ENERGYSOLUTIONS

December 13, 2023   CD-2023-246

Mr. Doug Hansen, Director
Division of Waste Management and Radiation Control
P.O. Box 144880
Salt Lake City, UT 84114-4880

Subject: Federal Cell Facility Application: Responses to the Director's Request for Information
Request for Information - DRC-2023-002477

Dear Mr. Hansen,

Energy*Solutions* hereby responds to the Utah Division of Waste Management and Radiation Control's
March 28, 2023 Request for Information (RFI) on our Federal Cell Facility Application.[1] A response is
provided for each request using the Director's assigned reference number.

Validate the Model Assumptions and Formulation

O-31: *The PA for the Federal Cell depends on the validity of the percolation rate predicted with a
water balance model that has not been validated with field data. The model needs the necessary
validation. Apply the methodology used to create and parameterize the unsaturated zone model for the
earthen cover to similar covers in Utah, which have extensive performance data, namely the water
balance covers at the White Mesa Mill in Blanding, Utah, and the Monticello Uranium Mill Tailings
Disposal Facility in Monticello, Utah. Compare the predictions made by the model for each site,
particularly percolation vs. time, to measured field data documented for these sites. Describe and
explain any differences between measured and predicted percolation.*

The hybrid cover design proposed for the Federal Cell is compared with similar covers at
Blanding and Monticello, Utah; and the estimated percolation rates through the Federal Cell are
compared with percolation data collected from the covers at the other two sites. Figure 1 depicts
the basic layering of the cover designs.

Table 1, Table 2, and

Table *3* summarize important engineering/hydraulic properties of the various layers in the Clive,
Monticello, and Blanding cover designs.

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[1] Hansen, D.J. "Federal Cell Facility Application Request for Information." via DRC-2023-002477 from
the Utah Division of Waste Management and Radiation Control to Vern Rogers of Energy*Solutions*,
March 28, 2023.

Table *4* summarizes precipitation and percolation data available across these sites, including monitoring from a Cover Test Cell at Clive, UT that was constructed to evaluate a previous riprap cover design.
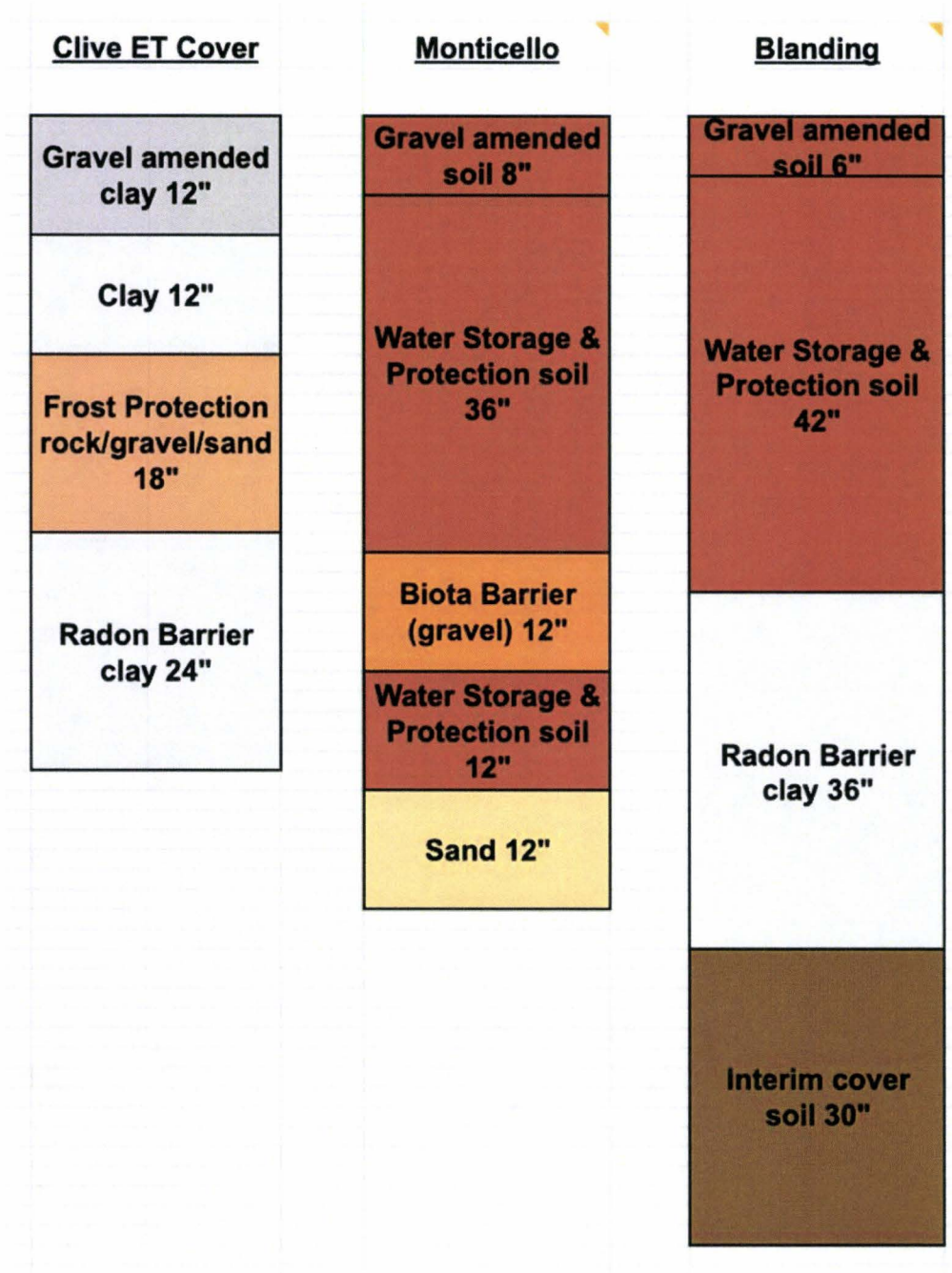
Figure 1. Layering of ET cover systems at Clive, Monticello, and Blanding, Utah.

Table 1. Engineering properties of cover layers in the Clive Federal Cell, DU PA v2.0.

Layer	Input Parameter[2]	ET Cover DU PA v2.0 (actual, 1000 sims)
Surface	θ_r (unitless)	0.111
	θ_s (unitless)	0.4089
	α (1/cm)	0.017*
	n (unitless)	1.32*
	K_{sat} (cm/day)	6.97*
Evaporative Zone	θ_r (unitless)	0.111
	θ_s (unitless)	0.481
	α (1/cm)	0.017*
	n (unitless)	1.32*
	K_{sat} (cm/day)	6.97*
Frost Protection	θ_r (unitless)	0.056*
	θ_s (unitless)	0.40*
	α (1/cm)	0.056*
	n (unitless)	1.69*
	K_{sat} (cm/day)	72.7*
Upper Radon Barrier	θ_r (unitless)	0.1
	θ_s (unitless)	0.432
	α (1/cm)	0.003
	n (unitless)	1.172
	K_{sat} (cm/day)	6.97*
Lower Radon Barrier	θ_r (unitless)	0.1
	θ_s (unitless)	0.432
	α (1/cm)	0.003
	n (unitless)	1.172
	K_{sat} (cm/day)	6.97*

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* Values varied for each realization; mean reported here. See Unsaturated Zone Modeling White Paper, v2.0, for details.

Table 2. Engineering properties of cover layers in the Monticello disposal facility.

Monticello Input Parameter Table		
Layer	Input Parameter	Monticello
Gravel Amended	θ_r (unitless)	n/a
	θ_s (unitless)	n/a
	α (1/cm)	n/a
	n (unitless)	n/a
	K_{sat} (cm/day)	30.24
Water Storage & Protection	θ_r (unitless)	0
	θ_s (unitless)	0.3
	α (1/cm)	0.0011
	n (unitless)	1.31
	K_{sat} (cm/day)	3.6288
Biota Barrier	θ_r (unitless)	n/a
	θ_s (unitless)	n/a
	α (1/cm)	n/a
	n (unitless)	n/a
	K_{sat} (cm/day)	n/a
Water Storage & Protection	θ_r (unitless)	0
	θ_s (unitless)	0.29
	α (1/cm)	0.001
	n (unitless)	1.5
	K_{sat} (cm/day)	0.0320
Sand	θ_r (unitless)	n/a
	θ_s (unitless)	n/a
	α (1/cm)	n/a
	n (unitless)	n/a
	K_{sat} (cm/day)	n/a
Tailings	θ_r (unitless)	n/a
	θ_s (unitless)	n/a
	α (1/cm)	n/a
	n (unitless)	n/a
	K_{sat} (cm/day)	n/a

Table 3. Engineering properties of cover layers in the Blanding White Mesa Mill Tailings Facility.

Blanding Input Parameter Table		
Layer	Input Parameter	Blanding
Gravel Amended	θ_r (unitless)	0.045
	θ_s (unitless)	0.254
	α (1/cm)	0.0145
	n (unitless)	1.406
	K_{sat} (cm/day)	5.6
Water Storage & Protection	θ_r (unitless)	0.055
	θ_s (unitless)	0.404
	α (1/cm)	0.0145
	n (unitless)	1.406
	K_{sat} (cm/day)	7.4
Compacted Cover (Clay Radon Barrier)	θ_r (unitless)	0.046
	θ_s (unitless)	0.334
	α (1/cm)	0.0229
	n (unitless)	1.261
	K_{sat} (cm/day)	3.6
Interim	θ_r (unitless)	0.059
	θ_s (unitless)	0.439
	α (1/cm)	0.0125
	n (unitless)	1.461
	K_{sat} (cm/day)	10.4
Tailings	θ_r (unitless)	n/a
	θ_s (unitless)	n/a
	α (1/cm)	n/a
	n (unitless)	n/a
	K_{sat} (cm/day)	n/a

Table 4. Precipitation and percolation data for the Clive Cover Test Cell, Monticello, and Blanding facilities. Clive precipitation average calculated for the years 2002–2016 to match with Cover Test Cell period of service; site average across 28-year meteorological record is 217.41 mm/yr.

Reference	Trinity Consultants (2021)	Energy*Solutions* (2017)	Benson et al. (2008)		Energy Fuels (2021)	
Study	Clive	Clive Test Cell	Monticello		Blanding	
Year	Precipitation (mm/yr)	Percolation (mm/yr)	Precipitation (mm/yr)	Percolation (mm/yr)	Precipitation (mm/yr)	Percolation (mm/yr)
2001	172.5	--	377.7	0	--	--
2002	147.9	0.652	228.6	0	--	--
2003	183.8	0.446	364	0	--	--
2004	230.1	0.178	442	0.2	--	--
2005	258.1	0.455	519.7	3.8	--	--
2006	187.7	0.256	447.3	0.2	--	--
2007	210.6	0.237	304.5	0	--	--
2008	81.3	0.229	99.8	0.4	--	--
2009	206.2	0.14	--	--	--	--
2010	227.8	0.164	--	--	--	--
2011	246.1	0.11	--	--	--	--
2012	167.4	0.023	--	--	--	--
2013	209.8	0.0001	--	--	--	--
2014	213.6	0	--	--	--	--
2015	247.7	0	--	--	--	--
2016	271.3	0.231	--	--	59.9	0
2017	193.8	--	--	--	222.7	0.65
2018	170.2	--	--	--	163.4	0.9
2019	342.6	--	--	--	307.9	1.01
2020	116.3	--	--	--	127.8	0.89
Average	205.96	0.208	347.95	0.575	176.34	0.69

There are several important distinctions between the designs. The Clive and Monticello designs both employ fine materials at the surface, creating an evaporative zone where water is stored and released through evapotranspiration processes, combined with a layer of coarse material placed below the fine materials that creates a capillary barrier to prevent downward flow, holding water in the evaporative zone more effectively. From the Monticello design, it is surmised that the biota barrier gravel likely creates an effective capillary barrier; however, parameterization for this layer was not available in the references reviewed.

In contrast, the Clive Test Cell and the cover design for the Blanding site do not include a capillary break. While fine materials are used in the upper layers of the Blanding cover to create a water storage zone, the design lacks a capillary break that would allow this water to be held in the storage zone more effectively. The Clive test cell lacks both a storage zone in the surface layers (consisting of riprap and coarse filter materials), and a capillary break between the evaporative zone and lower clay radon barrier layers.

The differences in cover design and average precipitation between the sites provides some insight into the difference in percolation measured from the covers, and the predicted performance for the Clive cover design from HYDRUS modeling completed in support of the DU PA.

Precipitation is higher for the Monticello site compared to Clive and Blanding. While measured percolation rates are higher for the Monticello site compared to the Clive Test Cell, they are similar to those monitored at Blanding. At first glance, the higher rates of percolation at Monticello, compared to the Clive Test Cell, may be intuitive since Monticello has roughly double the precipitation. However, another way to look at the results is that, despite Monticello receiving roughly double the amount of annual precipitation, only a very small fraction of this additional water is able to successfully travel through the cover. As such, despite the markedly higher precipitation at Monticello, the cover is effective at limiting percolation. The rates of percolation through the Clive Test Cell and Blanding covers may reflect the more arid climate at these sites, as these covers lack both the storage *and* capillary barrier features employed in the Monticello cover design.

In fact, this is what the HYDRUS modeling results indicate when a similar design is subjected to the climate at Clive, UT. As noted in Section **Error! Reference source not found.** above, average percolation for the 1000 simulations run in DU PA v2.0 is 0.0167 mm/yr; about an order of magnitude lower than the Cover Test Cell and slightly more than an order of magnitude lower than the reference Monticello and Blanding sites.

Figure 1 offers some possible explanations for this predicted difference in percolation. The Federal Cell design is like that of the high-performance Monticello cover and includes an evaporative zone in the surface layers to store and release water through time, and a strong capillary break between the evaporative zone and lower radon barrier layers. Employing similar features used in the Monticello cover but subjecting such a cover to only half the amount of precipitation, results in very low predicted rates of infiltration. Additionally, it is also possible that the Monticello design has shown increased performance in the years following those reported in

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Table *4*.

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## Number of Realizations and Statistical Sufficiency.

O-32: *Predictions from the water balance model are now being used directly to characterize the uncertainty in the performance of the earthen cover and the broader uncertainty assessment for the Federal Cell. Understanding whether the distribution of predicted outputs is comprised of a sufficient number of realizations is necessary to have confidence in the subsequent predictions from the GoldSim analysis. NAC-0015_R5 indicates that 1000 realizations were simulated, each for the 1000-yr meteorological record. Outputs from these simulations are then input directly to GoldSim for further analysis, avoiding the abstraction employed previously. Provide documentation indicating that 1000 realizations are sufficient to define the probabilistic characteristics of the model predictions, especially in the tails.*

There are 1,000 values of Net Infiltration simulated by the HYDRUS model that are used to inform the Clive DU PA GoldSim model. In order to assess the sufficiency of the 1,000 simulated values with respect to the behavior of the tails of the distribution, a repeated sampling approach is employed. The idea behind this approach is to evaluate the behavior of key statistics (i.e., the mean and 95th percentile) as a function of sample size.

For a given sample size, samples are randomly selected with replacement from the 1,000 available. This is repeated 100 times so that the distribution of the mean and of 95th percentiles can be estimated. This is repeated for samples sizes at every 50 from 50 to 1,500.

Figure 2 shows a series of boxplots illustrating the variation in means for each n as n increases. It indicates that the spread of the distribution of the mean stabilizes around samples of about size 500. In this context, stabilization refers to the spread of the distribution not changing with larger sample sizes. For samples of size 100, the distribution is not stable since the spread for samples of size 150 is relatively smaller.

To quantitatively assess this stabilization, the variances of the means are compared for consecutive pairs of sample sizes. That is, the variance of the distribution of the means for samples of size 50 is statistically compared to the variance of the means of samples of size 100, etc. This results in 100 p-values for each consecutive pair of sample sizes. The null hypothesis for this test is that the variances of the distributions of means between samples of size n and $n + 50$ are equal. Small p-values give evidence that the variances are not equal (i.e., the sample size is not sufficient for stabilization) and larger p-value suggest that stabilization has occurred. To demonstrate the impact of sample sizes on stabilization in this context, the median p-value from the 100 tests performed for each n versus $n+50$ sample size comparison is shown in Figure 3, with a red horizontal line representing $\alpha = 0.05$, and a spline is fit to show the trend in p-values. Figure 3 shows that variances among the distributions of means are not different in a statistically significant sense after a sample size of approximately 400 and they appear to be effectively equivalent after a sample size of 700.
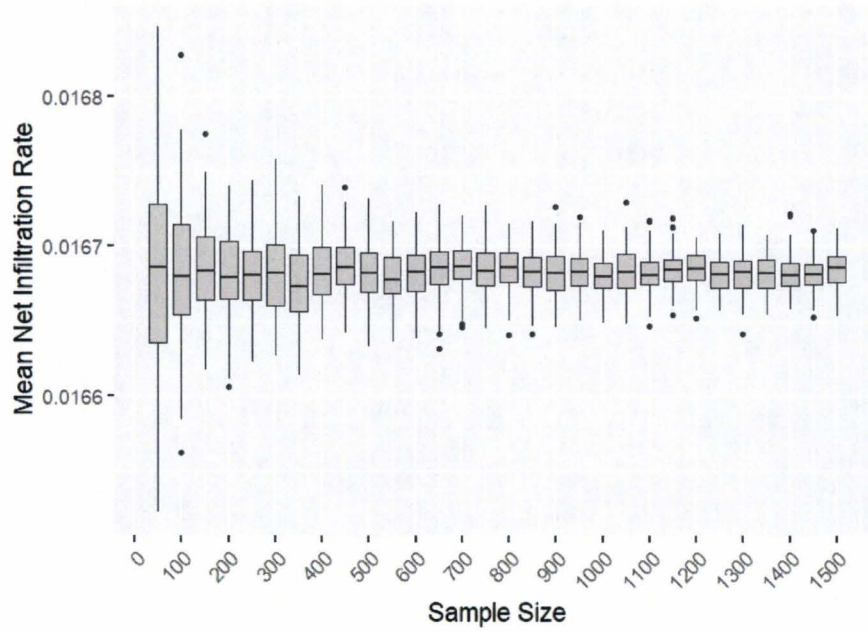
Figure 2: Mean Net Infiltration Rate vs Sample Size
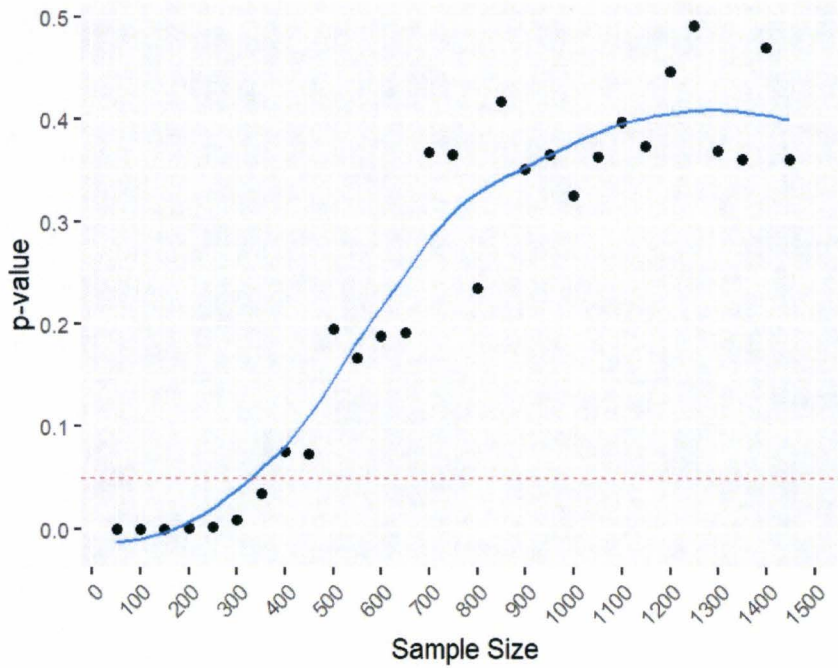
Figure 3: Median p-value vs. Sample Size (Means)

To assess the stability of the tail of the distribution, this same process was repeated using the 95th percentile to summarize each random sample of size n instead of the use of the mean. Figure 4 shows the distributions of the 95th percentiles for each n, and visually suggests that stabilization has occurred around a sample size of 500.

