Advancing Performance Assessment for Disposal of Depleted Uranium at Clive Utah - 12493

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ABSTRACT

A Performance Assessment (PA) for disposal of depleted uranium (DU) waste has recently been completed for a potential disposal facility at Clive in northwestern Utah. For the purposes of this PA, "DU waste" includes uranium oxides of all naturally-occurring isotopes, though depleted in U-235, varying quantities of other radionuclides introduced to the uranium enrichment process in the form of used nuclear reactor fuel (reactor returns), and decay products of all of these radionuclides. The PA will be used by the State of Utah to inform an approval decision for disposal of DU waste at the facility, and will be available to federal regulators as they revisit rulemaking for the disposal of DU. The specific performance objectives of the Clive DU PA relate to annual individual radiation dose within a 10,000-year performance period, groundwater concentrations of specific radionuclides within a 500-year compliance period, and site stability in the longer term. Fate and transport processes that underlie the PA model include radioactive decay and ingrowth, diffusion in gaseous and water phases, water advection in unsaturated and saturated zones, transport caused by plant and animal activity, cover naturalization, natural and anthropogenic erosion, and air dispersion. Fate and transport models were used to support the dose assessment and the evaluation of groundwater concentrations. Exposure assessment was based on site-specific scenarios, since the traditional human exposure scenarios suggested by DOE and NRC guidance are unrealistic for this site. Because the U-238 in DU waste reaches peak radioactivity (secular equilibrium) after 2 million years (My) following its separation, the PA must also evaluate the impact of climate change cycles, including the return of pluvial lakes such as Lake Bonneville.

The first draft of the PA has been submitted to the State of Utah for review. The results of this preliminary analysis indicate that doses are very low for the site-specific receptors for the 10,000-year compliance period. This is primarily because DU waste is not highly radioactive within this time frame, the DU waste is assumed to be buried beneath zones exposed by erosion, groundwater concentrations of DU waste constituents do not exceed groundwater protection limits with in the 500-year compliance period, and the first deep lake occurrence will disperse DU waste across a large area, and will ultimately be covered by lake-derived sediment.

INTRODUCTION

Background on Depleted Uranium Waste Disposal

The American Recovery and Reinvestment Act of 2009 (ARRA) spurred significant radioactive waste management actions across the U.S. Department of Energy (DOE) complex, including the shipment of tens of thousands of barrels of depleted uranium (DU) trioxide from the Savannah River Site (SRS) for disposal at the Clive (Utah) low-level radioactive waste (LLW) disposal facility (the Clive Facility) operated by Energy*Solutions*, LLC. Although disposal of this waste stream and other DU wastes at this facility had been occurring for some time, the proposed disposal of large amounts of DU waste caused concern with local stakeholders. The stakeholders' contention was that DU should not be considered to be merely Class A LLW, as it has been regulated under the Utah Administrative Code (UAC R313-25) [1], which itself was developed in concordance with the U.S. Nuclear Regulatory Commission's (NRC's) 10 CFR 61 [2]. Under these regulations, uranium is not considered explicitly, thereby allowing classification and disposal of DU as Class A waste.

In another recent development, the DOE decided that the nation's stockpile of DU hexafluoride (DUF_6), a byproduct of the uranium enrichment process, was to be treated as waste [3]. The plan is to "deconvert" the DUF_6 to uranium oxides (DUOx), which would be significantly more stable and therefore more suitable for disposal, using new purpose-built "deconversion" plants at the Portsmouth, Ohio, and Paducah, Kentucky gaseous diffusion plant (GDP) sites. The term "deconversion" is used because the process of producing natural-assay UF_6 from UOx in preparation for enrichment is called "conversion". Once deconverted, the roughly 0.7 Tg (700,000 Mg, or metric tons) of DU will require disposal, which is several orders of magnitude greater than the SRS DU. However, whereas the composition of the SRS DU is reasonably well known, the content of the GDP DU is not well documented.Consequently, it was necessary to assume that some uncertain fraction of the GDP DU waste was contaminated to the same extent as the SRS DU. DU waste from both sources is considered in the Clive DU PA Model.

In general, DU contains very small amounts of decay products in the uranium, thorium, actinium, and neptunium series of decay chains. Some types of DU waste, resulting from introduction of uranium retrieved from used nuclear reactor fuel (reactor returns) in the separations process, contains varying amounts of contaminants in the form of fission and activation products. Because the material is not only uranium and its decay products, it is termed "DU waste" in this PA.

