied to estimate potential doses from the waste disposal facility and to determine risk.



The focus of this paper is on NRC's review of DOE's PA models described above. NRC generated requests for additional information and will document the results of its review after evaluating DOE's responses to the information requests. The following sections describe the types of calculations, modeling, and other analysis NRC performed to evaluate DOE's PA.

Independent Calculations

NRC staff used multiple methods to support its review of the Hanford PA. The review approach included use of basic models and calculations to provide high-level information on the key processes driving risk (or resulting in the greatest risk reduction). NRC staff determined a rough estimate of the magnitude of risk reduction afforded by (i) the hydraulic barrier effect of the engineered (grouted tank) system, and (ii) dilution in the natural system. These calculations focused around the only key radionuclide identified in DOE's PA, Tc-99. To provide information on the relative benefits of engineered and natural barriers in reducing risk, a maximum possible concentration for Tc-99 in the waste pore fluid (assuming the entire inventory was present in one inch of residual waste pore fluid) was calculated. While it is virtually impossible for the entire inventory to be present in the waste pore fluid, this calculation was performed to provide information regarding the relative impact of engineered and natural system barriers on reducing the potential risk from residual waste remaining in the tanks. As discussed above, the grouted tank system is assumed to remain intact over the 10,000 year simulation period with diffusion-limited releases from the engineered system. Because Tc-99 is assumed to be relatively non-reactive, dilution is assumed to be the only natural attenuation mechanism in the calculations summarized in Table II below. While the engineered surface barrier, or cap, contribution is not specifically included in these calculations[1], the engineered surface barrier is expected to reduce the natural infiltration rate (which ranges from 0.1 to 130 mm/yr) to 0.5 mm/yr from closure until 500 years post-closure and to 1 mm/yr for the remainder of the 10,000 year simulation period. As discussed above, for most radionuclides sorption is also expected to be a significant barrier limiting risk in DOE's PA but this natural attenuation mechanism is not specifically listed as a barrier below because Tc-99 is not expected to sorb appreciably in the subsurface at Hanford.

Table II. Rough Estimates of Relative Credit of Various Barriers for Nonreactive Constituents

	Barrier	**Credit Needed/Provided**
1	Total Barrier Performance Needed for Compliance (Assuming total inventory is located in waste pore fluid)	~4 orders of magnitude[2]
2	Engineered Barrier (Fractional Release)	~3 orders of magnitude
3	Natural System (Dilution)	~4-5 orders of magnitude
4	Total Barrier Performance (Sum of rows 2 and 3)	~7-8 orders of magnitude
5	Total Safety Margin (Difference between rows 4 and 1)	~3-4

The simple calculations agreed reasonably well with DOE PA results (i.e., the required risk reduction necessary to meet performance objectives minus the estimated risk reduction of engineered and natural system components are roughly within an order of magnitude of DOE's predicted safety margin). Among other requests for additional information, NRC requested clarification from DOE regarding barrier contributions to better understand the risk-significance of key features of the disposal facility considered in DOE's PA. It is important to note that the simple calculations reflect DOE's conceptual model for

[1] Engineered surface barrier effects are implicitly considered in the dilution factor for the natural system. For example, higher infiltration rates lead to higher mass flux into saturated groundwater, thereby reducing the effective dilution factor of the natural system.
[2] The total barrier performance needed for compliance pertains to Tc-99, the only key radionuclide identified in DOE's PA.

radionuclide release; and flow and transport in its compliance case and that other processes not accounted for by DOE may also be operable as discussed below.

Independent Modeling

NRC also performed independent modeling using the proprietary software package GoldSim[4][3] and analysis to focus its review of the Hanford PA. NRC implemented a (i) diffusion model to evaluate DOE's conceptual model for waste release, and (ii) an alternative waste release model that included consideration of cementitious material degradation and resulting impacts to hydraulic and chemical properties of the waste form over time (e.g., changes in solubility and sorption over time). For both independent models, decreased infiltration due to the presence of an engineered surface barrier is modeled with infiltration increasing linearly with time to a maximum value assumed to occur at some point in the future when the engineered surface barrier is assumed to completely fail. A simple one-dimensional groundwater model was used to simulate vertical flow and transport through the vadose zone and horizontal flow in the saturated zone from Tank C-106 to a well assumed to be located at the WMA C fenceline. A biosphere model developed for NRC by the Center for Nuclear Waste Regulatory Analyses (CNWRA) BDose™ [5][4] was used to calculate the expected groundwater all-pathways dose to a residential farmer. As the main focus of the independent modeling was on the waste release and groundwater transport parameters, uncertainty associated with biosphere model parameters was not considered.