In a similar manner to the analysis above, the variances of the 95th percentiles were compared for samples of size n and $n + 50$ (e.g., $n = 50$ and $n = 100$, $n = 100$ and $n = 150$, etc.), again resulting in 100 p-values for each sample size n. The null hypothesis for this test is that the variances of the distributions of 95th percentiles between samples of size n and $n + 50$ are equal. Small p-values give evidence that the 95th percentiles are not equal (i.e., the sample size is not sufficient for stabilization) and larger p-value suggest that stabilization has occurred. To demonstrate the impact of sample sizes on stabilization in this context, the median p-value from the 100 tests performed for each n versus $n+50$ sample size comparison is shown in Figure 5, with a red horizontal line representing $\alpha = 0.05$, and a spline is fit to show the trend in p-values. Figure 5 shows that variances among the distributions of 95th percentiles are not different in a statistically significant sense after a sample size of approximately 400 and they appear to be effectively equivalent after a sample size of 700. This result is like the results for the mean above and suggests that the 1,000 HYDRUS results sufficiently characterize the tail of the distribution.
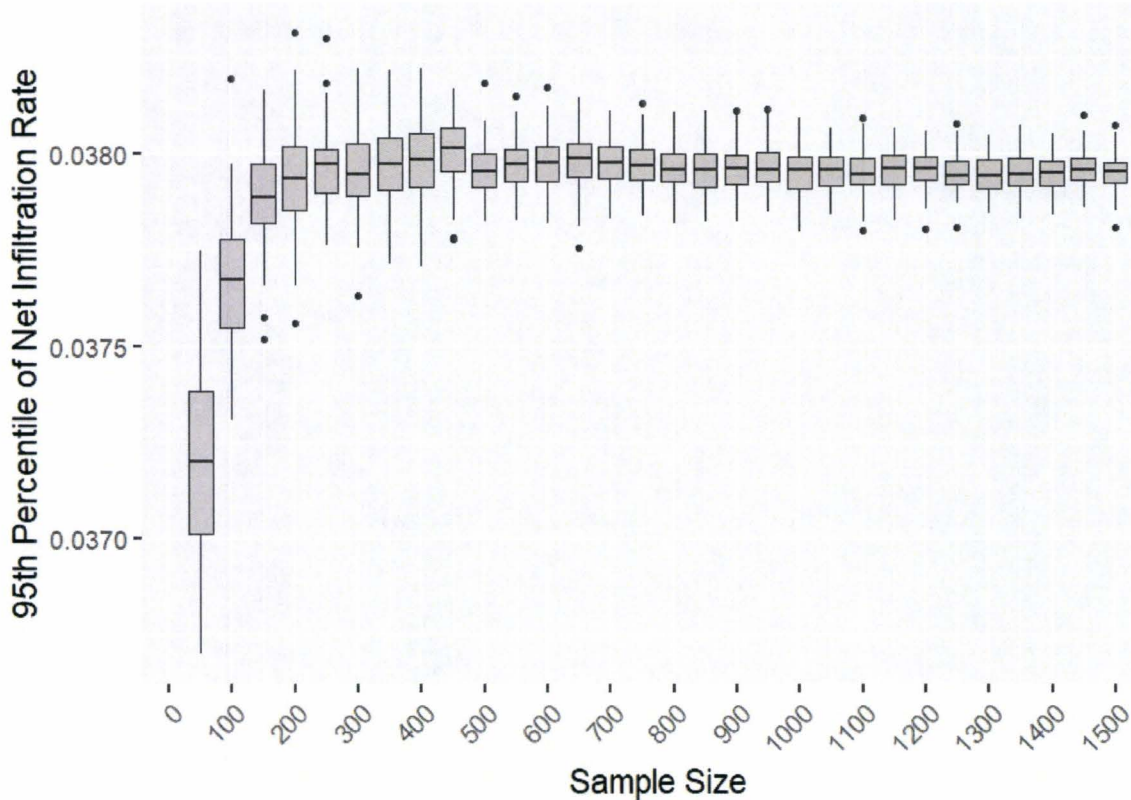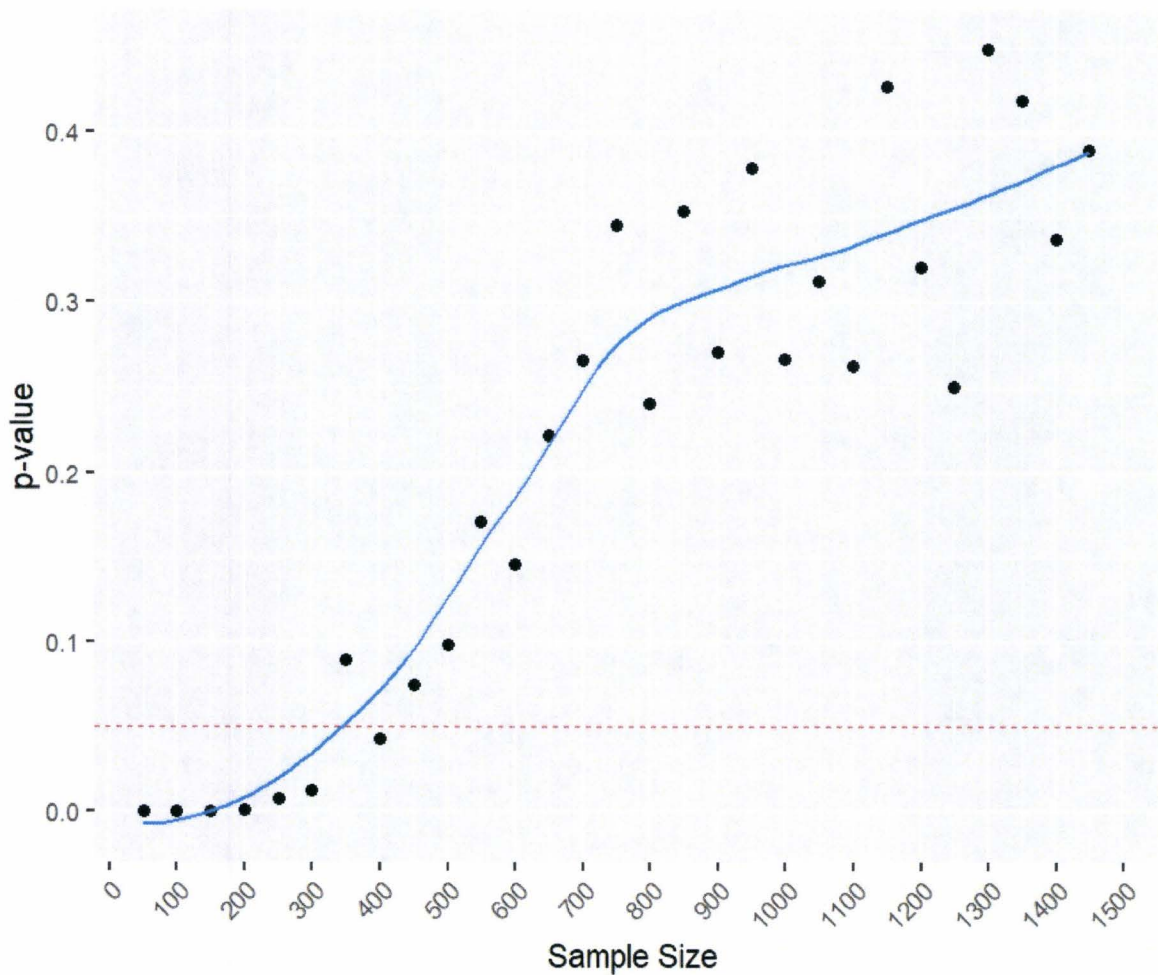

Figure 4: 95th Percentile of Net Infiltration Rate vs. Sample Size

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Figure 5: Median p-value vs. Sample Size (95th Percentile)

Sidewall Ingress

O-33: *Output from the 2-D models described in NAC-0015_R5 indicate that the percolation rate will be higher on the side slopes than on the top deck. Higher percolation rate on the side slope results in higher water saturation and lower matric potential in earthen materials under the side slopes than in the materials beneath the top slopes. The gradients in matric potential caused by these two different conditions can result in pore water in the side slope area migrating laterally into the materials below the top slope, which will be drier and have higher matric potential. This type of phenomenon was predicted for the Hanford Barrier at the US Department of Energy's Hanford Site in Richland, Washington, and lateral ingress as addressed by ensuring sufficient overhang of the top deck. The cover for the Federal Cell includes an earthen cover on the top slopes and rock-armored surfaces on the side slopes. Provide documentation confirming that the higher percolation rate on the side slopes will not cause porewater to migrate laterally inward, increasing the overall amount of water entering and flowing through the material below the top slope.*

The RFI states: "Provide documentation confirming that the higher percolation rate on the side slopes will not cause porewater to migrate laterally inward, increasing the overall amount of

water entering and flowing through the material below the top slope." NAC-0015_R5, Appendix C (Neptune 2021) in fact documents the opposite - that percolation out of the bottom of the radon barrier increases slightly across a transition zone of 10 to 35 meters inward from the transition point from the ET top slope to the riprap side slope (figure 36). Figure 39 quantifies the increase in drainage, which is still quite small at less than 0.5 mm/year total in the maximum case. Appendix C quantifies the impact as follows:

> Despite the lateral hydraulic gradient, the low conductivity of the radon barrier material does not permit enough lateral flow to cause a sizeable increase in the average percolation under the ET portion of the hybrid cover. As seen in Figure 36 [of (Neptune 2021)], percolation out of the lower radon barrier beneath the ET cover does increase near the transition zone. However, Figure 39 [of (Neptune 2021)] shows that the average percolation out of the lower radon barrier over the proposed 135 m of ET cover in the revised cover design ranges from 0.11 to 0.41 mm/yr for the four models explored.

NAC-0015 R5 Reference Excel File:

O-34: *NAC-0015_R5 indicates that "A complete listing of the inputs and outputs of the simulations are provided as an electronic attachment to this document." However, the version of NAC-0015_R5 that was provided in the application has no electronic attachments. This spreadsheet is needed to interpret the outcomes of the modeling. Please provide the following Excel file that is cited in NAC-0015_R5:*

o HYDRUS 1D Inputs and Outputs v2.0 Sept 2021.xlsx

All electronic files requested under RFIs O-34 and O-35 are made available electronically (electronically under the folders named 'Files requested in O-34' and 'Files requested in O-35').

Electronic Files:

O-35: *A preliminary review of the Federal Cell License application and its appendices identifies several electronic files that the license application indicates are included in the application but were not located. Some files could have been requested in earlier RFIs and additional review of the application may find other electronic files necessary for the review. These electronic files are needed to verify and interpret the results of the modeling. Please provide the electronic files or indicate where they are in the application. These files, listed under the appropriate appendices, are:*

Atmospheric Modeling
o Cowherd Particle Resuspension Model
o AERMOD
o CAP-88

Biological Modeling
o GoldSim files (general request for all analyses)

Deep Time Assessment

o **ES external DCF modifiers.xlsx**

Dose Assessment
o **Dose Assessment Appendix II.xls**
o **DCF conversions QAed Rev 1.xlsx**
o **Ingestion dose conversion factors (DCF_Ing)**

Embankment Model
o **GoldSim files**

Erosion Modeling
o **RHEM/ KINEROS2 input and output files**
o **SIBERIA input and output files**
o **IRS and HEM input and output files**
o **CLIGEN climate station database**

Geochemical Modeling
o **Visual MINTEQ input and output files**

Model Parameters
o **Clive PA Model Parameters.xls**

Saturated Zone Modeling
o **Hydraulic Cond.xls**
o **Auto-regressive, moving-average (ARMA) models input and output**

Sensitivity Analysis and Results
o **GBM algorithm, input and output files**

Unsaturated Zone Modeling
o **HYDRUS 1-D and 2-D input and output files (ask for in a separate question)**
o **WGEN/SWAT input and output files**

Waste Inventory
o **100105 9021-33 Iso with Calcs.xls**

All electronic files requested under RFIs O-34 and O-35 are made available electronically (electronically under the folders named 'Files requested in O-34' and 'Files requested in O-35').

Several of the requests call for additional clarification.

Atmospheric Modeling: The file 'air modeling file descriptions' summarizes the input/output files provided and how they relate to each other. The Cowherd Particle Resuspension Model is an equation rather than an electronic model or file.

Biological Modeling: This appears to be alluding to the Clive PA Model Parameters.xls workbook, which is called out in table 1 of that white paper. Accordingly, that is the file provided.

Dose Assessment: Ingestion dose conversion factors are stated in the white paper text to be defined in "Dose Assessment Appendix II.xls" rather than as a separate file. Accordingly, two spreadsheets are provided.

Embankment Model: The GoldSim player includes all relevant files to run the model. The Embankment Modeling white paper does not reference any supplemental electronic files.

Erosion Modeling: Erosion modeling files in support of DU PA v2.0 were provided to Energy*Solutions* via filerun on Jan 10, 2023. These have since been replaced with updated erosion modeling as v3.0; and electronic files were provided to Energy*Solutions* via filerun on March 15, 2023, (electronically found under the folder named 'Erosion Modeling' which is within the folder named 'Files requested in O-34').

Geochemical Modeling: The original Visual MINTEQ files could not be located; so the code was re-run with input and output files retained. This resulted in revised values for solubility of UO_3 and U_3O_8. The white paper *Geochemical Modeling for the Clive DU PA* has been revised accordingly and is included with this response. The DU PA will be updated to v3.0 once all RFIs that could lead to additional revisions have been addressed.

Model Parameters: This is the file "Clive PA Model Parameters.xls" provided in response to *Biological Modeling* above.

Saturated Zone Modeling: Hydraulic Cond.xls is provided. The auto-regressive, moving-average (ARMA) models discussed in the white paper are calculations applied to data found in site_wide_gradients.xls resulting in the distribution shown in GradientDensity.jpg, both of which are also provided.

Sensitivity Analysis and Results: The requested material is found in the compressed folder "clive_du_sensitivity_analysis_code.zip" which includes several files.

Unsaturated Zone Modeling: The HYDRUS input and output files are provided in response to RFI O-34. A total of six files are provided, with the Word file "SWAT_procedure.docx" summarizing how they are used to generate WGEN/SWAT input/output.

Appendix Y:

Y-6-1: *A response to RFI Y-6 stated that Appendix V (Corporate Quality Assurance and Procedures) included the procedure ES-AD-PR-008, Condition Reports. This procedure could not be located. Please provide the operating procedure ES-AD-PR-008, Condition Reports.*

An electronic copy of this procedure is found in the folder 'Files requested in Y-6-1'

References

Benson, C.H., et al., 2008. *Hydraulic Properties and Geomorphology of the Earthen Component of the Final Cover at the Monticello Uranium Mill Tailings Repository,* Geo Engineering Report No. 08-04, April 2008

Energy Fuels, 2021. *Q4-20 Data Quality Report for the Primary Test Section, White Mesa Mill—Tailings Management Cell 2,* Energy Fuels Resources (USA) Inc., San Juan County UT, January 2021

Energy*Solutions*, 2017. *Radioactive Material License No. UT2300249, License Condition 28B: 2016 Cover Test Cell Annual Report,* Energy*Solutions* LLC, Salt Lake City UT, February 2017

Neptune, 2021. *Unsaturated Zone Modeling for the Clive DU PA, Clive DU PA Model v2.0,* NAC-0015_R5, prepared for Energy*Solutions,* Neptune and Company Inc., Los Alamos NM, September 2021

Trinity Consultants, 2021. *Summary Report of Meteorological Data Collected at EnergySolutions' Clive, Utah Facility, January 2020 through December 2020 and January 1993 through December 2020,* Trinity Consultants, Salt Lake City UT, February 2021

If you have further questions regarding the additional responses to the director's requests of DRC-2023-002477, please contact me at (801) 649-2000.