The principal cause for concern is not the radioactivity of DU waste per se, which is primarily U-238 and therefore minimally radioactive at the present time, but its future radioactivity and perhaps its non-radioactive toxicity (e.g., kidney toxicity). As such, handling and disposal of DU waste is not a serious concern for workers or potential radiation doses to the public, although its toxicity as a heavy metal requires handling with appropriate safeguards. However, given sufficient time, the decay products of DU waste eventually exceed concentrations well over those found in natural uranium ores. Given the extremely long half-life of U-238 (nearly 4.5 billion years), the time at which the rate of ingrowth of the decay products equals the rate of their decay is over 2 million years (My) from now. This state is called secular equilibrium, and the total radioactivity from the simultaneous decay of the 20 radionuclides in the uranium decay chain is much greater.

Depleted Uranium waste has, by default, been disposed as Class A waste. The NRC has initiated a revision or 10 CFR 61 [2] in order to specifically address the disposal of DU waste, as the large masses proposed have not been previously considered. This process is likely to take several years, yet the management of this waste is a pressing issue.

Clive Facility DU Waste PA Requirements

At the request of Energy*Solutions*, Neptune and Company, Inc. (Neptune) developed a model to support the performance assessment (PA) for proposed disposal of DU waste at the Clive Facility. The model is presented in full in Appendix A of the EnergySolutions Compliance Report (EnergySolutions 2001) [4]. The PA model will be used by the State of Utah to inform an approval decision for the facility and by federal regulators to inform rulemaking in general for DU waste disposal facilities in the United States. The specific performance objectives of the PA, as stated in UAC R313-25 [1], *License Requirements for Land Disposal of Radioactive Waste* (specifically UAC R313-25-8, *Technical Analyses*), require:

- assessment of annual individual radiation dose within a 10,000-year performance period,
- qualitative analysis of effects at the time of maximum dose,
- estimation of groundwater concentrations within a 500-year compliance period, and
- assessment of site stability in the long term.

The problem of estimating a peak dose is that it would depend on exposure scenarios that are not defined that far into the future. The immediate question, impossible to answer, is, "Peak dose to whom?" Instead of attempting to model peak dose to some future receptor over 2 My from now, the long-term model is evaluated until peak activity. Site stability is addressed for similar time frames.

METHOD

Clive Facility DU Waste PA Approach

Given that the NRC regulation regarding DU waste is currently in revision, and that the State of Utah (as well as other states) are reluctant to develop independent regulations that could potentially create compatibility issues with the upcoming NRC position, Neptune has pursued a path that is in accordance with a risk-informed, performance-based approach developed by the NRC in NUREG-1573, *A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities* [5] and the National Research Council in their publication *Risk and Decisions About Disposition of Transuranic and High-Level Radioactive Waste* [6]. Although DU waste is neither transuranic or high-level waste, many of the concepts put forth in this work are relevant to all types of radioactive waste.

The Clive DU PA model is developed using the GoldSim probabilistic system analysis software. In order to provide decision makers with a broad perspective of the physical behavior and capabilities of the Clive Facility, the model considers uncertainty in input parameters and to some extent in modeling approaches. This probabilistic assessment methodology is encouraged by the NRC [5] and the DOE [7,8] for constructing PA models. The PA model can be run in deterministic mode, where a single set of model inputs is used, but running in probabilistic (Monte Carlo) mode provides greater insight into the model behavior. In probabilistic mode, a large number of equally-probable realizations is executed, and the results reflect the uncertainty in the model. To the extent that the model reflects the uncertain state of knowledge at a site, the model provides insight about how the site behaves over time, and where additional information or data would be most valuable.

Because the model is probabilistic, the output distributions of dose or concentration are also probabilistic. Once the model is run, it is subjected to uncertainty analysis and global sensitivity analysis. The primary goal of the uncertainty analysis is to evaluate results against the performance objectives. This involved comparing the output distribution to a performance metric, and, in particular, comparing summary statistics (e.g., the mean, median, 95^{th} percentile) of the output to the performance metrics. The sensitivity analysis is used to identify components (e.g., variables or parameters) of the model that are most influential on the output. For simulated results of a probabilistic model, sensitivity analysis is performed by evaluating changes in all input parameters simultaneously.

PA Model Description

The Clive Facility is located at the eastern edge of the Great Salt Desert, west of the Cedar Mountains, and approximately 100 km (60 mi) west of Salt Lake City, Utah. Clive is a remote and environmentally inhospitable area (see Figure 1).

Fig. 1. Location of the Clive Facility in the Great Salt Desert, Utah.