Results from NRC's first independent (diffusion) model were used to evaluate DOE's PA modeling results. A major difference between DOE's diffusion model and NRC's probabilistic model is the treatment of uncertain parameters. For example, a large range of values for the tank grout diffusivity was considered in the probabilistic model to represent both intact and degraded conditions. Because the primary purpose of the independent modeling was to identify important parameters and processes for waste release and groundwater transport modeling, broad parameter distributions were oftentimes employed. Thus, the sensitivity of model results to various inputs and the relative impact of model changes to results is emphasized in this paper rather than the actual magnitude of the peak dose from the independent models.

Sensitivity analyses of the diffusion model were conducted using Neuralware Predict®[6], a commercially available software program that can be used to build neural networks for predictive modeling. A variable selection genetic algorithm (i.e., cascaded variable selection) available in Neuralware Predict® was used to identify the most important input variables to predicting various model outputs (e.g., peak dose and time of peak dose). Results of the sensitivity analysis (Table III) emphasized the importance of mixing length (parameter that accounts for distribution of contaminants in grouted waste form that is used to define the diffusion length), infiltration rate, diffusivities, and groundwater flow velocities for the diffusion-limited waste release model. Results from the sensitivity analysis for 10,000 and 100,000 year simulation timeframes are presented in Table III below. Two different time periods were evaluated because the peak dose was not expected to occur within the 10,000 time period for the diffusion model given the long travel times in the vadose zone for many constituents.[5] As expected, the timing of the peak dose is sensitive to various radionuclide K_ds, as well as diffusivity, mixed length, cap lifetime, porosity, and infiltration. While Tc-99 dominates the dose at earlier times, plutonium isotopes

[3] The GoldSim software package is a visual model building platform for performing dynamic, probabilistic simulations. The software includes a radionuclide transport module that can simulate radioactive decay and in-growth, advection, dispersion, adsorption, diffusion, and matrix diffusion for fracture flow.
[4] © Copyright 2007 by Southwest Research Institute®. BDOSE™ 2.0 was originally prepared by CNWRA for NRC under Contract No. NRC–02–02–012.
[5] For most of the realizations in the 10,000 year simulation, the peak dose does not occur until after 10,000 years (the peak dose is not realized for 80 percent of the realizations).

(i.e., Pu-239 and Pu-240) dominate the dose at longer simulation time periods and determine the peak dose. However, the diffusion model did not consider chemical barrier effects of the tank grout which were evaluated with NRC's second independent model discussed below.

Table III. Sensitivity Analysis Results for Diffusion Waste Release Model

Rank	**Peak Dose** **1E04 Yr Simulation**	**Peak Dose** **1E5 Yr Simulation**	**Time of Peak** **1E05 Yr Simulation**
1	Infiltration	Infiltration	Radium K_d SZ
2	Diffusivity	Mixed Length	Diffusivity
3	Mixed Length	Diffusivity	Mixed Length
4	Groundwater Flow	Groundwater Flow	Nickel K_d SZ

To test the sensitivity of the results to the waste release model selected, NRC constructed a second independent probabilistic model to evaluate the impact of use of an advection-dominated waste release model (in lieu of assuming diffusion-limited release through intact grout). This model considers the impact of hydraulic degradation of the tank grout that serves as a significant barrier to waste release. Hydraulic properties of the tank grout were allowed to increase linearly on a log scale over time (given the large variation in hydraulic conductivity of intact versus degraded grout) from a minimum value representative of intact grout to a maximum value representative of completely degraded grout at some time in the future when the tank grout was assumed to completely fail. The alternative waste release model considered solubility and sorption controls assumed with initially high pH and low Eh reducing grout (simulations assuming no solubility or sorption control were also conducted). A stochastic parameter is used to simulate chemical failure of the tank grout at some point in the future with a resultant step change in chemical retention properties of the waste form. Solubility and sorption control representative of oxidized conditions for the concrete basemat was also assumed. Because the cementitious system is expected to fracture over time, the alternative conceptual model also considers bypassing flow through fractures in the basemat underneath the carbon steel tanks, although the concrete basemat is expected to fail hydraulically prior to the tank grout which minimizes the importance of these fractures. Similar to the diffusion model, decreased infiltration for some period of time due to the presence of an engineered surface barrier is also considered. Example results from the second independent probabilistic model are presented in Figure 3.