Sincerely,

Vern C. Rogers

Digitally signed by Vern C. Rogers
DN: cn=Vern C. Rogers, o=EnergySolutions,
ou=Waste Management Division,
email=vcrogers@energysolutions.com, c=US
Date: 2023.12.13 13:15:45 -07'00'

Vern C. Rogers
Director, Regulatory Affairs

enclosure

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

Final Report for the Clive DU PA Model

Clive DU PA Model v3.0

8 December 2023

Prepared by

NEPTUNE AND COMPANY, INC.

1505 15th St, Suite B, Los Alamos, NM 87544

1. Title: Final Report for the Clive DU PA Model		
2. Filename: Clive DU PA Model Final Report v3.0.docx		
3. Description: This report describes results of the Clive DU PA Model v3.0.		
4. Originator	Kate Catlett	8 December 2023
5. Reviewers	Paul Black, Sean McCandless	8 December 2023
6. Remarks 8 Dec 2023: R6; Review and update for DU PA v3.0. – K. Catlett 1 Oct 2021: R5; Review and update for DU PA v2.0. – K. Catlett, A. Fleury 24 Nov 2015: R4; Review, edit, add SA results. – K. Catlett, G. Occhiogrosso 28 Oct 2015: R3; Updated for v1.4 with new disposal unit description and updated model results based on latest engineering drawings. – G. Occhiogrosso 30 May 2014: R2; Update for DU PA v1.2. – P. Black 1 June 2011: R1; Initial issue.		

CONTENTS

Figures

Tables

Executive Summary

Neptune and Company, Inc. (Neptune), under contract to Energy*Solutions*, LLC (Energy*Solutions*), has developed a computer model (the Clive DU PA Model, or the Model) to support decision making related to the proposed disposal of depleted uranium (DU) wastes at the low-level radioactive waste (LLW) disposal facility at Clive, Utah, operated by Energy*Solutions*. The Model provides a platform on which to conduct analyses relevant to performance assessment (PA), as required by the State of Utah in Utah Administrative Code (UAC) R313-25, *License Requirements for Land Disposal of Radioactive Waste* (UAC 2018). Specifically, a PA is required in UAC R313-25-9, Technical Analyses. The Model may also serve to inform decisions made by the Site operator to gain maximum utility of the resource that is the Clive Facility. This report presents results for DU PA v3.0.

Depleted uranium is the remains of the uranium enrichment process, of which the fissionable uranium isotope ^{235}U is the product. The leftover uranium, depleted in ^{235}U, is predominantly ^{238}U, but may include small amounts of other U isotopes. In general, DU contains very small amounts of decay products in the uranium, thorium, actinium, and neptunium series of decay chains. Some specific DU waste, resulting from introduction of uranium recycled from used nuclear reactor fuel (reactor returns) into the separations process, contains varying amounts of contaminants, in the form of fission and activation products. Since some of the DU evaluated in this PA includes reactor returns, it is here termed "DU waste." The national inventory of DU is on the order of 700 Gg (700,000 Mg, or metric tons) in mass as uranium hexafluoride (DUF$_6$), and the bulk of it exists in its original storage cylinders, undergoing conversion to oxide form for disposal. This conversion is being performed at the Portsmouth, Ohio, and Paducah, Kentucky, gaseous diffusion plant (GDP) sites, using new purpose-built "deconversion" plants to produce triuranium octoxide (U$_3$O$_8$). A much smaller mass of DU waste was generated by the Savannah River Site (SRS) in the form of uranium trioxide (UO$_3$), a powder stored in several thousand 200-L (55-gal) drums. While the composition of the SRS DU is reasonably well known, the content of the GDP DU is not well documented. For the purposes of this assessment, it was necessary to assume that some uncertain fraction of the GDP DU waste was contaminated to the same extent as the SRS DU waste. DU waste from both sources is considered in the Clive DU PA Model.

The Model is written using the GoldSim probabilistic systems analysis software, which is well-suited for the purpose. In order to provide decision makers with a broad perspective of the behavior and capabilities of the Facility, the Model considers uncertainty in input parameter values. This probabilistic assessment methodology is encouraged by the Nuclear Regulatory Commission (NRC) and the Department of Energy (DOE) in constructing PAs and the models that support them. The Model can be run in deterministic mode, where a single set of median model inputs is used, but running in probabilistic *Monte Carlo* mode provides greater insight into the model behavior, and especially into model sensitivity to the distribution of input parameter values. In *Monte Carlo* mode, a large number of realizations are executed with values drawn at random from the input parameter distributions using Latin Hypercube Sampling to ensure equal probability across the range of the input distributions. The distributions of results, therefore, reflect the uncertainty in these values. To the extent that the Model reflects the uncertain state of knowledge at a site, the Model provides insight about how the site works, and what should be

expected if different actions are taken or different wastes are disposed. In this way, the Model aids in decision making, even in the face of uncertainty.

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 for human habitation. Human activity at Clive has historically been very limited, due largely to the lack of potable water, or even water suitable for irrigation. The site is located on flat ground, with the bottom of 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 Federal Cell. This cell is modeled with an engineered cover, as per design documents. The top of the cell is above grade, and the cover has layers of an evapotranspiration (ET) cover system of earthen origin on its top slope, with a riprap surface layer on its side slope. In time, this cover is expected to become vegetated with native plants, and occupied to a limited extent by animals including insects and mammals. As plant communities become established, they are likely to keep the cover system fairly dry through transpiration.

Water balance modeling of the cover indicates that some water may penetrate the cover system, and this infiltration has the potential to leach radionuclides from the waste and transport them down through the cell liner and unsaturated zone to the aquifer. In the saturated zone (aquifer), contaminants are transported laterally to a hypothetical monitoring well located about 27 m (90 ft) from the edge of the interior of the cell. Since the side slopes of the cell are modeled to not contain DU waste, the effective distance to the well from the DU waste itself is about 81 m (265 ft). This environmental transport pathway is relevant for long-lived and readily leached radionuclides such as ^{99}Tc. Contributions to groundwater radionuclide concentrations from the proposed DU waste are calculated for comparison to groundwater protection limits (GWPLs) during the next 500 years, as stipulated in the water discharge permit (Utah 2014).

In addition to water advective transport, radionuclides are transported via diffusion in both water and air phases within the cover system, which can provide upward transport pathways. Gaseous radionuclides, such as ^{222}Rn, partition between air and water. Soluble constituents partition between water and solid porous media. Coupled with all these processes are the activities of biota, with plants transporting contaminants to their above-ground surface tissues via their roots, and burrowing animals (ants and small mammals) moving bulk materials upward and downward through burrow excavation and collapse. Biota do not play a major role in contaminant transport contributing to human doses or uranium hazard according to model results. The Model considers the effects of a compromised radon barrier with respect to facility performance.

Once radionuclides reach the ground surface at the top of the engineered cover via the aforementioned processes, they are subject to suspension into the atmosphere and dispersion to the surrounding landscape. Atmospheric transport of gases (^{222}Rn) and contaminants sorbed to suspended particles is modeled using a standard modeling platform approved by the U.S. 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 impact of sheet and gully erosion in the Model is evaluated by the application of results of landscape evolution models of hillslope erosion loss and channel development. The model domain includes the Federal Cell as designed, with a gently sloping top slope ET cover system and a steeper riprap covered side slope. Gully depths estimated by the erosion model are calculated at 10,000 years and used to derive values of the percentage of the cover where gullies end within a given depth interval. This model provides an estimate of the volume of embankment cover material removed by erosion. The depositional area of the gully fan is assumed to be the same as the area of waste exposed in the gullies, using projections onto the horizontal plane. If these embankment materials include DU waste contaminants, then this leads to some contribution to doses and uranium hazards. No associated effects, such as biotic processes, effects on radon dispersion, or local changes in infiltration are considered within the gullies.

Given the remote and inhospitable environment of Clive, it is not reasonable to assume that the traditional residential receptors considered in other PAs will be present here. Traditionally, and based on DOE (DOE M 435.1) and NRC guidance (10 CFR 61), members of the public are evaluated 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 house 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 for a site in the arid west, such as Clive, usually results in unrealistic underestimation of the performance of a disposal system, which does not lend itself to effective decision making for the Nation's needs to dispose of radioactive waste.

At Clive, there is no potable water resource to drill for, and historical evidence suggests there is little 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 work in the vicinity. Pronghorn antelope are found in the region, and hunters will follow them. Both of these activities are facilitated by the use of off-highway vehicles (OHVs). OHV enthusiasts also ride recreationally for sport in areas near the facility.

In addition to these receptors, there are specific points of exposure within the vicinity of the Clive Facility where individuals might be exposed. About 12 km (8 miles) to the west, OHV enthusiasts use the Knolls Recreation Area. Interstate-80 and a railroad are located to the north, with an associated rest area on the highway. Closer to the Clive Facility, the Utah Test and Training Range access road is used on occasion. The Model hence evaluates dose and uranium hazard to these site-specific receptors.

The State of Utah follows federal guidance by categorizing receptors in a PA in UAC Rule R313-25-9 (UAC 2018) and 10 CFR 61.41 (CFR 2014) according to the labels "member of the public" (MOP) and "inadvertent human intruder" (IHI). NRC offers two definitions of inadvertent intruders in 10 CFR 61:

> **§ 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.

NRC offers one reference to an MOP in the context of the general population:

§ 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.

DOE definitions in DOE M 435.1 (the Manual accompanying DOE Order 435.1) are much more specific. However, the applicable federal agency that regulates disposal of low-level radioactive waste at the Clive Facility is NRC. For the Clive Facility and the Model, based on the NRC definitions, the ranch hand, hunter, and OHV enthusiast are expected to engage in activities both on and off the site. These receptors fit the NRC definition of inadvertent intrusion because they are assumed to occupy the site, albeit for limited periods of time. The receptors that are located at specific offsite locations, instead, fit the NRC definition of MOP. The Model presents predicted doses to the receptors identified above, under the conditions and assumptions that provide the basis for the Model. These doses are presented as the results of the Model. A comparison of doses to both MOP and IHI performance objectives is also presented.

The Model addresses radiation doses to human receptors who might come in contact with radionuclides released from the disposal facility into the environment subsequent to facility closure. In accordance with UAC Rule R313-25-9, doses are calculated within a 10,000-year compliance period. The doses are compared to a performance criterion of 25 mrem in a year for a MOP, and 500 mrem in a year for an inadvertent intruder. The dose assessment component of the PA model, like the transport modeling components described above, supports probabilistic *Monte Carlo* analysis. Spatiotemporal scaling is a critical component of Model development. For example, the Model differentiates the impact of short-term variability in exposure parameters (values applicable over a few years or decades, such as individual physiological and behavioral parameters) from the longer-term variability of transport parameters (values applied over the full 10,000-year performance period, such as hydraulic and geochemical parameters). This distinction facilitates assessment of uncertainties that relate to physical processes from uncertainties relating to inter-individual differences in potential future receptors.

In addition to radiation dose, uranium is also associated with non-radiological toxicity. The potential chemical toxicity of uranium disposed at the Clive Facility is evaluated in the Model.

Potential receptor chronic daily intake of uranium is compared to toxicological criteria developed by EPA that pertain to a threshold of adverse effect associated with kidney toxicity.

These doses and the supporting contaminant transport modeling that provides the dose model with radionuclide concentrations in exposure media are evaluated for 10,000 years, in accordance with UAC R313-25-9(5)(a). After that time, the modeling focus turns to long-term, or "deep time" scenarios. Peak activity of the waste occurs when the progeny of the principal parent, ^{238}U (with a half-life that is approximately the age of the earth—over 4 billion years), reach secular equilibrium. This occurs at roughly 2.1 My from the time of isotopic separation, and the Model evaluates the potential future of the site in this context. At 2.1 My the activity of the last modeled member of the chain, ^{210}Pb, is equal to that of ^{238}U, within less than one half of one percent. While the calculation could be carried out further in time to achieve a greater degree of accuracy, there is no benefit in doing so for decision-making purposes. This is now a geologic time frame, and needs to take into account the likely possibility of future deep 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. Many lakes, of intermediate and deep size, are expected to occur in the 2.1-My time frame, following the climate cycle periodicity of about 100,000 yr, based on current scientific understanding of paleoclimatology. In these time frames, it is also important to consider processes such as eolian (i.e., wind-borne) deposition, which can be seen in geologic formations in the Clive area. Deposition builds up the ground surface over time, such that the ground surface each time a lake returns is 2 – 3 m higher than the ground surface between lake cycles.

As each lake returns, estimates are made of the radionuclide concentrations in 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 conservative assumptions. Upward movement of radionuclides, via diffusion and biota, is assumed to occur until the first lake returns. At that point in time, the radionuclides that are above ground are assumed to comingle with sediments, dispersed over an uncertain area approximately the size of an intermediate lake. In the presence of a lake, the radionuclides migrate into the water, in accordance with their aqueous solubility. For U_3O_8, which is considered to be the only form of uranium oxide remaining by the time the first lake arrives (since UO_3 moves out of the waste first and what is left will become more like U_3O_8 or UO_2 in the presence of a wetter climate), the solubility of U is very low. As each lake recedes, radionuclides are co-deposited with the sediment, only to be dissolved into the water again with the next lake. This is a very conservative approach, especially for the lake concentrations, since in reality each blanket of sediment could entrap constituents, and the concentrations in water and sediment over time should decrease consequently. 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.

The utility of such a calculation, aside from responding to the UAC, is to inform decisions regarding the placement of wastes in the embankment. 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. In version 1.0 of the Clive DU PA Model (Neptune 2011), three different options for configuration of the DU waste within

the Class A South embankment (subsequently renamed the Federal Cell) were evaluated. These options included a "3-m model," named because the top of the DU waste was 3 m below the embankment cover, and also 5-m and 10-m models. No DU waste is included under the side slopes for this PA. In addition to these disposal options, two scenarios related to embankment erosion were evaluated in the Clive DU PA Model v1.0. The first essentially assumed a stable embankment for 10 ky, with infilling of the cap and continual airborne deposition replacing fine sediments that are resuspended themselves and subsequently dispersed offsite. The second scenario was one in which gullies were formed that, depending on the DU waste disposal configuration, might intersect and expose the DU waste to the environment.

In version 3.0 of the Model, which supports the results described herein, modeling is conducted under the assumption that gullies will occur on the embankment. Additionally, the only DU waste configuration presently evaluated is for disposal of these wastes in layers of the embankment below the current grade of surrounding soil. Dose results for each type of potential receptor are presented in Table ES-1.

There is a question of which statistic from the many Model realizations is most appropriate for comparison to performance criteria. The statistics in Table ES-1 represent summaries of the mean, median, and 95th percentiles of the peak dose at 10,000 yr for the 10,000 realizations. The peak of the mean dose is recommended by NRC for comparison with performance objectives (NRC 2006). However, the GoldSim model structure typically presents peak dose across time as a result; thus, when comparing across model realizations the result is a mean of the peaks. In the DU PA, the peak dose occurs at or near 10 ky in nearly all realizations. In effect, 10 ky is the worst-case year in terms of dose. Under these circumstances, the 95th percentile is analogous to the 95% upper confidence interval of the mean at 10 ky that is commonly used to represent reasonable maximum exposure in CERCLA risk assessments. In other words, because the peak dose occurs in the same time step in each model realization, the peak of the mean dose is equivalent to the mean of the peaks. Thus, for the DU PA, the distinction is moot.

Compliance with the performance objectives for the inadvertent intruder dose of 500 mrem in a year and for the MOP of 25 mrem in a year is clearly established for all three types of potential future receptors. This indicates that, for the disposal configuration where DU wastes are placed below grade, doses are expected to remain well below applicable dose thresholds even if gullies are assumed to occur on the embankment.

Results are also available for the offsite (MOP) receptors. None of the 95th percentile dose estimates for these receptors exceeds 0.1 mrem in a year, and all of the peak mean dose estimates are also at or below 0.1 mrem in a year.

Table ES-1. Peak TEDE: statistical summary.

receptor	peak TEDE (mrem/yr) within 10,000 yr		
	mean	median (50th %ile)	95th %ile
ranch worker	3.1E-2	2.5E-2	7.3E-2
hunter	2.7E-3	2.1E-3	6.8E-3
OHV enthusiast	4.0E-3	3.5E-3	8.7E-3

Results are based on 10,000 realizations of the Model.
TEDE: Total effective dose equivalent

For those radionuclides for which GWPLs exist, as specified in the facility's permit (Utah 2014), results are shown in Table ES-2. For all such radionuclides compliance with the GWPLs is clearly demonstrated. The mean values for ^{99}Tc and ^{129}I are much greater than the median, indicating that the distributions of these concentrations have a very strong degree of skewness.

Table ES-2. Peak groundwater activity concentrations within 500 yr, compared to GWPLs.

radionuclide	GWPL[1] (pCi/L)	peak activity concentration within 500 yr (pCi/L)		
		mean	median (50th %ile)	95th %ile
^{90}Sr	42	0	0	0
^{99}Tc	3790	24	3.1E-1	135
^{129}I	21	9.9E-3	5.7E-9	6.2E-2
^{230}Th	83	1.8E-28	0	9.1E-33
^{232}Th	92	1.4E-34	0	0
^{237}Np	7	8.6E-21	0	7.1E-27
^{233}U	26	1.6E-23	0	3.1E-27
^{234}U	26	1.0E-22	0	4.8E-27
^{235}U	27	8.0E-24	0	4.1E-28
^{236}U	27	1.5E-23	0	6.6E-28
^{238}U	26	7.6E-22	0	3.9E-26

[1]GWPLs are from Utah (2014), Table 1A.
Results are based on 10,000 realizations of the Model.

Sensitivity analyses on the Model results indicate that receptor doses are dominated by radon inhalation, whereas the downward migration pathway is dominated by net infiltration and molecular diffusion. A trade-off is indicated in terms of DU waste placement. The lower the DU waste is placed, particularly the ^{99}Tc-contaminated DU waste, the greater the groundwater concentrations of ^{99}Tc, but the lower the doses due to increases in the diffusion path length to the ground surface. Conversely, the higher the DU waste is placed in the embankment, the lower the ^{99}Tc groundwater concentrations, and the greater the dose to receptors. Placement of DU waste below surface grade in the Federal Cell satisfies both dose and groundwater performance objectives.