PAs focus on potential human exposure to radioactive waste. Human activity at Clive has been very limited historically, due largely to the lack of potable or irrigation water (existing aquifers are saltier than sea water). Present day activities in the area include ranching, off-highway vehicle (OHV) use, and other activities described below. The site is located on relatively flat ground, with the waste disposal cells shallowly excavated into local lacustrine silts, sands, and clays. A single waste disposal cell, or embankment, is considered in this model: the Class A South (CAS) embankment (identified in Figure 2). This is modeled with the designed cover, with the top of the cell well above grade. The cover is constructed with layers of clay and soil, and armored with cobbles and small boulders. In time, this cover is expected to become infilled with loess (windblown silt from local lacustrine deposits), vegetated with native plants, and occupied to a limited extent by insects and mammals. As plant communities become established, they are likely to keep the cover system fairly dry through transpiration. Figure 3 illustrates a conceptual site model (CSM) that summarizes important processes.

Fig. 2. Location map of the Class A South embankment (width of map is 1.6 km [1 mi]).

Fate and Transport

Fate and transport processes that underlie the PA model include radioactive decay and ingrowth, diffusion in gaseous and water phases, water advection in unsaturated and saturated zones, transport caused by plant and animal activity, cover naturalization, natural and anthropogenic erosion, and air dispersion.

Water is modeled as penetrating the cover system, and this infiltration leaches radionuclides and transports them down through the cell liner and unsaturated zone to the aquifer a few meters below. In this saturated zone, contaminants are transported laterally to a hypothetical monitoring well located about 27 m (90 ft) from the edge of the interior of the cell. Because the side slopes of the cell are modeled to exclude DU waste, the effective distance to the well from the DU waste itself is about 73 m (240 ft). This pathway is important for long-lived and readily-leached radionuclides such as technetium-99 (Tc-99). Contributions to groundwater radionuclide concentrations from the proposed DU waste are calculated for comparison to State of Utah groundwater protection limits (GWPLs) [9] during the next 500 years, even though the groundwater is not potable.

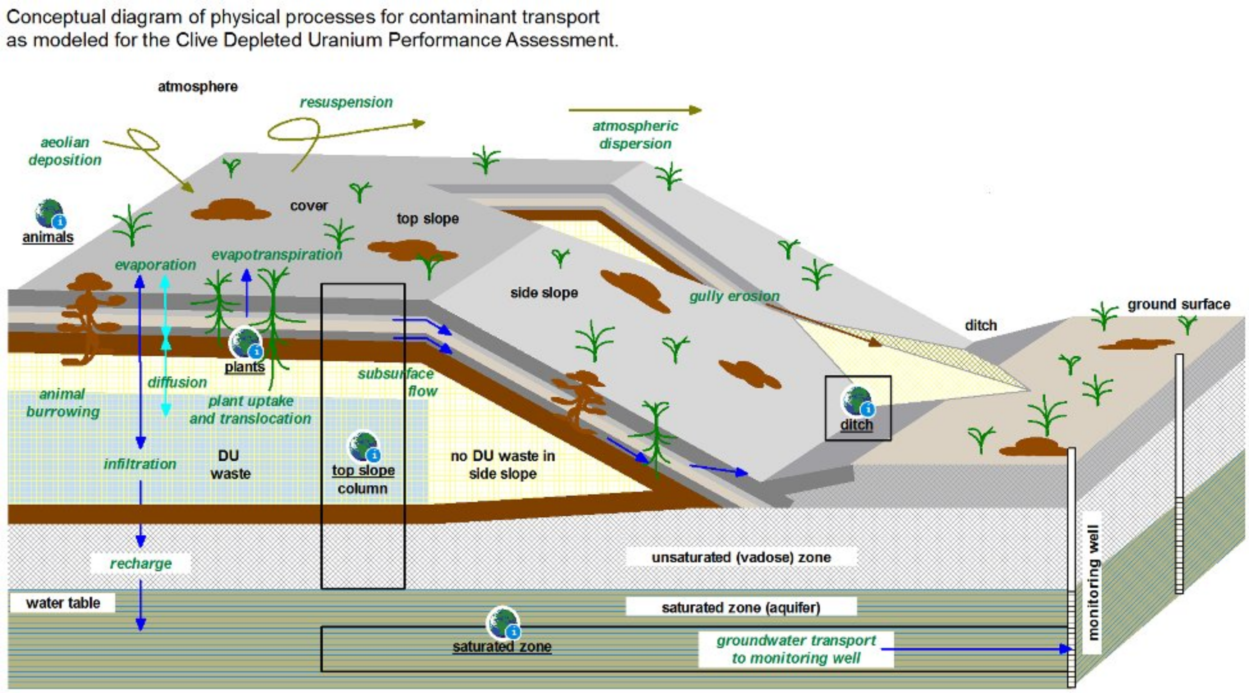

Fig. 3. Conceptual site model diagram for disposal of depleted uranium at the Clive Facility.