The results indicate that relatively long-lived Tc-99 dominates the peak of the mean dose in the advection-dominated release model. Redox sensitive Tc-99 release is attenuated within the first few thousand years primarily due to the chemical barrier afforded by the tank grout but is fairly mobile in the natural system leading to the early peak. At longer simulation time frames, Pu-239 dominates the peak of the mean dose for the advective release model. The delay in the Pu-239 peak dose is a result of the higher sorption coefficients in the basemat and natural system materials that slows the transport of Pu-239 compared to other simulated radionuclides such as Tc-99. While Pu-239 dominated the peak of the mean dose from the diffusion model, the advection-dominated release model results indicate that Tc-99 most significantly contributes to the peak dose. The predicted dose from Pu-239 in the advection-dominated release model is significantly reduced due to the assumptions regarding solubility and sorption control in the waste form that represent a significant barrier to waste release.

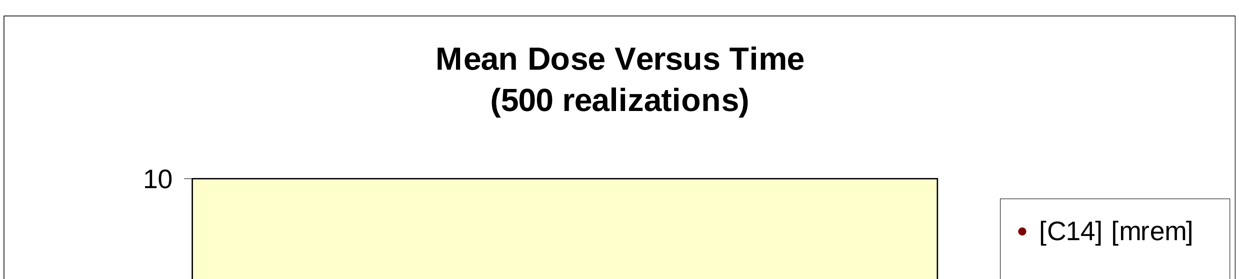


Fig. 3. Example output (mean dose) of NRC's probabilistic model used to test alternative conceptual models for waste release (advection-dominated waste release model)

A series of simulations was also conducted to study the impact of various barriers on overall system performance. Table IV lists the simulations conducted to study the contributions of various barriers limiting the peak dose. Simulation 2P shows that the peak dose increases by a factor of 3.5 when the impact of chemical retention of radionuclides in the tank grout and basemat is neglected (and by a factor of 1.4 when just basemat sorption is neglected). The results of the probabilistic simulations show moderate sensitivity with respect to waste form chemical performance. This conclusion points to the potentially conservative nature of the probabilistic analysis. Because (i) Tc-99 dominates the peak dose, (ii) the grouted waste form is assumed to degrade within a few thousand years, and (iii) the chemical retention of Tc-99 under degraded conditions is assumed to be low, there is not much variability in the peak dose from Tc-99, although the timing of the peak dose changes significantly. Changes in the chemical properties of the cementitious materials has a larger impact on peak dose for other radionuclides (e.g., bypassing of the chemical retention properties of the basemat in simulation 2P increases the peak dose from Pu-239 by almost an order of magnitude from 0.15 to 1.4 mrem/yr and leads to the peak dose being dominated by Pu-239 instead of Tc-99). Simulations 3P through 6P show that if K_ds reflecting chemically altered subsurface materials (e.g., from high ionic strength releases) are assumed or natural system sorption is neglected, the dose only increases by a factor of 1 to 2.5, as lack of consideration or decreased sorption, while significantly increasing the peak dose associated with sorbing radiological constituents, does not significantly affect the peak dose that is dominated by Tc-99. Upon closer inspection, simulation 6P results provide an indication of the potential risk-significance of short-lived radionuclides such as Sr-90 in the case of gross underperformance of the natural system. While simulation 6P is virtually impossible, the peak dose from Sr-90 increased from essentially zero dose to a fraction of a millirem. While not significant enough to affect the magnitude of the peak dose, the results indicate that the vadose zone can act as a substantial barrier limiting dose from short-lived radionuclides that are assumed to decay away to negligible levels during transport through the natural system.