In addition to the dose assessment for hypothetical individuals described above, the structure of the Model allows the cumulative population dose to be tracked. For the objective of keeping doses as low as reasonably achievable (ALARA), estimated dose to the entire population of ranch workers, hunters, and OHV enthusiasts over the 10,000-yr simulation is evaluated. These cumulative population doses are shown in Table ES-3.

The population doses presented in Table ES-3 may be evaluated relative to doses received from natural background radiation and by considering the person-rem costs suggested in NRC (2015) guidance. The NRC has suggested the value of a statistical life (VSL)-based cost of $5,100 per person rem. Using such a cost, the total ALARA cost over 10 ky (for example, $29,580 using the mean estimate of total population dose, or $3 per yr.) is very small compared to the cost of waste operations and disposal. Average annual individual background dose related to natural background radiation in the United States is approximately 3.1 mSv (310 mrem; NCRP (2009)), which for the total cumulative receptor population of about 3,200,000 individuals over 10,000 years is approximately 992,000 rem—a level that is many orders of magnitude greater than the population doses shown in Table ES-3. ALARA is intended to support evaluation of options to reduce doses in a cost-effective manner. Given the results of this ALARA analysis, it is not clear that further reduction in dose would have a net benefit.

Table ES-3. Cumulative population TEDE: statistical summary.

receptor type	population TEDE (person-rem) within 10,000 yr		
	mean	median (50th %ile)	95th %ile
total population	5.5	4.9	11
ranch worker	1.2	1.1	2.6
hunter	0.76	0.64	1.8
OHV enthusiast	3.5	3.1	7.3

Results are based on 10,000 realizations of the Model.
TEDE: Total effective dose equivalent

The final set of analyses conducted with the Model are the deep time analyses. As described above, the deep time model is very conservative in many ways with respect to dispersal of the DU waste material. Deep lakes that obliterate the Federal Cell are assumed to return periodically. Simplified processes are used to keep the deep time model from becoming overly complicated for the amount of uncertainty in both parameters and processes.

Concentrations of ^{238}U in lake water and sediment at the time of peak lake occurrence (82,500 years) are presented in Table ES-4 and Table ES-5. These results simply show the concentrations that might occur in response to obliteration of the site by wave action during return of a lake to the elevation of Clive and subsequent dispersal of the waste in a relatively confined system. The concentrations presented would continue to decrease with each lake and climate cycle as more sediment is deposited with each lake event, and each lake event allows radionuclides to be dispersed ever further afield.

Table ES-4. Statistical summary of lake water concentrations at peak lake occurrence, 82,500 yr.

| radionuclide | Lake concentrations (pCi/L) at 82,500 yr | | |
	mean	median (50th %ile)	95th %ile
uranium-238	4.6E-3	2.4E-5	0.023
radium-226	1.5	0.74	5.3
thorium-230	1.5	0.76	5.4

Results are based on 1,000 simulations of the Model.

Table ES-5. Statistical summary of sediment concentrations at peak lake occurrence, 82,500 yr.

| radionuclide | Sediment concentrations (pCi/g) at 82,500 yr | | |
	mean	median (50th %ile)	95th %ile
uranium-238	0.10	0.039	0.38
radium-226	0.014	6.2E-3	0.050
thorium-230	0.014	6.3E-3	0.051

Results are based on 1,000 simulations of the Model.

The deep time model disperses radionuclides that have migrated upward from the DU waste into above-ground layers of the embankment prior to the occurrence of the first returning lake. Because all DU waste is modeled to be disposed below grade, the model assumes that no material below grade is dispersed. In addition, the return of the first lake is considered likely to be several tens of thousands of years, or even a few hundreds of thousands of years, into the future, at which point eolian deposition will result in sedimentation deposits around the site of several meters. This deposition will both stabilize the site and make it even less likely that any below-grade material will be dispersed. Based on these results, it is reasonable to expect that the deep time concentrations could be close to or possibly less than background concentrations for uranium in soil of about 1 pCi/g (Myrick et al. (1981), Table 30) and approximately 2 pCi/L for background uranium concentrations in the Great Salt Lake (CRWQCB (1990), Table 5).

The quantitative results for all Model analyses are summarized in Table ES-6. Doses to all receptors are always less than the 500-mrem (IHI) and 25-mrem (MOP) annual performance criteria. Groundwater concentrations are always less than the GWPLs. Even in the case of ^{99}Tc, the peak median, mean, and 95% groundwater concentrations are well below the GWPL of 3,790 pCi/L.

Table ES-6. Summary of the results of the Clive DU PA Model.

performance objective	meets performance objective?
Dose to MOP below regulatory threshold of 25 mrem in a year	Yes
Dose to IHI below regulatory threshold of 500 mrem in a year	Yes
Groundwater maximum concentration of ^{99}Tc in 500 years < 3790 pCi/L	Yes
ALARA average total population cost equivalent over 10,000 years:	$28,050

The results overall demonstrate that the below-grade disposal configuration can be used to dispose of the quantities and types of DU waste included in the Model in a manner adequately protective of human health and the environment.

1.0   Background

One of the responsibilities of the Nuclear Regulatory Commission (NRC) is to ensure the safe disposal of commercially generated low-level radioactive waste. Non-defense-related depleted uranium (DU) waste falls under the jurisdiction of NRC, and requires a disposal option that is protective of human health and the environment. NRC currently regulates the disposal of DU waste as a low-level radioactive waste, in cooperation with "Agreement States." The Energy*Solutions* low-level radioactive waste disposal facility at Clive, Utah, is a candidate for disposal of DU waste, and Utah is an Agreement State that has regulatory authority to determine if such disposal can occur in compliance with Utah and NRC regulatory requirements.

A facility's ability to ensure protection of human health and the environment is evaluated by conducting a Performance Assessment (PA). A PA is used to model potential transport of radionuclides from the disposed inventory to the accessible environment, and to estimate radiation dose to potential human receptors. The estimated doses are compared to performance objectives, which are specified as dose limits. If the estimated doses are less than the performance objectives, then adequate protection of human health has been demonstrated.

The purpose of this report is to present the results of the Clive DU PA Model v3.0 (the Model), a computer model developed to inform PA for disposal of specific DU waste materials in the proposed Federal Cell at the Clive Facility. This report provides a summary of the approach taken and the results that can be obtained from the Model, and references supporting documentation that includes details of the Model development and quality assurance program.

1.1   Depleted Uranium

In order to produce suitable fuel for nuclear reactors and/or weapons, uranium has to be enriched in the fissionable ^{235}U isotope. Uranium enrichment in the U.S. began during the Manhattan Project in World War II. Enrichment for civilian and military uses continued after the war under the U.S. Atomic Energy Commission, and its successor agencies, including the DOE.

The uranium fuel cycle begins by extracting and milling natural uranium ore to produce "yellow cake," which is a varying mixture of uranium oxides. Low-grade natural ores contain about 0.05 to 0.3% by weight of uranium oxide while high-grade natural ores can contain up to 70% by weight of uranium oxide. Uranium found in natural ores contains two principal isotopes—uranium-238 (99.3% ^{238}U) and uranium-235 (0.7% ^{235}U). The uranium is enriched in ^{235}U before being made into nuclear fuel, which generates a product consisting of 3% to 5% ^{235}U for use as nuclear fuel and a by-product of DU (between 0.1% and 0.5 ^{235}U). The DU has some commercial applications including counterweights and military applications as artillery. However, the commercial demand for depleted uranium is currently much less than the amounts generated for nuclear fuel. Use of ^{238}U as fuel for breeder reactors has not been seriously considered in this country. The U.S. Department of Energy (DOE) has about 700 Gg (700,000 Mg or metric tons) of DUF_6 in storage, containing roughly 464 Gg of uranium. Hence, the need to find disposal options for DU waste.

1.2 The Clive Waste Disposal Facility

Energy*Solutions* operates a low-level radioactive waste disposal facility west of the Cedar Mountains in Clive, Utah, as shown in Figure 1. Clive is located along Interstate-80, approximately 5 km (3 mi) south of the highway, in Tooele County. The facility is approximately 80 km (50 mi) east of Wendover, Utah, and approximately 100 km (60 mi) west of Salt Lake City, Utah. The facility sits at an elevation of approximately 1302 m (4275 ft) above mean sea level (amsl) and is accessed by both road and rail transportation.

The Clive Facility receives low-level radioactive waste shipped via truck and rail. The Clive disposal facility is licensed to accept Class A low-level radioactive waste. Under current NRC regulations, DU waste is considered Class A waste, in which case the Clive site is an option for disposal. However, NRC is currently considering options for updating 10 CFR 61, and the State of Utah has updated their regulations (UAC-R313-25-9 (UAC 2018)), which force the requirement of a PA for disposal of large quantities of DU. Based in part on a PA demonstrating the facility's ability to comply with performance objectives, Energy*Solutions* proposes that large quantities of DU waste be disposed in the Federal Cell. This is an above-ground engineered disposal embankment that is clay-lined with clay barriers and an ET cover on its top slope and riprap erosion control cover on its side slope. The disposal embankment is designed to perform for a minimum of 500 years based on requirements of 10 CFR 61.7, and hence provides a possible solution for the long-term disposal of DU.

Clive is a remote and environmentally inhospitable area. Human activity at Clive has, historically, been very limited. The regulations (10 CFR 61 and Utah regulations R313-25-9) indicate the need to evaluate performance with respect to members of the public and inadvertent human intruders. However, the difference between these two categories of human receptors is somewhat blurred because of the types of human activities that are reasonable to consider in the general area of the disposal facility. These two categories of receptors are described further below in the regulatory context of the Clive DU PA.

1.3 Regulatory Context

Energy*Solutions* is permitted by the State of Utah to receive Class A Low Level under Utah Administrative Code (UAC) R313 25, *License Requirements for Land Disposal of Radioactive Waste.* The wastes that are received must be classified in accordance with the UAC R313 15 1009, *Classification and Characteristics of Low-Level Radioactive Waste.* The classification requirements in UAC R313-15-1009 reflect those outlined in NRC's 10 CFR 61 Section 55, but include additional references to radium 226 (^{226}Ra). Further, groundwater protection levels (GWPLs) must be adhered to, as outlined in the site's *Ground Water Quality Discharge Permit* (Utah 2014).

Title 10 CFR 61 (CFR 2014) is the Federal regulation for the disposal of certain radioactive wastes, including land disposal at privately-operated facilities such as that operated by Energy*Solutions* at Clive, Utah. It contains procedural requirements, performance objectives, and technical requirements for near-surface disposal, including disposal in engineered facilities with protective earthen covers, which may be built fully or partially above-grade. Near-surface

disposal is defined as disposal in or within the upper 30 m (100 ft) of the earth's surface (10 CFR 61.2).

Figure 1. Location of the Clive site operated by Energy*Solutions* (base image from Google Earth).

A facility's compliance with performance objectives is evaluated by preparing a PA model. DU presents an interesting case because the uranium is nearly all [238]U, meaning that secular equilibrium is not attained for more than 2 My, and, during that time, activity associated with the DU continues to increase due to ingrowth of progeny from [238]U. At the time of the development of the regulation, DU waste as such did not, and was not expected to, exist in significant quantities. The nature of the radiological hazards associated with DU presents challenges to the estimation of long-term effects from its disposal. Recognition of this special behavior of DU has prompted the NRC to revisit the regulation. Revision of 10 CFR 61 has been underway since 2010 but is not complete. In the interim, Utah has updated UAC R313-25-9 to require specific PA for the disposal of significant quantities of DU.

The key endpoints of a PA are estimated future potential doses to members of the public (MOP). The performance objectives specified in Subpart C of 10 CFR 61 are in the following section:

> **§ 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.

The location of a member of the public (MOP) is not defined clearly in the NRC statute. Under
DOE Order 435.1 the MOP is defined as someone who does not access the disposal facility, but
is located outside of the fence line or boundary of the facility. However, NRC does not similarly
define an MOP, unless the disposal facility is not considered part of the natural environment.
Otherwise, an MOP is not restricted other than through the activities in which the MOP might
engage.

In addition to addressing MOP, 10 CFR 61 requires additional assurance of protecting individuals
from the consequences of inadvertent intrusion. An inadvertent intruder is someone who is
exposed to waste without intent, and without realizing that exposure might occur (after loss of
institutional control). This is distinct from the intentional intruder, who might be interested in
deliberately disturbing the site, or extracting materials from it, or who might be driven by
curiosity or scientific interest. Intentional intruders are not evaluated in a PA.

> **§ 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.

The distinction between MOP and an inadvertent intruder is clear in DOE Order 435.1, but is not
as clear in NRC 10 CFR 61. Under DOE Orders, a MOP does not engage in activities within the
boundaries of the disposal facility, and an inadvertent intruder inadvertently accesses the waste
material directly. Consequently, the locations of MOP and intruder are different under DOE
Orders. However, the NRC indicates that an inadvertent intruder is defined as follows:

> **§ 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.

Because of the remoteness of the Clive Facility and, hence, the types of activities in which
humans might engage, the distinction is made for this PA that ranchers, hunters, and OHV
enthusiasts are inadvertent intruders because they "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." This facility is regulated under NRC, in which case the
definitions in 10 CFR 61 are most relevant. However, it is noted that the ranchers, hunters, and
OHV enthusiasts do not intrude into the waste to create a direct exposure. Other receptors
evaluated in the PA Model who are located offsite are regarded as MOPs. The results of this

Model are calculated without regard for MOP and IHI categorization. The Model simply evaluates dose to each receptor, providing the information necessary for comparison with performance objectives.

No dose limit is specified in 10 CFR 61 for the inadvertent intruder. However, since Part 61 has been issued, the standard used by NRC and others for LLW disposal licensing has been an annual dose of 500 mrem. The 500 mrem-in-a-year standard is also used in the DOE waste determinations implementing the Part 61 performance objectives (NUREG-1854), and as part of the license termination rule dose standard for intruders (10 CFR 20.1403).

The scope of a PA may be limited to the evaluation of MOP and inadvertent intrusion, and also to the issue of site stability. The performance standard for stability requires the facility to be sited, designed, and closed to achieve long-term stability to eliminate to the extent practicable the need for ongoing active maintenance of the site following closure. The intent was to provide reasonable assurance that long-term stability of the disposed waste and the disposal site will be achieved. To help achieve stability, the NRC suggested to the extent practicable that disposed waste should maintain gross physical properties and identity over 300 years, under the conditions of disposal, with a further suggestion that the disposal facility should be evaluated for at least a 500-year time frame. About the same time as Part 61 was promulgated, the NRC also put in place requirements for design of uranium mill tailings piles such as the Vitro site which is collocated with the Clive Facility. The NRC specified that the design shall provide reasonable assurance of control of radiological hazards to be effective for 1,000 years to the extent reasonably achievable, and, in any case, for at least 200 years.

This raises the issue of appropriate compliance periods for a waste form that does not reach peak radioactivity for more than 2 My. Section 2(a) of R313-25-9(5)(a) states:

> For purposes of this performance assessment, the compliance period shall be a minimum of 10,000 years. Additional simulations shall be performed for the period where peak dose occurs and the results shall be analyzed qualitatively.

The intent of this Model, therefore, is to evaluate impacts to receptors for a period of 10,000 years, and long-term performance of the disposal system beyond that time. The regulation does not address time frame for site stability. Given the long period of time before DU reaches secular equilibrium, it is difficult to determine when peak dose might occur. Consequently, the Clive DU PA Model has been implemented quantitatively for 10 ky, and has run additional simulations for 2.1 My, the time at which DU reaches peak activity. The results of the PA Model will be used to inform decisions about the suitability of the Clive Facility for disposal of DU waste, the amount of DU waste that can be disposed safely, and different options for the engineered design and the placement of the waste within the disposal system. These decisions will be made in light of the doses to the receptors identified for the Model, groundwater concentrations of ^{99}Tc and other radionuclides, and the long-term effects on site stability and dispersal of DU waste in returning lakes and lake sediment.

Site stability might also be considered to be a qualitative criterion for evaluating the concept of maintaining receptor impacts to be "as low as reasonably achievable" (ALARA). However, 10 CFR 20.1003 defines ALARA in the context of dose to populations. In addition, 10 CFR 61.42 states that "reasonable effort should be made to maintain releases of radioactivity in effluents to

the general environment as low as is reasonably achievable." The ALARA process is described in more detail in the white paper *Decision Analysis Methodology for Assessing ALARA Collective Radiation Doses and Risks* (Neptune 2021d). ALARA is evaluated in terms of population doses for the design options that are considered. This allows design options to be compared, and, ultimately, to be optimized. NRC suggests a value of $5,100 for the cost per person rem, with a possible range of $3000 to $7500 (NRC 2015).

In addition to the radiological criteria, the State of Utah imposes limits on groundwater contamination, as stated in the Ground Water Quality Discharge Permit (Utah 2014). Part I.C.1 of the Permit specifies that GWPLs in Table 1A of the Permit shall be used for the Class A LLW Cell. Table 1A in the Permit specifies general mass and radioactivity concentrations for several constituents of interest to DU waste disposal. These GWPLs are derived from Ground Water Quality Standards listed in UAC R317-6-2 *Ground Water Quality Standards*. Exceptions to values in that table are provided for specific constituents in specific wells, tabulated in Table 1B of the Permit. This includes values for mass concentration of total uranium, radium, and gross alpha and beta radioactivity concentrations for specific wells where background values were found to be in exceedance of the Table 1A limits.

As specified in the Permit, groundwater at Clive is classified as Class IV, saline ground water (according to UAC R317-6-3 *Ground Water Classes*)*,* and is highly unlikely to serve as a future water source. The underlying groundwater in the vicinity of the Clive site is of naturally poor quality because of its high salinity and, as a consequence, is not suitable for most human uses, and is not potable for humans. However, the Clive DU PA Model calculates estimates of groundwater concentrations at a virtual well near the Federal Cell for comparison with these GWPLs. Part I.D.1 of the Permit specifies that the performance standard for radionuclides is 500 years.