In addition to water advective transport, radionuclides in the model are transported via diffusion in both water and air phases, which can provide upward pathways. Gaseous radionuclides, such as radon-222 (Rn-222), are modeled to partition between air and water. Soluble constituents are modeled to partition between water and solid porous media. Coupled with these process are the activities of biota, with plants transporting contaminants to the ground surface in their tissues, and burrowing animals (i.e., ants and small mammals) moving bulk materials upward and downward through burrow excavation and collapse. The cover, with its upper layers infilled with loess (windblown sediment), will be largely self-healing from the effects of roots, burrows, and desiccation, but the degree to which the compacted clay radon barriers at the bottom of the cover would be affected by these processes is not well understood.

Once radionuclides reach the ground surface at the top of the engineered cover via processes described above, they are subject to suspension into the atmosphere and dispersion to the surrounding landscape. Atmospheric transport of Rn-222 and contaminants sorbed to suspended particles is modeled using a standard modeling platform approved by the Environmental Protection Agency (EPA) called AERMOD. The results of this model are abstracted into the Clive DU PA model, and contributions of airborne radionuclides to dose and uranium toxicity hazard are evaluated.

The potentially important cover degradation process of gully formation, due to natural or anthropogenic initiation, is evaluated in a preliminary way using a simple modeling construct in order to determine whether it warrants more sophisticated modeling approaches. It is assumed that a gully could form as a wedge-shaped incision into the cover, with the top end at the cover central ridgeline, and the mouth at the change in slope. Outwash from the gully forms a fan-shaped deposit on the side of the embankment and the adjacent flat terrain. Materials exposed in the gully bottom are presumed to be spread across the top of the fan. If these materials include DU waste components (including decay products), then this could contribute to radiation doses and uranium toxicity hazards.

Receptors, Exposure and Dose

Considering the remote and inhospitable environment of Clive, it is not reasonable to assume that the traditional residential receptors considered in PA will be present. Traditionally, based on DOE (DOE M 435.1) [7] and NRC guidance (10 CFR 61) [5], members of the public are assumed to inhabit land directly outside the fence line or boundary of the disposal facility, and inadvertent intruders are assumed to access the disposal facility and the disposed waste directly, in activities such as well drilling or basement construction. For disposal facilities in the arid west, these types of strictly defined default scenarios do not adequately describe likely human activities. Their inclusion in a PA model for a site such as the Clive Facility will usually result in underestimation of the performance of a disposal system, which does not lend itself to effective decision making for society's need to dispose of radioactive waste. At the Clive Facility there is no potable water resource to drill for, and historical evidence suggests there is minimal likelihood that anyone would construct a residence on or near the site.

There are present day activities in the vicinity, however, that might result in receptor exposures if these activities are projected into the future, when the facility is closed and after institutional control is lost. Large ranches operate in the area, so ranch hands may work in the vicinity. Pronghorn antelope are found in the region and may be hunted. Both of these activities are facilitated by the use of OHVs. OHV enthusiasts also ride recreationally for sport in areas near the Clive Facility.

In addition to these receptors, there are specific points of exposure within the vicinity of the Clive Facility where individuals might be exposed. OHV enthusiasts frequent the Knolls Recreation Area, about 12 km (8 mi) west of the Facility. Interstate-80 and a major railroad are located to the north, with an associated rest area on the highway. Adjacent to the Clive Facility property, an access road for the the Utah Test and Training Range is used on occasion.

Consideration of such site-specific scenarios should be matched with regulatory definitions or classifications of human receptors. The State of Utah follows federal guidance by categorizing receptors in a PA in UAC Rule R313-25-8 [1] and 10 CFR 61.41 [2] according to the labels "member of the public" (MOP) and "inadvertent [human] intruder" (IHI). NRC offers two definitions of inadvertent intruders and one of MOP in 10 CFR 61 [2]:

> **§ 61.2 Definitions.** Inadvertent intruder means a person who might occupy the disposal site after closure and engage in normal activities, such as agriculture, dwelling construction, or other pursuits in which the person might be unknowingly exposed to radiation from the waste.
>
> **§ 61.42 Protection of individuals from inadvertent intrusion.** Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste at any time after active institutional controls over the disposal site are removed.
>
> **§ 61.41 Protection of the general population from releases of radioactivity.** Concentrations of radioactive material which may be released to the general environment in ground water, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 millirems [0.25 mSv] to the whole body, 75 millirems [0.75 mSv] to the thyroid, and 25 millirems [0.25 mSv] to any other organ of any member of the public. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable.

For the Clive Facility, Neptune assumed that the major receptor classes are ranch hands, hunters and OHV enthusiasts. These receptors are expected to engage in activities both on and off the site. As such, these receptors fit the NRC definition of both MOPs and IHIs. The receptors that are located at specific offsite locations (e.g., Interstate-80) fit the NRC definition of MOPs. The PA model makes no explicit distinction between MOP and IHI, but simply addresses radiation dose to human receptors who may be exposed to radionuclides released from the disposal facility into the environment subsequent to facility closure. In accordance with UAC Rule R313-25-8 [1], doses are calculated within a 10,000-year compliance period and may be compared to a performance criterion of 0.25 mSv (25 mrem) in a year for a MOP, and 5 mSv (500 mrem) in a year for an inadvertent intruder.