Additional sensitivity analyses were conducted deterministically with the advection-dominated release model (see bottom half of Table IV). Simulation 1D shows the strong relationship between infiltration rate and peak dose. Predicted doses vary linearly with changes in infiltration rates at lower infiltration rates due to assumptions regarding hydraulic performance of the cap and grouted tank system performance (i.e., the cap is essentially a redundant barrier to the grouted tank system with rapid increases in infiltration to natural conditions over relatively short time periods and the grouted tank system is assumed to completely fail hydraulically within a few thousand years). At higher infiltration rates a non-linear effect is observed. The results of the modeling simulations with higher infiltration rates reflect the hydraulic performance of the engineered systems assumed to be more effective at earlier simulation times when the peak dose is expected to occur.

As results from the probabilistic simulations discussed above showed minimal sensitivity of waste form degradation on peak dose, additional simulations were also conducted deterministically to study the sensitivity of model results to chemical performance of the grouted waste form in attenuating releases of Tc-99. Simulation 3D indicates that with more optimistic assumptions regarding chemical performance of the grouted waste form the predicted doses could be significantly reduced. If increased solubility control of Tc-99 representative of intact conditions is assumed (Simulation 3D), the peak dose from Tc-99 is virtually eliminated. The impact of the time to grout chemical failure has less of an effect—if the grouted tank system is assumed to remain intact for 20,000 years (Simulation 2D), the predicted peak dose is expected to be a factor of 1.3 less than the reference case.

The results of the independent modeling emphasize important aspects of the waste release models evaluated (e.g., chemical retention of Tc-99 and Pu-239 for the advection-dominated model; diffusivity and mixed length for the diffusion model). Results of the modeling are also sensitive to various parameters affecting dilution in the natural system (e.g., infiltration rate and groundwater flow velocity). While predicted doses from the diffusion model can approach those of the advective model when pessimistic assumptions regarding waste form performance are made, the actual mechanisms of degradation and waste release are expected to be much more complex. In fact, the peak of the mean dose from the diffusion model is comparable (0.65 mrem/yr at year 11,000 with 92% of the realizations less than 1 mrem/yr) to the advection-dominated release model predicted dose (0.5 mrem/yr at year 5520) when a large range of

Table IV. Additional Simulations to Study Barrier Performance (Advection-Dominated Model)

Simulation	**Description**	**Peak Dose**	**Factor**[6]
Probabilistic	*Reference Case*	*0.48 mrem/yr (Tc-99)* *5520 yrs*	*1*
1P	No basemat sorption	0.72 mrem/yr (0.6 Pu-239) 18,000 yrs	1.5↑
2P	No grout/cement chemical control	1.7 mrem/yr (Pu-239) 14,000 yrs	3.5↑
3P	Chemically Impacted Kds	0.58 mrem/yr (Tc-99) 5880 yrs	1.2↑
4P	No vadose zone sorption	0.6 mrem/yr 9700 yrs	1.3↑
5P	No saturated zone sorption	0.48 mrem/yr 5520 yrs	1
6P	No natural system sorption and increased velocity through VZ	1.2 mrem/yr 4500 yrs	2.5↑
Deterministic	*Reference Case*	*0.71 mrem/yr (Tc-99)*	*1*
1D	Infiltration Rates[7]		

[6] Downward arrows indicate a factor decrease in peak dose, while upward arrows indicate a factor increase.