1.4   Performance Assessment

Within the regulatory framework described above, a PA addresses doses to potential human receptors within a time frame of compliance. The Clive DU PA Model also addresses performance of the system for approximately 2.1 My—until secular equilibrium of ^{238}U and its decay products is reached. The PA process starts with the regulatory context but is itself a decision support process. Decisions may be made based on the results of the PA modeling that is performed. In the context of decision analysis, this requires steps that include the following:

1. State a problem,
2. Identify objectives (and measures of those objectives—i.e., attributes or criteria),
3. Identify decision alternatives or options,
4. Gather relevant information, decompose and model the problem (structure, uncertainty, preferences),
5. Choose the "best" alternative (the option that maximizes the overall benefit),
6. Conduct uncertainty analysis, sensitivity analysis, and value of information analysis to determine if the decision should be made, or if more data/information should be collected to reduce uncertainty and, hence, increase confidence in the decision, and
7. Go back (iterate) if more data/information are collected.

The problem addressed here is one of potential disposal of DU waste at the Clive Facility. The objectives are to minimize risk to human health and the environment. Risk is measured in terms of dose and uranium toxicity hazard to the human receptors that are identified for analysis. The decision options that are evaluated relate to different waste configuration options for DU waste disposal. Given that context, the next step of the PA process is to gather information, and to build a PA model. There are several steps involved, each one building on the previous step. The modeling process starts with evaluating features, events, and processes (FEPs) that might be important for evaluating performance, and using the FEPs analysis to build a conceptual site model (CSM). These steps are described in full in the *FEP Analysis for Disposal of Depleted Uranium at the Clive Facility* (Neptune 2021k), and the *Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility* (Neptune 2021f).

Development of the CSM sets the stage for subsequent model structuring, which is the first step needed to build the numerical model of the system. All relevant FEPs are captured in the model structure, from waste inventory, mechanisms for transport through the engineered system, and migration through the natural environment to the accessible environment, to identification of human receptors, exposure pathways, and dose assessment. The model structure leads to specification of the model. Probability distributions are specified for each input parameter. The type of information available for each input parameter is highly variable, hence requiring varied approaches for specification. Different methods that are used are described in the white paper *Fitting Probability Distributions* (Neptune 2021e).

Model structuring and specification completes the numerical model. The model is computed using the GoldSim systems analysis software (GTG 2021). GoldSim is probabilistic simulation software that includes a graphical user-interface that is convenient for developing PA models. GoldSim is inherently a systems-level software framework. The focus of a GoldSim model is on the decision-making process, which includes managing uncertainty and coupling all processes. This PA model is intended to reflect the current state of knowledge with respect to the proposed DU disposal, and to support environmental decision making in light of inherent uncertainties.

The development of the model is iterative, where the iterations depend on model evaluation, which is performed at various levels. During model construction the model is evaluated iteratively as new components are added. Once a complete model is assembled, the model is then subjected to uncertainty and sensitivity analysis. The goals of the uncertainty analysis are to evaluate results against the performance objectives and to understand the values of the results with respect to the model formation. The sensitivity analysis is used to identify components of the model that are most influential on the output. This leads to model iteration as suggested in Step 7 above.

Building a model to inform PA is a large undertaking. There are many intricacies that must be accommodated starting with development of FEPs, moving through the CSM, mathematical abstraction of environmental processes, numerical model structuring, development of probability distributions for the input parameters, and model evaluation. This complex process is described briefly in this document, and is described in more detail in the supporting documents (see white papers). In addition to complete documentation, the GoldSim model itself is fully contained, with internal documentation of every aspect of the model structure. The extensive documentation is provided for two reasons: The first is simply that it provides access to all information used in the

Model. This is done in the spirit of openness, transparency, and, hence, defensibility. The second is in the context of the quality assurance program that requires tracking of all information from its source through to the final model. The QA program implemented for this Model is described in full in the *Quality Assurance Project Plan* (Neptune 2023e).

1.5   Technical Evolution of PA and PA Modeling

Since PA modeling began in the late 1970s through the early 1990s at many of the radioactive waste disposal facilities around the U.S., many different approaches to modeling have been used. These approaches span the range from deterministic process-level modeling to probabilistic systems-level modeling. Early PA models tended towards deterministic modeling for several reasons: 1) PA modeling was initially performed with a focus on groundwater modeling, which was, and still is, often performed using deterministic process-level models; 2) there were computational or technological difficulties with taking a probabilistic approach; and 3) PA regulations and guidance were established mostly with deterministic performance objectives, which was interpreted as a reason for performing deterministic modeling. In particular, PA for low-level radioactive waste (LLW) disposal facilities followed deterministic performance objectives. However, the regulations for the Waste Isolation Pilot Plant and the Yucca Mountain Project (YMP) (Title 40, *Code of Federal Regulations* (CFR), Part 191, "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes," and Title 40, CFR Part 197, "Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada") provide an exception to the deterministic objectives, and, consequently, probabilistic PA models have been developed for these radioactive waste disposal facilities.

Technological advances in the last decade have also allowed more PA modeling to move towards a probabilistic approach. Finally, PA modeling is multi-disciplinary, and as more technical disciplines have been brought into PA modeling, there has been increased recognition of the potential benefits of probabilistic systems-level modeling.

Systems-level models are usually computationally simpler than process-level models. However, the systems-level PA model might still have large numbers of parameters, which reveals the complexity of dealing with PA modeling even at a systems-level scale. The large number of parameters is a consequence of the many constituents of concern that are usually included in PA models, and the need to characterize transport properties for each of these constituents (e.g., partitioning coefficients, solubility, plant uptake factors). However, it is unlikely that more than a few of these parameters are important predictors for a given PA endpoint (e.g., dose to a member of the public, groundwater protection levels). Along these lines, another advantage of systems-level modeling performed in a probabilistic environment is the ability to identify parameters that are most important or sensitive for a given endpoint. Because system-level models may be probabilistic, global sensitivity analysis methods can be used to identify the most sensitive parameters (see the white paper *Machine Learning for Sensitivity Analysis of Probabilistic Environmental Models* (Neptune 2023f)).

The advantages of system-level models are that they are capable of 1) coupling of different processes without the need for the application of ad hoc boundary conditions, 2) using an appropriate spatial and temporal scaling relative to the decisions that need to be made, 3) having

the ability to characterize and manage uncertainty through probabilistic modeling, and 4) being used to perform global sensitivity analysis. Use of the global sensitivity analysis can potentially lead to refinement and enhancements of the underlying models or the identification and collection of new data (e.g., research studies or monitoring) as necessary to reduce uncertainty of certain parameters or variables. Use of a system-level model can also provide the ability to rapidly and efficiently explore alternative conceptualizations of the system, which allows a greater ability to address scenario and conceptual model uncertainties.

System-level models are often supported by process-level models. Each component of a system-level model requires model building, which can include abstraction from a process-level model. The purpose of the abstraction is to be able to capture the essence of the process-level model in the probabilistic system-level model, so that its relative importance or sensitivity can be evaluated. As a consequence of the development of system-level modeling frameworks such as GoldSim, PA models are often developed following this approach, with global sensitivity analysis driving iteration until the model results indicate a clear response and decision path.

1.6   Report Structure

The remainder of this report provides a more complete introduction to the PA modeling process applied to the Clive DU waste disposal option, briefly describes the FEPs process, and follows with a brief description of the CSM. The CSM description is aimed at identifying components of the model that might be significant in the model results. Model building always leads to insights into the important components of a model, and that is conveyed in terms of important aspects of the CSM.

The model structure is described prior to presentation of results, which are the main focus of this report. Results are presented for the 10-ky quantitative model and for the deep time model. For the 10-ky model, the important results from a regulatory perspective include doses to the receptors that have been identified as critical. Groundwater concentrations are evaluated for the next 500 yrs. For the deep time model, which models the performance of disposal of DU at Clive for the next 2.1 My, results are presented in terms of lake water concentrations assuming the return of a deep pluvial lake in the Bonneville Basin, and sediment concentrations that remain after the pluvial lake recedes.

A summary is provided that includes further interpretation of results and comparison with performance objectives. More complete documentation of the details of the model development is contained in the white papers, and also in the GoldSim model itself. Taken together, these documents present and support the Clive DU PA Model v3.0.

2.0   Introduction

The safe storage and disposal of DU waste is essential for mitigating releases of radioactive materials and reducing exposures to humans and the environment. The Federal Cell, a radioactive waste facility located in Clive, Utah, and operated by Energy*Solutions,* is proposed to receive and store DU waste. The Clive Facility has been tasked with evaluating disposal of the DU waste in an economically feasible manner that protects humans from future radiological releases.

To assess whether the Clive Facility location and containment technologies are suitable for protection of human health, specific performance objectives for land disposal of radioactive waste set forth in UAC R313-25, must be met. These Utah requirements reflect and expand on similar requirements in Title 10 Code of Federal Regulations Part 61 (10 CFR 61) Subpart C, and promulgated by the Nuclear Regulatory Commission (NRC). In order to support the required radiological PA, a model is needed to evaluate doses to human receptors that would result from the disposal of DU and its associated radioactive contaminants.

This section provides an introduction to the general approach taken for developing the Clive DU PA Model. The focus is on methods that have been undertaken at each step along the path, from description of the problem and the disposal facility under consideration, FEPs identification, CSM development, approaches to numerical modeling, and evaluation of results.

2.1   General Approach

Performance Assessment models are complex probabilistic systems-level models that evaluate the long-term effects to human health and the environment of disposal of radioactive waste. The approach includes the following steps:

1. Identification of disposal options—in this case use of the Federal Cell at the Clive Facility in Utah for disposal of DU waste, and specifics of the disposal configuration. This includes consideration of the regulatory environment in which the PA model is to be evaluated.

2. Identification of important FEPs that should be considered in the evaluation of the Clive disposal facility. This includes identification of human receptors who might be engaged in activities near or on the disposal facility.

3. Development of a CSM that captures the relevant FEPs. This includes evaluation of the FEPs for the likelihood of occurrence and their consequence. If, for a given FEP, the likelihood of occurrence or consequence is considered too small, then the FEP is not included in the CSM.

4. Development of a numerical or computational model for the PA. This translates the CSM into numerical code for processing. This includes model structure and model specification. The Clive DU PA Model is developed fully probabilistically, with coupling of all processes included in the model.

5. Model evaluation, including:

   a. uncertainty analysis, which compares the probabilistic output to the performance objectives, and

   b. sensitivity analysis, which is used to identify the important parameters or components of the model in terms of prediction of the model output. This may lead to model refinement or data collection if the uncertainties in the decisions that need to be made are considered to be too large.

6. Reporting of the PA model and its results, including:

   a. doses to potential human receptors,
   b. population doses evaluated in the context of ALARA,

    c.   groundwater concentrations at a specified location, and

    d.   deep time concentrations in lake water and lake sediment.

  7.   Quality Assurance.

A PA is a type of systematic (risk) analysis that addresses what can happen, how likely it is to happen, what the resulting impacts are, and how these impacts compare to regulatory standards. The essential elements of a performance assessment are

- a description of the site and engineered system,
- an understanding of events and processes likely to affect long-term facility performance,
- a description of processes controlling the movement of contaminants from waste sources to the general environment,
- a computation of metrics reflecting system performance including concentrations, doses, and other human health risk metrics to members of the general population, and
- an evaluation of uncertainties in the modeling results that support the assessment.

The role of PA in a regulatory context is often restricted to the narrow use of evaluating compliance. In the present case, the Clive DU PA Model v3.0 can be used to evaluate compliance—and inform a PA document that presents the argument that demonstrates compliance—with the applicable provisions of the Utah Administrative Code. In addition to that role, however, and because of the long-term nature of the analysis, the intent of the Model is not to estimate actual long-term human health impacts or risks from a closed facility. We believe that it is technically inappropriate to view the model results in terms of actual long-term human health effects. The purpose of the Model is to provide a robust analysis that can examine and identify the key elements and components of the site, the engineered system, and the environmental setting that could contribute to potential long-term impacts. Because of the time-scales of the analysis and the associated uncertainty in knowledge of characteristics of the site, the waste inventory, the engineered system and its potential to degrade over time, and changing environmental conditions, a critical part of the PA process is also the consideration of uncertainty and evaluation of model and parameter sensitivity in interpretation of PA modeling results.

A probabilistic model includes a mathematical analysis of stochastic events or processes and their consequences. Probabilistic analysis acknowledges that events and processes are inherently uncertain, and involves characterization of uncertainty around expectation. Model output hence is expressed with the same characteristics of expectation and uncertainty, which lends itself to a global or probabilistic sensitivity analysis. Sensitivity analysis for probabilistic models is used to identify the parameters (variables) that are the most important predictors of the output for a given endpoint (e.g., dose to a resident, concentrations in groundwater). The important predictors are those that explain most of the variability in the output variable of interest. Usually, for a given endpoint of interest, this is no more than a handful of input or explanatory variables. Because PA models are usually complex, dynamic, non-linear systems, these global sensitivity analysis methods involve complex non-linear regression models that capture the impact of each input variable across its specified range (range of its probability distribution).

Performance Assessment concerns modeling radioactive waste disposal facilities into the long-term future. As such, PA models must address both the spatial and temporal magnitude of PA. It is critical in a PA model to address the scale of the decisions that need to be made. Modeling is

performed at the spatial and temporal scale that is needed to support PA decisions related to closure. In effect, system-level models might be fairly coarse, but this has advantages for evaluating how the system evolves over time. For example, all processes involved are fully coupled in the same model; probabilistic modeling can be performed to both characterize and manage uncertainty; and statistics and decision analysis can be incorporated into the modeling framework.

Results from a systems-level model are aimed at the decision objectives at the spatial and temporal scales of interest. These results are presented as probability distributions for the endpoints of interest (peak doses, concentrations, etc.), and comparisons are made with performance objectives where appropriate (dose, groundwater concentrations).

Given the PA model construction with respect to the spatio-temporal scales of the model, there are two levels of response. The first is for each hypothetical individual included in the model; and the second is at a population level for the ALARA analysis. Dose results are available for each receptor in every year of the model, up to 10 ky. Each dose result at this level represents individual doses resulting from the concentrations in various exposure media predicted by the model at that time. The dose parameters, however, are specific to the individual. This approach to modeling dose was taken for a few reasons: 1) There are not many receptors at Clive, in which case, from a computational perspective it was feasible to consider each individual receptor, and 2) this approach allows population dose to be estimated directly from the individual doses.

Although individual peak doses are available in the model, the output of interest is the mean dose. Traditionally this has been estimated as the mean dose to a hypothetical average individual. With this model, the mean dose is estimated directly from the individual doses. Mean doses are evaluated in each year of the model, but, traditionally for PA, interest lies primarily in the worst-case year, in which case the peak mean dose across time is the metric of interest.

The effect is that average (mean) doses are available at multiple scales. Traditional comparison with performance objectives is performed with the peak mean dose, meaning the highest mean dose in a year across the 10-ky performance period. In this model, for which radioactivity is increasing with time for the DU waste, the greatest dose almost always occurs at 10 ky, and the highest groundwater concentrations at 500 years. So peak mean dose results at 10 ky are presented. Note that there will be 10,000 estimates of dose for each receptor if 10,000 realizations are run. This is usually enough simulations to stabilize an estimate of the mean. The dose assessment model is described in detail in the white paper *Dose Assessment for the Clive DU PA* (Neptune 2021b).

If the distribution of the peak of the means is treated as if each simulation result is independent, then the 95th percentile of the distribution is somewhat analogous to the notion of a 95% upper confidence interval that is commonly used under CERCLA. Comparisons may be made with the PA performance objectives using the median, mean, and 95th percentile of the output distribution for each endpoint of interest.

For the ALARA analysis, the model is set up so that the population dose can be estimated for each receptor class in each year of the model. The 10,000 realizations provide 10,000 estimates of population dose in each year of the model. The population dose distribution can also be processed to include the cost to human health and society by assigning a dollar value to

person-rem. This process is described in detail in the *Decision Analysis* white paper (Neptune 2021d).

Once the results are obtained and compared to the performance objectives, a global sensitivity analysis is performed to identify the parameters that are the most influential in predicting each endpoint of interest. Often this is only a handful of parameters for each endpoint. The results of the sensitivity analysis can be used to determine if it might be useful to collect more data or to otherwise refine the model before making final decisions. This is ostensibly a decision analysis task, which can be performed using the sensitivity analysis results as a basis for determining the benefit of collecting new data. The potential benefits would be seen in reduction in uncertainty in the model results. The sensitivity analysis methods used for this model are described in the white paper *Machine Learning for Sensitivity Analysis of Probabilistic Environmental Models* (Neptune 2023f).

This holistic approach to PA modeling is aimed at providing insights into disposal system performance. Although the model predicts or estimates doses to human receptors, among other endpoints, the more important aspect of this type of modeling is to gain an understanding of how the system might evolve over the time frames of interest, and to use this understanding to support decision making including the ability to safely dispose of waste and optimization of waste placement within the disposal system. No matter what doses are predicted, it is important to understand why those modeled doses are observed, and hence, what are the important features of the disposal system with regards to protection of human health and the environment.

2.2   General Facility Description

The Energy*Solutions* low-level radioactive waste disposal facility is west of the Cedar Mountains in Clive, Utah, as shown in Figure 1. Clive is located along Interstate-80, approximately 5 km (3 mi) south of the highway, in Tooele County. The facility is approximately 80 km (50 mi) east of Wendover, Utah, and approximately 100 km (60 mi) west of Salt Lake City, Utah. The facility sits at an elevation of approximately 1302 m (4275 ft) above mean sea level (amsl). The Clive Facility is adjacent to the above-ground disposal cell used for uranium mill tailings that were removed from the former Vitro Chemical company site in South Salt Lake City between 1984 and 1988 (Baird et al. 1990).

The Clive Facility receives waste shipped via truck and rail. DU waste is proposed to be disposed in the Federal Cell (Figure 2), a permanent engineered disposal embankment that will be clay-lined with composite clay barriers and an ET cover over the top slope, and a riprap cover over the side slopes. The disposal embankment is designed to perform for a minimum of 500 years. The Clive Facility includes the following:

- the Bulk Waste Facility, including the Mixed Waste, Low Activity Radioactive Waste (LARW), 11e.(2), and Class A LLW disposal cells plus support facilities,
- the Containerized Waste Facility (CWF), located within the Class A LLW area, and
- the Treatment Facility (TF), located in the southeast corner of the Mixed Waste area.