The site-specific scenarios fully integrate receptor behavior with dose consequences, and are evaluated probabilistically in a way that separates the impact of variability in exposure parameter values applicable over a few years or decades, such as individual physiological and behavioral parameters, and transport parameters (values applied over the full 10,000-year performance period, such as solubility and adsorption parameters). This led to a two-stage probabilistic model and Monte Carlo analysis that was implemented in GoldSim. This distinction facilitates assessment of uncertainties that relate to physical processes from uncertainties relating to inter-individual differences in potential future receptors. Although probabilistic methods have been used in PAs to evaluate uncertainties in radionuclide release and transport over time, to date these methods have not commonly extended to receptor exposure and dose models, and have not involved a two-dimensional probabilistic approach.

In addition to radiation dose, uranium is also associated with non-radiological toxicity, e.g. kidney damage. The potential chemical toxicity of uranium disposed at the Clive Facility is evaluated in the PA Model. Potential receptor exposure to uranium is compared to a toxicological criterion that represents a threshold of adverse effects associated with kidney toxicity.

Deep Time

After the 10,000-year performance period for receptor doses the focus turns to very long-term, or “deep time” scenarios. Peak activity of the waste occurs when the principal parent U-238 reaches secular equilibrium with its decay products. This occurs at roughly 2.1 My from the time of isotopic separation, and the model evaluates the potential future state of the site in this context. This time frame borders on geologic, and must take into account the possibility of future large lakes in the Bonneville Basin. The return of such lakes is understood to be inevitable, and the Clive Facility, as constructed, will not survive in its current configuration as it succumbs to the assault of waves. Many lakes, of intermediate and large size, are expected to occur in the 2.1-My time frame, following the climate cycle periodicity of about 100,000 years, based on current scientific understanding of paleoclimatology.

For the deep time assessment the potential impacts of climate change on the disposal facility and general area were considered directly. The most important aspect of the deep-time assessment is the return of lakes that reach the elevation of Clive, or even the elevation of previous pluvial lakes. The climate change modeling is performed at a systems level, capturing the essential features of climate cycles and their potential to affect site stability. This analysis takes into account historical records based on marine sediment and ice core data, as well as specific deep bore hole data in the general area of the Utah basins. The most important effect occurs when wave action attacks the disposal embankments, hence dispersing at least some of their contents throughout the lake, with subsequent deposition as the lake recedes. Each lake deposits sediment in the general area—collectively about 15 m per climate cycle. Hence, the area of the disposal facility is covered with a substantial layer of lacustrine sediment during the 2-My period of interest.

As each lake returns, the model estimates radionuclide concentrations in a local part of the lake, and in the sediments surrounding and subsuming the site. Because the exact behavior of lake intrusion and site destruction is speculative, the model makes several assumptions. The entirety of the DU waste is assumed to comingle with sediments, dispersed over an uncertain area. In the presence of a lake, the radionuclides migrate into the water column, in accordance with their aqueous solubility. UO_3 has a relatively high solubility and will be dissolved from the DU wastes and washed out of the embankment in roughly 50,000 yr. For the remaining and relatively insoluble U_3O_8, on the other hand, sediment concentration is relatively high. As each lake recedes, radionuclides are co-deposited with the sediment, only to be dissolved into the water column again with the next lake. This is a very conservative approach, since in reality each blanket of sediment could entrap constituents, and the concentrations in water and sediment over time should consequently decrease. The analysis, therefore, focuses on the arrival of the first lake, which will be the most destructive in terms of sudden release of radionuclides, and would provide the least amount of sediment to encapsulate them. Subsequent lakes would see progressively less radionuclide activity as the site is slowly buried under ever-deeper lacustrine deposits through the eons.

Disposal Options

With downward pathways influencing groundwater concentrations, and upward pathways influencing dose and uranium hazard, a balance must be achieved in the placement of different kinds of waste. The Clive DU PA Model was run considering three different options for configuration of the DU waste within the CAS embankment. The volume within the embankment that is available for waste disposal is about 13.5 m deep, below the engineered cap. The 13.5-m waste volume is divided into 27 layers that are each 0.5 m thick. The layers are labeled 1 through 27 from top to bottom of the available volume. No DU waste is included under the side slopes of the embankment for this PA.