	0.1 mm/yr 5.0 mm/yr 100.0 mm/yr	0.06 mrem/yr (Tc-99) 3.6 mrem/yr (Tc-99) 18.7 mrem/yr (Tc-99)	12↓ 5↑ 27↑
2D	Time to Grout Chemical Failure[8] 1000 yrs 20,000 yrs	 0.73 mrem/yr 0.56 mrem/yr	 1.0↑ 1.3↓
3D	Tc-99 Solubility Limit[9] 1E-5 mg/L 5E-3 mg/L	 0.01 mrem/yr (from Se-79)[10] 0.59 mrem/yr (from Tc-99)	 70↓ 1.2↓

diffusivities that encompass the values associated with degraded grout are assumed. However, if intact conditions are assumed for the diffusion model (i.e., diffusivity of 1E-09 cm^2/s) and other parameters selected similar to DOE's waste release model, the deterministic dose from the diffusion model is predicted to be significantly lower at approximately 0.05 mrem/yr (primarily from Pu-239 and Tc-99) at year 75,000. Thus, consideration of hydraulic degradation of the grout has a significant impact on the results of the modeling.

The rate of change of hydraulic and chemical conditions in the cementitious waste form as the cementitious waste form degrades is highly complex and in many cases is risk-significant. Thus, conceptualization and parameterization of degradation and oxidation mechanisms of the cementitious materials that comprise the engineered tank system is a challenge for NRC staff. The carbon steel tank liner may also provide a significant barrier to waste release but no credit was provided in DOE or NRC PA models. Because of the risk-significance of engineered barrier performance, NRC is conducting work to study the mechanisms and parameters related to modeling cementitious material performance and degradation and associated impacts on waste release. Information gained from these studies will be incorporated by NRC staff in future probabilistic analyses.

Review of Independent Information

NRC staff also takes into account information regarding the natural system in which the disposal facility is located. Valuable information regarding the hydrogeological system at Hanford was obtained through review of data, studies, and modeling reports related to a historical releases. This information is useful in assessing whether DOE's conceptual model development and implementation is consistent with current knowledge of the disposal system and of the surrounding environment. The natural hydrogeologic system at the Hanford site is very complex. Supporting information is needed to provide confidence in models and model parameters. DOE spent considerable effort analyzing and modeling previous releases from the tank farm facilities. This information is particularly useful to NRC staff evaluating the adequacy of DOE's models.

CONCLUSIONS

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[7] The reference case infiltration rate is 1 mm/yr.
[8] The reference case time to grout chemical failure is approximately 5000 years.
[9] The reference case Tc-99 solubility limit is 9E-03 mg/L for intact conditions and 1E+06 mg/L (arbitrarily set high for no solubility control) for degraded conditions.
[10] Virtually no dose from Tc-99 was realized for simulation 3D. The peak dose from Se-79 is reported.

NRC staff uses independent modeling as a tool to risk-inform reviews of DOE PA models and to identify the most important parameters and processes affecting peak dose. Thus, results of NRC's independent modeling are not expected to be used, nor should they be directly compared to performance standards. It is DOE's responsibility to make its own compliance demonstration and to provide support for its models and model parameters. NRC simply uses probabilistic models as one tool of many to assist with focusing its review and providing risk-informed recommendations regarding models and model parameters that may require additional support given their uncertainty and risk significance.

Although probabilistic models can be limited in predicting the actual magnitude and timing of peak dose when important processes are not considered or parameter distributions are not well known, they nonetheless serve as valuable tools, supplementing information provided by deterministic models by evaluating uncertainty in dose predictions associated with a larger range of parameter space, as well as allowing consideration of alternative conceptual models important to dose predictions. In some cases, when a particular conceptual model is not fully supported it might be more appropriate to present results of multiple conceptual models probabilistically. Performance assessment modeling should be viewed as an iterative process and initial analyses should be focused on identifying the most risk-significant processes and parameters. Additional resources can then be spent gathering more information or requesting that DOE provide additional support for process models or parameter values that are important to its compliance demonstration to provide additional confidence that performance objectives can be met over the long time periods relied on for radioactive waste disposal.

NRC's review of the safety of near-surface disposal of radioactive waste at the Hanford site was facilitated and focused by risk insights developed with confirmatory calculations; independent probabilistic modeling; and analysis of independent information. 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 and natural attenuation of any releases from the disposal facility. The risk insights developed from NRC staff's review of DOE's PA were used to develop requests for additional information and will help guide recommendations for DOE with respect to demonstrating compliance with performance objectives for radioactive waste disposal.

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