The DU waste under consideration is proposed for disposal in the Federal Cell. The terms "cell" and "embankment" are here used interchangeably. The DU PA Model v3.0 considers only the

long-term performance of DU disposed in this waste cell. The Federal Cell is next to the 11e.(2) cell, which is licensed for disposal of uranium processing by-product waste and is not considered in this analysis.
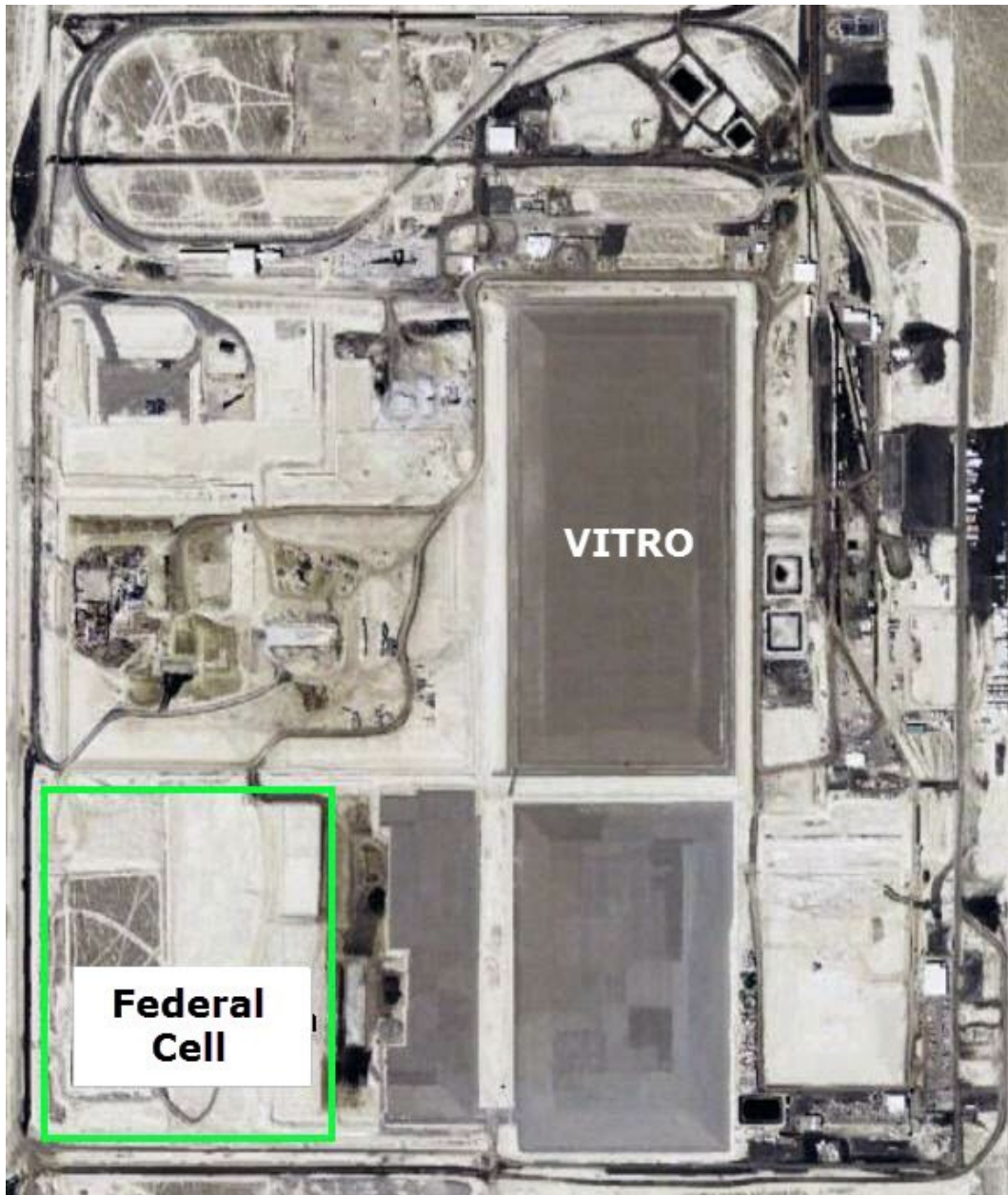
Figure 2. The Energy*Solutions* Clive site, with the Federal Cell location indicated.

The general aspect of the Federal Cell is that of a hipped cap, with relatively steeper sloping sides nearer the edges. The upper part of the embankment, known as the top slope, has a moderate slope, while the side slope is markedly steeper (20% as opposed to 2.4%). For DU PA v3.0, no waste is placed under the side slopes, in which case modeling focuses on waste placed under the top slope. The embankment is also constructed such that a portion of it lies below-grade; and this represents the modeled disposal location for DU. Details of the design of the embankment are contained in the white paper *Embankment Modeling for the Clive DU PA* (Neptune 2021a).

DU waste from the Savannah River Site (SRS) and the gaseous diffusion plants (GDP) at Portsmouth, Ohio and Paducah, Kentucky is proposed for disposal at the Clive facility. Three categories of DU waste are considered:

1. Depleted uranium oxide (UO_3) waste from the Savannah River Site (SRS) presently on site at the Clive facility,

2. DU from the GDPs, which exists in two principal populations:

   a) DU contaminated with fission and activation products from reactor returns introduced to the diffusion cascades, and

   b) DU consisting of only "clean" uranium, with no such contamination.

The DU oxides that are to be produced at the GDP "deconversion" plants will be primarily U_3O_8. The contamination problem arises from the past practice of introducing irradiated nuclear materials (reactor returns) into the isotopic separations process. Irradiated nuclear fuel underwent a chemical separation process to remove the plutonium for use in nuclear weapons. Uranium, then thought to be a rare substance, was also separated out, but contained some residual contamination from activation and fission products. This uranium was again converted to UF_6 for re-enrichment, and was introduced to the gaseous diffusion cascades, contaminating them and the storage cylinders as well. Decay products (^{226}Ra), activation products (^{232}U, ^{233}U, ^{236}U, ^{241}Am, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu), and fission products (^{90}Sr, ^{99}Tc, ^{129}I, ^{137}Cs) potentially contaminate the DU waste. The proposed inventory evaluated in the Model is described fully in the white paper *Radioactive Waste Inventory for the Clive DU PA* (Neptune 2023g).

3.0   Features, Events, and Processes

The conceptual site model (CSM) describes the physical, chemical, and biological characteristics of the Clive Facility. The CSM, therefore, encompasses the inventory of disposed wastes, the migration of radionuclides contained in the waste through the engineered and natural systems, and the exposure and radiation doses to hypothetical future humans. These site characteristics are used to define variables for the quantitative PA model that is used to provide understanding of the future potential human radiation doses from the disposal of DU waste.

The content of the CSM informs the Model with respect to regional and site-specific features, events, and processes, such as climate, groundwater, and human receptor scenarios. The CSM accounts for and defines relevant features, events, and processes (FEPs) at the site, materials and their properties, interrelationships, and boundaries. These constitute the basis of the Model, on which, or through which, radionuclides are transported to locations where receptors might be exposed.

A key activity in developing a PA for a radiological waste repository is the comprehensive identification of relevant external factors that should be included in quantitative analyses. These factors, termed "features, events, and processes" (FEPs), form the basis for scenarios that are evaluated to assess site performance.

The universe of FEPs screened and identified as relevant for the Clive DU PA Model are documented in the white paper *FEP Analysis for Disposal of Depleted Uranium at the Clive Facility* (Neptune 2021k) and further elaborated in the CSM document (*Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility* (Neptune 2021f)).

4.0 Conceptual Site Model

Important components of the conceptual site model are described in the following sections. Details are contained in the white paper *Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility* (Neptune 2021f).

4.1.1 Disposal Site Location

Energy*Solutions* operates a low-level radioactive waste disposal facility west of the Cedar Mountains in Clive, Utah, as shown in Figure 1. Clive is located along Interstate-80, approximately 5 km (3 mi) south of the highway, in Tooele County. The facility is approximately 80 km (50 mi) east of Wendover, Utah, and approximately 100 km (60 mi) west of Salt Lake City, Utah. The facility sits at an elevation of approximately 1302 m (4275 ft) above mean sea level (amsl) and is accessed by both highway and rail transportation. The Clive Facility is adjacent to the above-ground disposal cell used for uranium mill tailings that were removed from the former Vitro Chemical company site in South Salt Lake City between 1984 and 1988 (Baird et al. 1990) (Figure 2).

4.1.2 Disposal Site Description

The Clive Facility receives waste shipped via truck and rail. DU waste is proposed for disposal in the Federal Cell, a permanent above-ground engineered disposal embankment that is clay-lined with clay barriers and an ET cover. The disposal embankment is designed to perform for a minimum of 500 years with minimal need for active maintenance after site closure. More detail relating to the properties of the disposal embankment is provided in Section 4.1.2.1.

The Energy*Solutions* Clive Facility is divided into the following areas: the Bulk Waste Facility, including the Mixed Waste, Low Activity Radioactive Waste (LARW), 11e.(2), and Class A LLW disposal cells; the Containerized Waste Facility (CWF), located within the Class A LLW area; and the Treatment Facility (TF), located in the southeast corner of the Mixed Waste area. This analysis considers only the Federal Cell (Figure 2).

4.1.2.1 Federal Cell

Depleted uranium waste is proposed for disposal in the Federal Cell. The Federal Cell is about 374 × 585 m (1226.5 × 1920 ft), with an area of approximately 22 ha (54 acres), and an estimated total waste volume of about 2 million m^3 (2.6 million yd^3). A drainage ditch surrounds the disposal cell. The cell is constructed on top of a compacted clay liner. Waste will be placed above the liner and will be covered with a layered engineered cover constructed of natural materials. The top slopes will be finished at a 2.4% grade while the side slopes will be no steeper than 5:1 (20% grade).

The design of the Federal Cell cover has been engineered to discourage erosion, to reduce the effects of infiltration, and to protect workers and the public from radionuclide exposure. The cell top slope cover consists of layers including two clay radon barriers, a frost protection layer, an evaporative zone layer, and a surface layer. The side slopes will have a riprap cover intended to discourage erosion. The clay radon barriers are designed to minimize infiltration of precipitation and runoff and to reduce the migration of radon from the waste cell. Further details on the Federal Cell design are provided in the *Embankment Modeling* white paper (Neptune 2021a).

4.1.2.2 Waste Inventory

The waste inventory is limited to the disposal of DU wastes of two general waste types:
1) depleted uranium trioxide (DUO_3) waste from the Savannah River Site (SRS) and
2) anticipated DU waste as U_3O_8 from gaseous diffusion plants (GDPs) at Portsmouth, Ohio and Paducah, Kentucky. The quantity and characteristics of DU waste from other sources that has previously been disposed in other embankments at the Clive Facility is not included. A full list of radionuclides has been established for the PA modeling effort. The radionuclide species list is based upon process knowledge, radionuclides analyzed for (though not necessarily detected) in the DU waste material, and decay products with half-lives over five years. The species list consists of the following radionuclides:

> *fission products*:
> Sr-90, Tc-99, I-129, Cs-137
>
> *progeny of uranium isotopes*:
> Pb-210, Rn-222, Ra-226, -228, Ac-227, Th-228, -229, -230, -232, Pa-231
>
> *uranium isotopes*:
> U-232, -233, -234, -235, -236, -238
>
> *transuranic radionuclides*:
> Np-237, Pu-239, -239, -240, -241, -242, Am-241

The waste inventory is discussed in more detail in the *Waste Inventory* white paper (Neptune 2023g) and in the *Conceptual Site Model* white paper (Neptune 2021f).

4.1.2.3 Climate

The following sections briefly describe the aspects of the regional climate that influence the performance of the site and engineered features. Further details are provided in the *Conceptual Site Model* white paper (Neptune 2021f), and in the *Unsaturated Zone Modeling* white paper (Neptune 2021c). In general, the climate is dry, with evapotranspiration potential that exceeds precipitation on an annual basis. This leads to low infiltration rates, and subsequent relatively slow movement of radionuclides to groundwater.

4.1.2.3.1 Temperature

Regional climate is regulated by the surrounding mountain ranges, which restrict movement of weather systems in the vicinity of the Clive Facility. The most influential feature affecting

regional climate is the presence of the Great Salt Lake, which can moderate downwind temperatures since it never freezes (NRC 1993). The climatic conditions at the Clive Facility are characterized by hot and dry summers, cool springs and falls, and moderately cold winters (NRC 1993). Frequent invasions of cold air are restricted by the mountain ranges in the area. Data from the Clive facility from 1993 to 2020 indicate that monthly temperatures range from about -2.9°C (26.8°F) in December to 26.6°C (79.9°F) in July (Trinity Consultants 2021).

4.1.2.3.2   Precipitation

The Clive Facility is characterized as being an arid to semi-arid environment where evaporation greatly exceeds annual precipitation (AdrianBrown 1997). Data collected at the Clive Facility from 1993 to 2020 indicate that average annual rainfall is on the order of 21.4 cm (8.4 in) per year (Trinity Consultants 2021). Precipitation generally reaches a maximum in the spring (1998-2020 monthly average of 3.2 cm [1.25 in] in April), when storms from the Pacific Ocean are strong enough to move over the mountains (NRC 1993; Whetstone Associates 2006). Precipitation is generally lighter during the summer and fall months (1998-2020 monthly average of 0.6 cm [0.25 in] in August) with snowfall occurring during the winter months (Trinity Consultants 2021).

4.1.2.3.3   Evaporation

Because of warm temperatures and low relative humidity, the Clive Facility is located in an area of high evaporation rates. NRC (1993) indicates that average annual pond evaporation rate at the Clive Facility is 150 cm/yr (59 in/yr), with the highest evaporation rates between the months of May and October. Previous modeling studies indicate that the Dugway climatological station nearby is comparable to the Clive site with respect to evaporation and have reported pan-evaporation estimates of 183 cm/yr (72 in/yr), which is considerably greater than average annual rainfall (AdrianBrown 1997). While the data range for the site is more limited, annual pan evaporation measured at the site greatly exceeds annual precipitation. Average annual pan evaporation is 139 cm (54 in) (Trinity Consultants 2021).

4.1.2.4   Unsaturated Zone

The engineered features of the landfill, including cap, waste, and liner, are all in the unsaturated zone (UZ)[1]. The part of the UZ that extends from the bottom of the cell liner to the water table consists of naturally occurring lake sediments from the ancestral Lake Bonneville.

Diffusion in the water phase may also play a role in the transport of waterborne contaminants in the UZ, since the advective flux is expected to be small. The concentration gradients in the UZ are also expected to be predominantly vertical, so diffusion will also occur in the vertical direction, oriented with the column of cells.

Diffusion in the air phase within the UZ below the facility will not be modeled, since the only diffusive species would be radon, which is of greater concern at the ground surface. Upward

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[1] The deep time model (*Deep Time Assessment for the Clive DU PA* (Neptune 2021h)) acknowledges the likelihood of intermediate and deep lakes returning to the Great Basin, including the Clive facility, during future glacial cycles, which are projected to occur well after the 10,000-yr duration of the quantitative model.

radon diffusion to the ground surface will be dominated by radon parents in the waste zone, and is modeled within the engineered cap. Unsaturated zone processes, material properties, and parameters represented in the PA model are described in detail in the *Unsaturated Zone Modeling* white paper (Neptune 2021c). The primary concerns for the PA are movement through the unsaturated zone of mobile radionuclides, such as ^{90}Sr, ^{99}Tc, and ^{129}I to groundwater and the upward diffusive movement of radon.

4.1.2.4.1 Infiltration

Recharge is an important process in controlling the release of contaminants to the groundwater pathway. Site characteristics influencing movement of water from precipitation through the vadose zone to the water table include climate, soil characteristics, and native vegetation. Engineered barriers are used to control the flow of water into the waste. A hydrologic model of the waste disposal system must realistically represent precipitation, the source of water to the system, runoff, evaporation, transpiration, and changes in storage to estimate the flow through the system. Under natural conditions plants remove water from the upper soil zone through root uptake and transpiration, reducing the water available for seepage deeper into the profile. The same processes occur in an engineered cover layer that has been revegetated. Seepage through a cover system can occur when soils become wet enough to increase their conductivity to water. Cover surface layers with adequate storage capacity can hold the water in the near surface until it can move back into the atmosphere through evaporation, reducing the seepage of water to the waste.

Steady-state water infiltration rates and water contents for the cover layers required as input for the DU PA Model are developed from infiltration modeling using the HYDRUS-1D software package. This section describes the development of HYDRUS-1D models for the Clive DU PA Model and implementation of HYDRUS-1D results into the probabilistic framework employed by GoldSim. The HYDRUS-1D model (Šimůnek et al. 2018) was selected for simulating the performance of the ET cover proposed for the Federal Cell top slope because of its ability to simulate processes known to have a significant role in water flow in landfill covers in arid regions.

The one-dimensional version of the software (rather than the two-dimensional version) was selected for simulating flow in the Federal Cell ET cover since previous numerical modeling of flow in the similar ET cover design for the Class A West cover demonstrated that subsurface lateral flow was not significant (Energy*Solutions* 2012). To test the importance of 2-D flow effects in the ET cover design, 2-D transient flow simulations were conducted for representative sections of the cover. The approach taken was to model a section of the side slope in two dimensions. Representative hydraulic properties were assigned to the ET cover layers and the models were run with daily atmospheric boundary conditions for 100 years. Root water uptake was modeled assuming the roots extended to the bottom of the evaporative zone layer and assuming a rooting density that decreased with depth. The results of these 2-D simulations demonstrated that water flow in the cover system for both designs is predominantly vertical with no significant horizontal component. These results demonstrate that 1-D models can be used to provide a defensible analysis of cover performance for the ET cover design due to the lack of lateral flow.

Model development requires construction of a computational grid based on the geometry of the model domain. Hydraulic properties for each layer required for the model were available from previous studies at the site or were estimated from site-specific measurements such as particle size distributions. Some of the hydraulic properties were variable in this modeling as described below. HYDRUS requires daily values of precipitation, potential evaporation, and potential transpiration to represent the time-variable boundary conditions on the upper surface of the cover. Representative boundary conditions were developed from records of nearby meteorological observations. Parameters for describing root water uptake are available from the literature.