The disposal options that were evaluated include:

> **GDP contaminated waste in Layer 7 – SRS waste in Layer 8 – GDP uncontaminated waste in Layers 9-27.** This model is termed the 3-m model, because the top of Layer 7 is 3 m below the embankment cover. Note that clean fill material is assumed for the 3 m between the cap and Layer 7.
>
> **GDP contaminated waste in Layer 11 – SRS waste in Layer 12 – GDP uncontaminated waste in Layers 13-27.** This model is termed the 5-m model, because the top of Layer 11 is 5 m below the cap. Note that fill material is assumed for the 5 m between the cap and Layer 11.
>
> **GDP contaminated waste in Layer 21 – SRS waste in Layer 22 – GDP uncontaminated waste in Layers 23-27.** This model is termed the 10-m model, because the top of Layer 21 is 10 m below the cap. Note that fill material is assumed for the 10 m between the cap and Layer 21. This model places all waste below grade.

These cover a range of possible disposal options, from disposal only below grade to disposal throughout most of the system. In addition to these options, two scenarios are considered that are related to erosion. The first assumes a stable embankment for 10,000 years, with infilling of the cap and continual airborne deposition replacing fine sediments that are resuspended and subsequently dispersed offsite. This model assumes a balance so that substantial erosion from airborne and waterborne forces is unlikely. The second scenario is one in which gullies are formed that, depending on the DU waste disposal configuration, might intersect and expose the DU waste to the environment. Consequently, six different models are considered for the dose and groundwater concentration endpoints.

RESULTS

Projected Doses to Site-Specific Receptors

It should be noted that all results are preliminary, and are subject to change depending upon review and subsequent modification of the model and its inputs.

Dose results for future ranch hands are presented in Tables I (without gullies) and II (with gullies), as total effective dose equivalent (TEDE). Doses to ranch hands are more than an order of magnitude greater than doses to hunters and OHV enthusiasts. Groundwater results for Tc-99 are presented in Table III.

The statistics in Tables I and II represent summaries of the peak of the mean doses. The PA model construction includes spatio-temporal scaling that properly addresses the needs of a systems level model. Consequently, the outputs of each simulation are estimates of mean dose. Considering that doses increase with time, the peak mean dose occurs at or near 10,000 years, and the 95th percentile is analogous to a 95% upper confidence interval of the peak of the means.

When gullies are not included in the model (Table I), compliance with the performance objectives for the IHI and the MOP is clearly established for all three disposal configurations. The doses increase as waste is placed nearer the top of the embankment, but the more stringent MOP performance objectives are not exceeded in any of the cases.

When gullies are included (Table II), all doses are still less than the 500-mrem-in-a-year IHI performance objective. However, the 95th percentile peak mean dose to ranch hands exceeds the MOP performance objective of 250 μSv (0.25 mSv, or 25 mrem) in a year.

Results are also available from the PA model for the offsite (MOP) receptors. None of the 95th percentile dose estimates for these receptors exceeds 10 μSv (1 mrem) in a year, and most of the peak mean dose estimates are much less than 10 μSv (1 mrem) in a year.

Summary statistics for the distribution of the peak of the mean Tc-99 concentrations in groundwater are presented in Table III. For the 3-m and 5-m models, compliance with the GWPLs is clearly demonstrated. For the 10-m model the situation is not as clear; both the mean (of the peak of the means) and the 95th percentile exceed the GWPL. The results depend critically on the model structure, specification and underlying assumptions. Infiltration rates and Tc-99 inventory concentrations might be overestimated. However, based on the model assumptions the 10-m model does not comply with the GWPL performance objective for Tc-99. These results suggest, however, that there are waste disposal configurations that comply with the GWPLs.

Table I. Peak Mean TEDE, without consideration of gullies

receptor	Peak TEDE (μSv in a yr) within 10,000 yr		
	mean	median (50^{th} %ile)	95^{th} %ile
waste emplaced > 3 m below embankment cover			
ranch hand	43.7	34.4	116
waste emplaced > 5 m below embankment cover			
ranch hand	5.98	4.73	15.2
waste emplaced > 10 m below embankment cover			
ranch hand	0.0596	0.0471	0.152

Table II. Peak mean TEDE, with gully screening calculation

receptor	Peak TEDE (μSv in a yr) within 10,000 yr		
	mean	median (50^{th} %ile)	95^{th} %ile
waste emplaced > 3 m below embankment cover			
ranch hand	209	116	723
waste emplaced > 5 m below embankment cover			
ranch hand	5.64	4.43	14.4
waste emplaced > 10 m below embankment cover			
ranch hand	0.0594	0.0457	0.155

Table III. Peak groundwater activity concentrations for Tc-99 within 500 yr

radionuclide	GWPL (Bq/L)	peak activity concentration within 500 yr (Bq/L)		
		mean	median (50^{th} %ile)	95^{th} %ile
waste emplaced > 3 m below embankment cover				
Tc-99	140 (3790 pCi/L)	3.18	5.29e-7	7.73
waste emplaced > 5 m below embankment cover				
Tc-99	140	16.2	9.77e-5	63.3
waste emplaced > 10 m below embankment cover				
Tc-99	140	533	4.18	3010

Groundwater concentrations for all other radionuclides are much less than their respective GWPLs, with the exception of iodine-129 (I-129), which, although postulated as a contaminant in the SRS DU waste, has never been detected in the DU waste proposed for disposal at the Clive Facility.

The dose and groundwater concentration results indicate that the downward pathway is dominated by groundwater concentrations of Tc-99, whereas, the upward pathway is dominated by dose from Rn-222 (and progeny). A trade-off is indicated in terms of DU waste placement. The lower the DU waste is placed, particularly the Tc-99 contaminated DU waste, the greater the groundwater concentrations of Tc-99, but the lower the doses. Conversely the higher the DU waste is placed in the embankment, the lower the Tc-99 groundwater concentrations, and the greater the dose to ranch workers. However, there is a wide range of DU waste configurations in the CAS embankment that satisfy both dose and groundwater performance objectives.

Sensitivity Analysis

Global sensitivity analyses were conducted using the data mining technique of Gradient Boosting Machines [10,11], wherein variance decomposition of the machine learning model fit to the GoldSim results was used to estimate sensitivity indices for each variable. Global sensitivity analysis performed on simulated output of probabilistic models effectively allows exploration of changes in all input parameters simultaneously. This approach to global sensitivity analysis is used to identify the important predictors of the model results for each endpoint of interest (separately), including those shown in Tables I and II. Doses under the condition of gully erosion are related to the waste emplacement depth, as shown in Table II. When gully erosion is included in the > 3-m below cover case, the number of gullies and the angle of repose of the gully outwash fan are the critical factors driving TEDE. For all results where gullies are not evaluated (Table I), dose results are most sensitive to parameters that control radon transport through the cover.

Sensitivity analysis results are presented in Figure 4 for the peak annual mean dose for ranch hands with an emplacement depth of > 3 m and no gullies. In the 1st panel, quartiles of the peak annual mean dose results are shown by color shading, and the peak dose metric of 250 μSv (25 mrem) in a year is also indicated. This shows that the dose metric is satisfied for most of the simulations (e.g., the 99th percentile is 160 μSv [16 mrem] in a year).

The 2nd, 3rd, and 4th panels show partial dependence plots (the dark blue line) for the most sensitive input parameters for this endpoint. The sensitivity indices (SI) sum to 100% for all input parameters. For models of this type, and SI of greater than 10 is often considered important. In this case, the radon E/P ratio (escape-to-production ratio) is the most significant predictor of dose (SI = 45.9), followed by the moisture content in the sacrificial soil layer (SI = 21.6), and the K_d for radium in sandy soils (SI = 8.29). The sensitive parameters are all associated with the impact of radon on the doses. Radium is the pre-cursor to radon in the decay chain, increased moisture content mitigates radon transport, and the radon E/P ratio affects the amount of radon that can leave the system. Radon is the greatest dose driver in the model.

Similar sensitivity analyses were performed for the other dose endpoints and for the groundwater concentrations endpoints. The most sensitive parameters for all dose endpoints were associated with radon. Whereas, for the groundwater pathway, the most sensitive parameters were associated with partitioning coefficients for each specific radionuclide.