The process of abstracting a detailed flow model into a probabilistic model that could be implemented in GoldSim required the development of distributions for hydraulic property parameters for the cover materials that influence water balance. Included in the distributions used was a distribution for the saturated hydraulic conductivity (K_s) of the radon barriers for the modeling. This distribution included values from a range of in-service ("naturalized") clay barrier K_s values described by Benson et al. (2011), Section 6.4, pp. 6–12. Multiple HYDRUS-1D simulations with varying hydraulic property inputs were conducted to provide values of infiltration flux into the waste zone, and water content within each ET cover layer. From these simulation results, a 1000-row table was developed that represents 1000 outputs of the HYDRUS model, for values of net infiltration flux and cover layer water content. This table is then implemented in the Clive DU PA Model to provide for each realization a steady-state infiltration flux and layer water contents that include the uncertainty in these parameters. The ET cover and unsaturated zone infiltration modeling approaches and results are described in detail in the *Unsaturated Zone Modeling* white paper (Neptune 2021c).

4.1.2.5 Geochemical

The conceptual model for the transport of radionuclides at the Clive Facility allows sufficient meteoric water infiltration into the waste zone to allow dissolution of uranium and daughters, fission products, and potential transuranic contaminants (along with native soluble minerals). At first, leaching is likely to be solubility-limited with respect to uranium, and the leachate will migrate away from the source with the uranium concentration at the solubility limit. The other radionuclides are unlikely to be at a solubility limit. Depending upon the amount of water available, these radionuclides will either re-precipitate once the thermodynamic conditions for saturation are reached, or remain in solution and be transported to the saturated zone. This water is expected to be oxidizing, with circum-neutral to slightly alkaline pH (similar to the upper unconfined aquifer), and an atmospheric partial pressure of carbon dioxide. However, the amount of total dissolved solids (TDS) is expected to be initially lower than the upper aquifer.

The composition of this aqueous phase will change as it reaches the saturated zone, with some increase in dissolved solids and potentially lower dissolved oxygen and carbon dioxide. The saturated zone for this PA model includes only the shallow, unconfined aquifer. Transport of radionuclides is expected to be restricted to this aquifer and to not migrate to the lower aquifer due to a natural upward gradient at the facility. The chemical composition of the saturated zone is characterized as having a somewhat alkaline pH likely due to the presence of carbonates, mainly oxidizing though transient reduced conditions may exist, with high levels of dissolved ions of mainly sodium and chlorine.

The transport of dissolved radionuclides can also be limited by sorption onto the solid phase of associated minerals and soils within each of the zones considered in this PA model. The transport of uranium is limited by both solubility and the sorption of radionuclides in groundwater. Sorption consists of several physicochemical processes including ion exchange, adsorption, and chemisorption. Sorption is represented in the PA model as a partitioning coefficient (K_d) value.

Distributions of radionuclide-specific partitioning coefficients and solubilities were developed for the PA model considering the geochemical conditions in the cell, the unsaturated zone, and the shallow aquifer at the Clive Facility. The development of these distributions is described in detail in the *Geochemical Modeling* white paper (Neptune 2023a). The primary concerns for the model include the geochemical properties of ^{99}Tc as they affect movement to groundwater and of uranium in its different chemical forms for the 10-ky and deep time models.

4.1.2.6 Saturated Zone

Contaminants moving vertically in the UZ below the cell enter the saturated zone (SZ) beneath the disposal facility. The rate of recharge is the same as the Darcy flux (the rate of volume flow of water per unit area) through the overlying UZ, and is expected to be small enough that vertical transport within the SZ would be small. Most SZ waterborne contaminant transport will be in the horizontal direction, following the local pressure gradients, which are reflected in water table elevations in the shallow aquifer. A point of compliance in the groundwater has been established at 27 m (90 ft) from the edge of the embankment interior, so saturated transport is modeled to that point. Note that, in the case of the DU PA, only the top slope section of the embankment would contain DU waste, so the effective distance from the DU waste to the well is lengthened by the width of the side slope section, to about 81 m (265 ft).

Saturated zone groundwater transport generally involves the processes of advection-dispersion and diffusion. Mean pore water velocity in the saturated zone is assumed to be determined by the Darcy flux and the porosity of the sediment. A range of values will allow the sensitivity analysis (SA) to determine if this is a sensitive parameter in the determination of concentrations at the compliance well and resultant potential doses. Modeling of fate and transport for the saturated zone pathway will include advection, linear sorption, mechanical dispersion, and molecular diffusion. Saturated zone processes and parameters represented in the PA model are described in detail in the *Saturated Zone Modeling* white paper (Neptune 2021l). The primary concern for the model is the breakthrough of ^{99}Tc at the monitoring well.

4.1.2.7 Air Modeling

Gaseous and particle-bound contaminants that have migrated to the surface soil layer are potentially subject to dispersion in the atmosphere. The effect of mechanical disturbance on human exposure to soil particulates is evaluated in the PA based on the effect of off-highway vehicle (OHV) use. However, although this mechanism may be consequential for human exposure, it is not likely to be a significant contributor to the overall rate of fine particulates emissions from the embankment over time. Eolian (or aeolian, meaning wind-related) disturbance is the primary cause of particulates emissions from the embankment and is the process modeled in the PA to estimate particulate emissions.

In addition to particulate emissions of contaminated surface soil due to eolian erosion, emissions of gas-phase radionuclides diffusing across the surface of the embankment into the atmosphere are considered in the PA model. Note that this effect is counter-balanced by replacement with eolian material that moves onto the cap. Diffusion modeling of radionuclide gases in the embankment, and estimation of flux into the atmosphere, is described in the *Radon Diffusion Modeling* white paper (Neptune 2021j). For both particulate-bound and gaseous radionuclides, atmospheric dispersion modeling employing local meteorological data is conducted to calculate breathing-zone air concentrations above the embankment and at specific locations in the area where off-site receptors may be exposed (see *Dose Assessment* white paper (Neptune 2021b)).

Atmospheric dispersion may result in significant bulk transport of fine particles off of the embankment. Atmospheric dispersion modeling is also used to calculate the deposition flux of resuspended embankment particles in the areas adjacent to the embankment where ranchers and recreational receptors may be exposed. As particulates from the embankment are deposited on surrounding land, this surrounding area may become a secondary source of radionuclide exposure.

Atmospheric dispersion modeling is conducted outside of the GoldSim modeling environment, into which the model is abstracted. An atmospheric dispersion model is a mathematical model that employs meteorological and terrain elevation data, in conjunction with information on the release of contamination from a source, to calculate breathing-zone air concentrations at locations above or downwind of the release. Some models may also be used to calculate surface deposition rates of contamination at locations downwind of the release.

Both particle resuspension and atmospheric dispersion are first modeled outside of the GoldSim PA model, and the results are then incorporated into GoldSim. The particulate emission model used is AERMOD, a relatively simple model that has been adopted by EPA to estimate an annual-average emission rate of respirable particulates (approximately 10 μm and less, i.e., PM_{10}) from the ground surface. AERMOD is EPA's recommended regulatory air modeling system for steady-state releases; and is suitable for calculating annual-average contaminant breathing zone air concentrations at various distances and in various directions from a source release. These models are described in detail in the *Atmospheric Transport Modeling* white paper (Neptune 2021i).

4.1.2.8 Biologically Induced Transport

Biotic fate and transport models have been developed to evaluate the redistribution of soils, and contaminants within the soil, by native flora and fauna. The Clive Facility is located in the eastern side of the Great Salt Lake Desert, with flora and fauna characteristic of Great Basin alkali flat and Great Basin desert shrub communities.

Biological organisms play an important role in soil mixing processes, and therefore are potentially important mediators of transport of buried wastes from deeper layers to shallower layers or the soil surface. Three broad categories are evaluated for their potential effect on the redistribution of radionuclides at the Clive Facility: plants, ants, and burrowing mammals. The impact of these flora and fauna will be limited largely to the top several meters, based on the depth of their roots and burrows. Details for all three categories can be found in the *Biological Modeling* white paper (Neptune 2021g).

4.1.2.8.1 Plants

Plant-induced transport of contaminants is assumed to proceed by absorption of contaminants into the plant roots, followed by redistribution throughout all the tissues of the plant, both above ground and below ground. Upon senescence, the above-ground plant parts are incorporated into surface soils, and the roots are incorporated into soils at their respective depths.

Functional factors that contribute to the plant section of the biotic transport model include: identifying dominant plant species; grouping plant species into categories that are significantly similar in form and function with respect to the transport processes; estimating net annual primary productivity (NAPP), a measure of combined above-ground and below-ground biomass generation; determining relative abundance of plants or plant groups; and representing the density of plant roots as a function of depth below the ground surface.

Field surveys of the Clive site and surrounding areas were conducted by SWCA Environmental Consultants in September and December 2010 to identify plant species present in different vegetative associations around the Clive site (SWCA 2011). Five different vegetative associations were surveyed, with three associations representing the alkali flat/desert flat type soils found in the vicinity of Clive, and two associations representative of desert scrub/shrub-steppe habitat characteristic of slopes and slightly higher elevations with less-saline soil chemistry. A one hectare (100 m × 100 m) plot was established in each vegetative association, and each plot was surveyed for dominant plant species present, and the percent cover and density of each species. In addition, a small number of black greasewood, shadscale, halogeton, and Mojave seablite plants were excavated to obtain root profile measurements and above-ground plant dimensions.

A total of 41 plant species were identified on the five survey plots. Eighteen species each comprised at least 1% of the total cover on at least one plot. These 18 species were considered the most important for the purpose of modeling plant mediated transport of radiochemical contaminants at Clive. Species were grouped into five functional plant groups: grasses, forbs, greasewood, other shrubs, and trees. Greasewood is separated from other shrubs because of its status as a phreatophyte that can extend taproots in excess of five meters to reach groundwater. Annual and perennial grasses were grouped due to similar maximum rooting depths. Despite the ability of Greasewood to extend taproots, it will only do so if there is a water source to mine. There is no evidence in the Clive data that greasewood in the area of Clive extends to the water table. Also, the radon barrier acts as an impediment to deep rooting.

4.1.2.8.2 Ants

Ants fill a broad ecological niche in arid ecosystems as predators, scavengers, trophobionts, and granivores. However, it is their role as burrowers that is of main concern for the purposes of this model. Ants burrow for the procurement of shelter, the rearing of young, and the storage of foodstuffs. How and where ant nests are constructed plays a role in quantifying the amount and rate of subsurface soil transport to the ground surface at the Clive site. Factors relating to the physical construction of the nests, including the size, shape, and depth of the nest, are key to quantifying excavation volumes. Factors limiting the abundance and distribution of ant nests such as the abundance and distribution of plant species, and intra-specific or inter-specific competitors, also can affect excavated soil volumes. Important parameters related to ant burrowing activities

include nest area, nest depth, rate of new nest additions, excavation volume, excavation rates, colony density, and colony lifespan.

Modeling soil and contaminant transport by ant species assumes that ants move materials from lower cells to those cells above while excavating chambers and tunnels within a nest. These chambers and tunnels are assumed to collapse over time and return soil from upper cells back to lower cells.

Surveys for ants at Clive were limited to surface surveys of ant colonies, including identification of ant species, measurements (length, width, and height) of ant mounds, and determination of ant nest densities in each vegetative association (SWCA 2011). Total nest depth and nest volume were extrapolated from mound surface dimensions based on correlations from data observed at the Nevada National Security Site (NNSS) (Neptune 2006) for the dominant ant species at Clive.

Only two species of ants were identified during the surveys, with the western harvester ant, *Pogonomyrmex occidentalis*, accounting for 62 of the 64 nests identified. The second ant species, a member of the genus *Lasius,* was only encountered twice, both times in the mixed grassland plot. Harvester ants also tend to create the largest and deepest burrows. Consequently, the characteristics of the harvester ants were included in the model. Site-specific investigations indicate that most ant burrowing will occur in the upper layers of the cover and will be minimal below a depth of 42 inches (SWCA (2013), p.28). For details of biological models, refer to the *Biological Modeling* white paper (Neptune 2021g).

4.1.2.8.3 Burrowing Mammals

Burrowing mammals can have a profound impact on the distribution of soil and its contents near the soil surface. The degree to which mammals influence soil structure is dependent on the behavioral habits of individual species. While some species account for a large volume of soil displacement, others are less influential. Functional factors such as burrowing depth, burrow depth distributions, percent burrow by depth, tunnel cross-section dimension, tunnel lengths, soil displacement by weight, soil displacement by volume, and animal density per hectare play a critical role in determining the final soil constituent mass by depth within the soil.

Modeling soil and contaminant transport by mammal species within the Clive DU PA Model assumes animals move materials from lower cells to those cells above while excavating burrows. Burrows are assumed to collapse over time and return soil from upper cells back to lower cells. Thus, the balance of materials is preserved through time.

Each Clive plot was surveyed for small mammal burrows during September and October 2010 (SWCA 2011). Burrows were identified by animal category. Within the survey area four categories of mammal burrows were identified: ground squirrels, kangaroo rats, mouse/rats/voles, and one badger. Due to the small number of badger and ground squirrel burrows, the decision was made to treat all burrowing mammals as a single unit for modeling purposes. Small mammal trapping was conducted on the five Clive plots during the new moon in October 2010 to identify the principal small mammal fauna present in each vegetative association. Each 1-ha plot was subdivided into 25 20-m × 20-m subplots. At the center of each subplot, two Sherman® live traps were placed, for a total of 50 traps per plot.

Deer mice (*Peromyscus maniculatus*) were the most abundant small mammal captured during trapping, and were the only mammal captured in the plots located on the Clive Facility. These plots were characterized by very low mammal densities, as evidenced by both the trapping results and the burrow surveys. With such a small population in these plots, the decision was made to average the plots. For details of biological models, refer to the *Biological Modeling* white paper (Neptune 2021g).

4.1.2.9   Erosion

The Federal Cell is subject to erosion by the forces of wind and water. The conceptual model assumes that wind blows material off-site (see Section 4.1.2.7), even while it replaces material that is removed from the cap. Water removes cap material through sheet erosion and the formation of channels (gullies).

The formation of gullies is a concern on uranium mill tailings sites and other long-term above-ground radioactive waste sites (NRC 2010). Gully erosion has the potential to move substantial quantities of both cover materials and waste, should the waste material be buried close to the surface. Gully outwash forms depositional fans on the slopes of the embankment. Gullies might form initially on the embankment through disturbance attributed to animal burrowing, or by human-induced mechanisms such as cattle paths or OHV tracks.

Version 3.0 of the Clive DU PA Model evaluates the influence of erosion on embankment performance using SIBERIA, a landscape evolution model (LEM). The LEM is applied to a representation of the Federal Cell design, with uncertainty associated with model parameters assessed through the development of probability distributions. SIBERIA was run for 1000 simulations using these distributions.

From these simulation results, a 1000-row table was developed that represents 1000 outputs of the model, for values of net erosion by depth in the top cover. This table is then implemented in the Clive DU PA Model to provide for each realization a steady-state erosion profile that includes the uncertainty in these parameters. Implementation of this approach in GoldSim is described in more detail in the *Erosion Modeling* white paper (Neptune 2023h).

4.1.2.10 Dose Assessment

The dose assessment in the Clive DU PA Model addresses potential radiation dose to any receptor who may come in contact with radioactivity released from the disposal facility into the general environment. The objective of a dose assessment in a radiological PA is to provide estimates of potential doses to humans over time from radioactive releases from a disposal facility after closure, as described in Section 3.3.7 of NRC (2000), NUREG 1573. As described below, the critical groups in the Model are defined as ranchers and recreationalists.

The radiation dose limit for protection of the general population is 25 mrem/yr, as a total effective dose equivalent (TEDE). Dose limits for radiological PAs are defined in UAC Rule R313-25-20 and10 CFR 61.41as an equivalent of 0.25 mSv (25 mrem) to the whole body, 0.75 mSv (75 mrem) to the thyroid, and 0.25 mSv (25 mrem) to any other organ of any member of the public. However, the radiation dosimetry underlying these dose metrics is based on a methodology published by the International Commission on Radiation Protection (ICRP) in

1959. More recent dose assessment methodology has been published as ICRP Publication 30 (ICRP 1979) and ICRP Publication 56 (ICRP 1989), employing the TEDE approach. As stated in Section 3.3.7.1.2 of NRC (2000), "As a matter of policy, the Commission considers 0.25 mSv/year (25 mrem/year) TEDE as the appropriate dose limit to compare with the range of potential doses represented by the older limits…"

The period of performance for a radiological PA defined in UAC Rule R313-25-9 requires evaluation for a minimum compliance period of 10 ky, with additional simulations for a qualitative analysis for the period where peak hypothetical dose occurs. The scope of this Model includes modeling of the disposal system performance to the time of peak hypothetical radiological dose (or peak radioactivity, as a proxy), and to quantify dose within the time frame of 10 ky.

4.1.2.10.1 Receptors and Exposure Scenarios

Receptors in a PA are categorized in UAC Rule R313-25-20 and -21 and10 CFR 61.41 according to the labels "member of the public" (MOP) and "inadvertent human intruder" (IHI). The regulatory basis for, and interpretation of these categories of receptors is provided in Section 1.3. The MOP is essentially a receptor who is exposed outside the boundaries of the facility. Refer to Section 5.1.7 where the definition of IHI as specifically applied in the PA is described:

> "Inadvertent intrusion is often used in terms of direct but inadvertent access to the waste (e.g., through well drilling or basement construction), for which the initiator is exposed. However, such direct activities are unlikely at this site. The types of activities here do not result in direct exposure to the waste by the initiator, but potentially to future receptors."

Ranching Scenario. The land surrounding the Clive Facility is currently utilized for cattle and sheep grazing. Ranchers typically use off-highway vehicles (OHVs, including four-wheel drive trucks) for transport. Activities are expected to include herding, maintenance of fencing and other infrastructure, and assistance in calving and weaning. Ranchers may be exposed to contamination via the pathways outlined in Table 1.