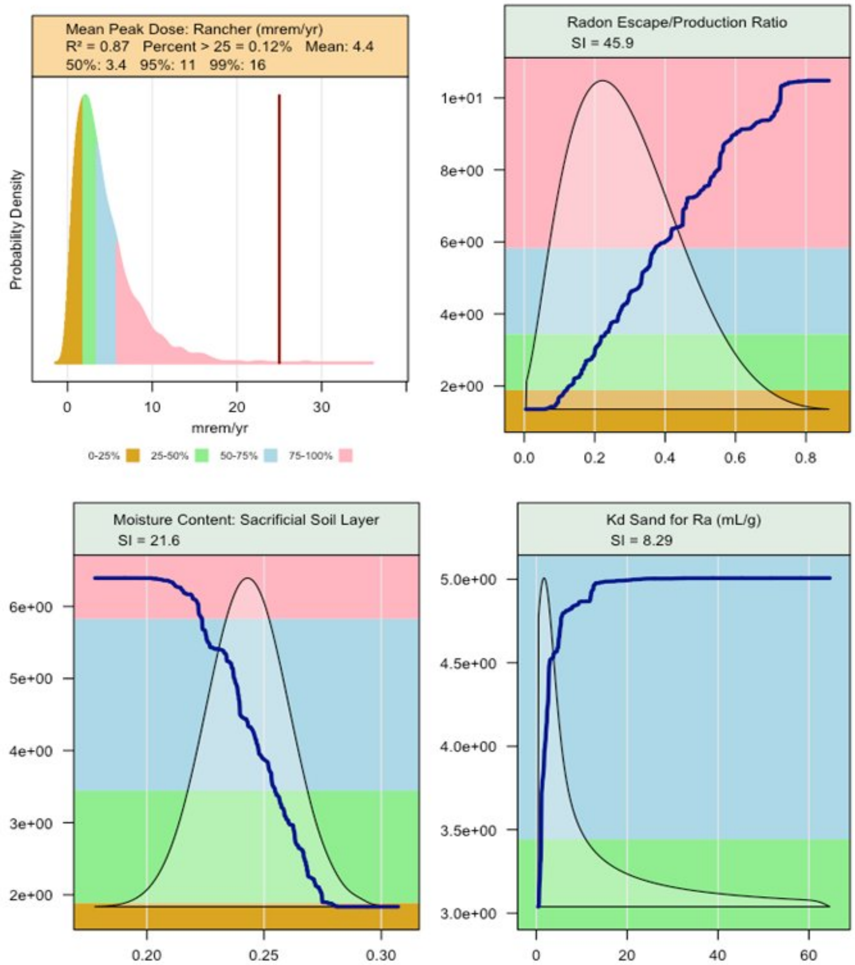

Fig. 4. Sensitivity analysis results for ranch hand dose; > 3 m cover, no gullies.

Deep Time Results

The final set of analyses that are important are those that consider effects in deep time. As described above, the deep time model is very conservative in many ways with respect to dispersal of the DU waste material. Large lakes that obliterate the CAS embankment are assumed to return periodically, but the models of dispersion of the waste are very confined, and hence conservative.

Peak mean concentrations of U-238 in lake water and sediment for the next 100 ky are presented in Tables V and VI. These results demonstrate the concentrations that might occur in response to obliteration of the site, and subsequent dispersal of the waste in a relatively confined system. The concentrations presented would decrease with each lake and climate cycle as more sediment is deposited with each lake event, and each lake event allows the remnants of the DU waste to be dispersed ever further afield.

Table V. Peak mean uranium-238 concentrations in lake water within 100 ky

simulation scenario	Peak mean lake water concentration of uranium-238 within 100 ky (Bq/L)[a]		
	mean	median (50^{th} %ile)	95^{th} %ile
no gullies; waste > 3 m below cover	6.7e-3	3.7e-5	1.1
no gullies; waste > 5 m below cover	6.3e-3	3.3e-5	1.0
no gullies; waste > 10 m below cover	6.7e-3	3.3e-5	1.3

Table VI. Peak mean uranium-238 concentrations in sediment within 100 ky

simulation scenario	Peak mean sediment concentration of uranium-238 within 100 ky (Bq/g)		
	mean	median (50^{th} %ile)	95^{th} %ile
no gullies; waste > 3 m below cover	59	48	130
no gullies; waste > 5 m below cover	56	48	126
no gullies; waste > 10 m below cover	56	48	126

Summary and Discussion

A probabilistic PA model was constructed that considered DU waste and decay product doses to site-specific receptors for a 10,000-yr performance period, as well as deep-time effects. The quantitative results are summarized in Table VII. Doses (as TEDE) are always less than 5 mSv in a year, and doses to the offsite receptors are always much less than 0.25 mSv in a year. Groundwater concentrations of Tc-99 are always less than its GWPL except when the Tc-99 contaminated waste is disposed below grade. Even in this case, the median groundwater concentration is only 4.18 Bq/L (113 pCi/L), which is more than one order of magnitude less than the GWPL for Tc-99. The results overall suggest that there are disposal configurations that can be used to dispose of the proposed quantities of DU waste that are adequately protective of human health.

Table VII. Summary of the results of the Clive DU PA model

performance objective	without gullies: top of waste at			with gullies: top of waste at		
	3 m	5 m	10 m	3 m	5 m	10 m
Dose to MOP below regulatory threshold of 0.25 mSv in a year	Yes	Yes	Yes	Maybe[a]	Yes	Yes
Dose to IHI below regulatory threshold of 5 mSv in a year	Yes	Yes	Yes	Yes	Yes	Yes
Groundwater maximum concentration of Tc-99 in 500 years < 140 Bq/L (3790 pCi/L)	Yes	Yes	No[b]	Yes	Yes	No[2]

[a] The expected dose to MOP is acceptable under this scenario, but the 95th percentile of the expected dose exceeds the regulatory threshold.
[b] These results might overestimate groundwater concentrations because of potential overestimation of infiltration rates and of the Tc-99 inventory.

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