Recreational Scenario. Recreational uses on the land surrounding the Clive Facility may involve OHV use, hunting, target shooting, rock-hounding, wild-horse viewing, and limited camping. It is assumed in the Clive DU PA Model that recreational OHV riders ("Sport" OHVers; i.e., OHV users who use their vehicles for recreation alone) and hunters using OHVs ("Hunters"), both of whom may also camp at the site, represent the most highly-exposed recreational receptors. Recreationalists may be exposed to contamination via the pathways outlined in Table 1.

Table 1. Exposure Pathways Summary.

exposure pathway	ranching	recreation
Inhalation (wind derived dust)	×	×
Inhalation (mechanically generated dust)	×	×
Inhalation (gas phase radionuclides)	×	×
Ingestion of surface soils (inadvertent)	×	×
Ingestion of game meat		× (Hunter)
Ingestion of beef	×	
External irradiation—soil	×	×
External irradiation—immersion in air	×	×

The ranching and recreation scenarios are characterized by potential exposure related to activities both on the disposal site and in the adjoining area. Specific off-site points of potential exposure also exist for other receptors based upon present-day conditions and infrastructure. Unlike ranching and recreational receptors, who might be exposed by a variety of pathways on or adjacent to the site, these off-site receptors would likely only be exposed to wind-dispersed contamination, for which inhalation exposures are likely to predominate. Five specific off-site locations and receptors are evaluated in the Clive DU PA Model, including:

- Travelers on Interstate-80, which passes 4 km to the north of the site;

- Travelers on the main east-west rail line, which passes 2 km to the north of the site;

- Workers at the Utah Test and Training Range (UTTR, a military facility) to the south of the Clive Facility, who may occasionally drive on an access road immediately to the west of the Clive Facility fence line;

- The resident caretaker at the east-bound Interstate-80 rest facility (the Grassy Mountain Rest Area at Aragonite) approximately 12 km to the northeast of the site, and,

- OHV riders at the Knolls OHV area (BLM land that is specifically managed for OHV recreation) 12 km to the west of the site.

4.1.2.11 ALARA

40 CFR (2014), Section 61.42, defines a second decision rule that pertains to populations as well as individuals. The regulation states "reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable" (or ALARA). The ALARA concept can be applied to either individuals or populations. In the context of the Clive DU PA Model, ALARA is applied to collective doses germane to the receptor populations described in Section 4.1.2.10.

The ALARA process is also described in DOE regulations and associated guidance documents such as 10 CFR Part 834 and DOE 5400.5 ALARA (CFR (1993); DOE (1993, 1997)), and in other NRC documents (NRC 1995, 2000, 2004, 2015). The definitions in each case are very similar, indicating that exposures should be controlled so that releases of radioactive material to the environment are as low as is reasonable taking into account social, technical, economic, practical, and public policy considerations.

The probabilistic Clive DU PA Model is designed to estimate individual annual doses to hypothetical individuals in future populations that may be exposed to radionuclide releases from the Clive Facility. The Model is also able to aggregate individual doses into estimates of collective and cumulative population dose on an annual basis as well as over the 10-ky period of performance. Given this model structure, an opportunity exists with the Clive DU PA Model to evaluate ALARA in the context of population dose.

The overall implication of the various Agency regulations and guidance documents regarding ALARA is that many factors should be taken into account when considering the potential benefits of different options for disposal of radioactive waste. Previous guidance from NRC (2004) suggests several different options for addressing consequences over thousands of years, as is necessary for the DU PA. The options essentially correspond to different discount rates. NRC recommends using 3 percent and 7 percent discount rates, where the former approximates the real rate of return on long-term government debt, and the latter approximates the marginal pretax real rate of return on average investment in the private sector. NRC relied on OMB (2003) for its central arguments, noting that OMB also recognizes that special circumstances might arise when considering long time frames, for which ethical and technical arguments might support the use of lower discount rates. Consequently, NRC suggests also performing analysis with a zero percent discount rate, and sensitivity analysis across a range of possible discount rates. The most recent NRC (2015) guidance does not mention discount rates, so none are applied here (which implicitly assumes a zero rate).

In order to implement ALARA in a logical system, and so that economic factors are taken into consideration, a decision analysis is implied. Decision analysis is the appropriate mechanism for evaluating and optimizing disposal, closure, and long-term monitoring and maintenance of a radioactive waste disposal system. Decision options for disposal at Clive include engineering options and waste placement. More generally, if decision analysis is applied, then a much wider range of options can be factored into the decision model, such as transportation of waste, risk to workers, and effect on the environment.

The decision analysis in this context is essentially a benefit-cost analysis, within which different options for the placement of waste are evaluated. For each option, the Model predicts doses to the array of receptors, and the consequences of those doses are assessed as part of an overall cost model, which also includes the costs of disposal of waste for each option. The goal is to find the best option, which is the option that provides the greatest overall benefit. The consequences of risk can be measured through a simplification that is available in ALARA guidance, including NRC (2015), which provides the basis for, and history of, assigning a dollar value to person-rem as a measure of radiation dose.

In assigning a value to the person-rem cost to society of radiation dose, the agencies have simplified the basis for a full decision analysis. This is reasonable for a first pass at a decision analysis associated with the proposed disposal at Clive. Hence, the value of $5,100 is applied to the population dose. Application of the ALARA process to the Clive DU PA Model is described more completely in the *Decision Analysis* white paper (Neptune 2021d).

4.1.2.12 Groundwater Concentrations

Apart from individual and population dose evaluations, evaluation of the PA also requires comparison of groundwater concentrations with groundwater protection levels, or GWPLs. That is, the State of Utah imposes limits on groundwater contamination, as stated in the Ground Water Quality Discharge Permit (Utah 2014). Part I.C.1 of the Permit specifies that GWPLs in Table 1A of the Permit shall be used for the Class A LLW Cell, which is directly north of the proposed Federal Cell location. Table 1A in the Permit specifies general mass and radioactivity concentrations for several constituents of interest to DU waste disposal. This includes values for mass concentration of total uranium, radium, and gross alpha and beta radioactivity concentrations for specific wells where background values were found to be in exceedance of the Table 1A limits. Part I.D.1 of the Permit specifies that the performance standard for radionuclides is 500 years. Relevant GWPLs for Clive are:

- Strontium-90   42 pCi/L,
- Technetium-99   3,790 pCi/L,
- Iodine-129   21 pCi/L,
- Thorium-230   83 pCi/L,
- Thorium-232   92 pCi/L,
- Neptunium-237   7 pCi/L,
- Uranium-233   26 pCi/L,
- Uranium-234   26 pCi/L,
- Uranium-235   27 pCi/L,
- Uranium-236   27 pCi/L, and
- Uranium-238   26 pCi/L.

The main concern for the PA model is the potential for transport of ^{99}Tc, a mobile contaminant in the DU waste, to the point of compliance.

Note that, as specified in the Permit, groundwater at Clive is classified as Class IV, saline ground water (according to UAC R317-6-3 *Ground Water Classes*)*,* and is highly unlikely to serve as a future water source. The underlying groundwater in the vicinity of the Clive site is of naturally poor quality because of its high salinity and, as a consequence, is not suitable for most human uses, and is not potable for humans. However, the Clive DU PA Model calculates estimates of groundwater concentrations at the location of a virtual well near Federal Cell for comparison with the GWPLs.

4.1.2.13 Deep Time Assessment

The approach to deep time modeling is briefly described in the *Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility* (Neptune 2021f). A more in-depth discussion of the deep time modeling methodology is described in *Deep Time Assessment for the Clive DU PA* (Neptune 2021h). The focus of the deep time evaluation is to assess the potential impact of glacial epoch pluvial lake events on the Federal Cell from 10 ky through 2.1 My post-closure. (Note that this model is termed the "deep time" model.) A pluvial lake is a consequence of periods of extensive glaciation, and results from low evaporation, increased cloud cover, increased albedo, and increased precipitation in landlocked areas. Given that long-term climatic cycles of 100 ky are considered very likely in the next 2.1 My (Hays et al. 1976; Shackleton 2000), it is assumed that deep lakes will return to the Bonneville Basin in the future. In addition to deep lakes, intermediate-sized lakes are also assumed to occur periodically during a 100-ky glacial cycle. Events that might occur in deep time other than the occurrence of intermediate lakes and the cyclic return of deep lakes (e.g., meteor strikes or a large eruption at Yellowstone) are not considered further in this model because their likelihood is relatively small, and their consequences are likely to be much greater and far reaching for human civilization.

For the deep time scenarios, the PA model provides a qualitative assessment of the future consequences of present-day disposal of DU waste to the environment. While no exposure or dose assessment is attempted, tracking of radioactive species concentrations provides insight into waste disposal and embankment construction design and performance. Long-term historical information on the area surrounding the Clive site is sparse, providing only a broad depiction of historical behavior of lake cycles in the Bonneville Basin. Thus, the model utilized for projecting into the long-term future is largely conceptual or stylized, providing a similarly broad depiction of future behavior.

There are two components of the model used to represent the deep time scenarios. The first is modeling lake formation and dynamics in the Bonneville Basin. The second is modeling the fate of the Federal Cell and disposed DU waste.

For the first component, the deep time evaluation focuses on potential releases of radioactivity following a series of pluvial lake events caused by glacial cycles assumed to occur (approximately) every 100 ky. The 100-ky glacial periodicity is based on historical ice core and the benthic marine isotope data for the past 800 ky. These cycles are also consistent with information regarding orbital forcing, and the periodicity suggested by the Milankovitch cycles.

These 100-ky glacial cycles form the basis for modeling the return and recurrence of lake events in the Bonneville Basin. The lake formation model is applied to each 100-ky cycle similarly. One deep lake is assumed to occur in each 100-ky cycle, and several intermediate lakes are allowed to form during the transgressive and regressive phases of the deep lake. Note that the current 100-ky cycle is not modeled differently than future glacial cycles, despite evidence that the current inter-glacial period might last for another 50 ky (Berger and Loutre 2002). In the model, therefore, an intermediate lake can return sooner than might be expected in the current 100-ky cycle. The precise timing of the return of a lake at or greater than the elevation of Clive is not as important as the event itself.

For the second component, it is assumed that destruction of the Federal Cell will result from the effects of wave action from an intermediate or deep lake. In effect, it is assumed that a lake is large enough that obliteration of the embankment will occur. In this scenario, all of the embankment material above grade is dispersed across a large localized area through wave action.. The waste material is mixed with sediment and then enters the lake system via dissolution. A simplifying, conservative assumption is to limit dissolution to a column above the waste dispersal area. This assumption is conservative because lake water will probably mix more extensively, creating greater dilution. As a result, these assumptions lead to greater concentrations of waste than is probably reasonable. The conservatism is included in this model because of the lack of data that exists to quantify the processes.

The deep time model assumes that the form of DU available for deep-time transport is U_3O_8, which is far less soluble than UO_3. Fate and transport modeling performed using the Clive DU PA Model indicates that the relative soluble UO_3 will have migrated to groundwater within 50 ky. Consequently, the deep time model focuses on U_3O_8 as the form of DU available for deep-time transport. While the lake is present, some waste in the water column will bind with carbonate ions and precipitate out into oolitic sediments, while the remaining waste will fall out with the sediment as the lake eventually recedes. The model assumes the waste is fully mixed with the accumulated sediments. This is a conservative assumption, since some waste is likely to be buried rather than mixed with future lake sediments. The extent of mixing of previous sediment with new sediment is not well understood; hence, an assumption that the sediments completely mix is expedient, and probably leads to conservative results. All of the waste that has dissolved into the lake re-enters the lake sediment once the lake recedes. Overall sediment concentrations decrease over time because the amount of waste does not change other than through decay and ingrowth, whereas more sediment is added over time.

Thus, the deep time model should be regarded as conceptual and heuristic. The intent is to present a picture of what the long-term future might hold for the DU waste disposal embankment, rather than to provide a quantitative, temporally specific, prediction of future conditions, or an assessment of exposure or dose to human receptors. The type of glacial climate change envisioned in the deep time model will probably have wide-reaching consequences for the planet and human society that are far beyond the scope of a PA for disposal of radioactive waste.

5.0   Model Structure

5.1   Summary of Important Assumptions

The results of the Clive DU PA Model depend critically on the model structure, the model specification (input probability distributions, for example), and the assumptions that underlie the Model. That is, the results are fully dependent, or conditional, on the Model. The most important assumptions are identified in this section.

5.1.1 Points of Compliance

Points of compliance in a PA are usually defined in terms of the location in the accessible environment at which human health is evaluated in the dose assessment, and the location at which groundwater concentrations are used for comparison to GWPLs. For this Model, the

primary receptors (ranchers, recreators) are assumed to spend time on the site, and off the site in the general vicinity. Other receptors are defined at points in space (see Section 4.1.2.10.1). Note that the ALARA analysis addresses the same points of compliance.

Groundwater concentrations are evaluated at a virtual well located 27 m (90 ft) from the interior of the waste embankment. In the case of the proposed DU waste disposal, only the top slope section of the embankment would contain DU waste, so the effective distance from the DU waste to the well is lengthened by the width of the side slope section, to about 81 m (265 ft).

For the deep time model, there are no receptors that are considered, and doses are not calculated. Instead, concentrations of radionuclides are estimated in lake water and in lake sediment in the general vicinity of the Federal Cell.

5.1.2 Time Periods of Concern

There are four time periods that have import in this PA. The Clive DU PA Model is run fully quantitatively for dose endpoints for 10 ky. Peak mean dose is estimated and used for comparison with performance objectives for this time frame. The ALARA analysis is also performed for this period of time.

An institutional control period of 100 y is assumed, during which time doses are not calculated, because access to the site is prevented.

Groundwater concentrations are compared to GWPLs for the first 500 years of the Model, since this is the compliance period that is applied to the GWPLs under Utah Code.

The deep time model is run for 2.1 My because the DU does not achieve secular equilibrium until about that time. That is, the model is run to peak activity of the DU, rather than to peak dose, which is undefined that far into the future.

5.1.3 Closure Cover Design Options

The engineered system in the Clive DU PA Model allows for evaluation of many different disposal configurations. DU waste is assumed to not be disposed under the side slopes. There are 27 waste layers in the Model, each about 0.45-m thick, starting with Layer 1 directly under the cap. The layers are numbered one through 27, with the 27th layer at the bottom of the waste cell. Layers 22 through 27 are below grade. Only one type of waste can be placed in a specific layer. Although the Model is set up to allow for many different waste disposal configurations, only one is considered in this version of the Clive DU PA Model:

GDP contaminated waste in Layer 22

GDP uncontaminated waste in Layers 23–26

SRS waste in Layer 27

Note that fill material is assumed for the 9 m between the cap and Layer 21. This model places all waste below grade.

The initial model v1.0 had three configurations that spanned a fairly wide range of options, from disposal near the cap, to disposal primarily below grade. In DU PA v3.0, DU waste is only being considered for disposal below grade.

5.1.4 Waste Concentration Averaging

Within each waste layer, the contents of the waste are assumed to include the waste material and the fill material needed to occupy the layer volume. Since each layer represents a mixing cell, the concentration of the radionuclides is averaged throughout the layer. That is, each drum or cylinder is not modeled separately. This is typical of PA models, and is reasonable provided transport from the actual configuration does not differ greatly from transport from the modeled configuration.

5.1.5 Environmental Media Concentration Averaging

Similar to the waste layers, concentrations in the environmental media are averaged throughout the model cell that represents the medium. For example, the concentration of uranium in deep-time lake sediment is the average concentration throughout the sediment layer that is defined by its model cell.

5.1.6 Members of the Public

MOP is defined in terms of the receptors who perform activities in the vicinity of the Clive Facility. This includes receptors at specific locations offsite as described in Section 4.1.2.10.1.

5.1.7 Inadvertent Human Intrusion

Following NRC 10 CFR 61, inadvertent intrusion is defined in terms of receptors who might perform some activities onsite. This includes ranchers, hunters, and OHV enthusiasts. Inadvertent intrusion is often used in terms of direct but inadvertent access to the waste (e.g., through well drilling or basement construction), for which the initiator is exposed. However, such direct activities are unlikely at this site. The types of activities here do not result in direct exposure to the waste by the initiator, but potentially to future receptors. However, the receptors identified here are engaged in onsite activities, and are hence indirectly exposed to the DU waste.

5.1.8 Deep Time Evaluation

The deep time evaluation anticipates the return of a lake in the Bonneville Basin that is large enough to obliterate the Federal Cell. Such a lake is assumed to occur more than once in each 100-ky glacial cycle. Once the Federal Cell is obliterated, the material is assumed to disperse within the vicinity of Clive. The dispersed radionuclides then migrate into lake water through diffusion. All radionuclides that leave the sediment return to the sediment as the lake recedes, either physically or chemically. The wastes are assumed to mix with lake sediment in each lake cycle.

The outputs of interest are concentrations of radionuclides in lake water and in lake sediment, as well as radon flux after the first lake recedes.

Note that, in version 1.0 of the Clive DU PA Model, all DU waste is assumed dispersed with the arrival of the first intermediate lake. However, the DU waste in versions 1.2, 1.4, 2.0, and 3.0 of the Clive DU PA Model is disposed below grade, in which case dispersion of the waste itself does not occur. In these updated model versions, only the radionuclides that have moved above the ground surface are dispersed.

5.2   Distribution Averaging

Most parameters in the Clive DU PA Model correspond to physical quantities that represent an average of some type. Some parameters represent averages over time, as they represent typical behavior that will be used throughout the 10-ky performance period, such as annual precipitation. Other parameters represent averages over space. For example, properties of vegetation represent an average vegetation effect across a model area, while soil properties represent an average across a volume of material represented by a model cell. When data are available that represent small amounts of time relative to the 10,000 years, or small areas/volumes relative to the model cells, then it is the *mean* of the data distribution that needs to be modeled.

To capture the temporal domain of the Model, time steps in this type of systems-level dynamic probabilistic model are usually on the order of several to many years. Consequently, the average effects over long time frames, assuming no catastrophic changes in the system, are far more important than the effects on the scale of days, hours, minutes, or seconds. Spatial and temporal scaling of available data, which are usually collected at points in time and space, is critical for the success of systems-level models. Scaling in this context is essentially an averaging process both spatially and temporally. Simple averaging works well if the effect on the response of a variable or parameter is linear. Otherwise, some care needs to be taken in the spatio-temporal averaging process. In addition, these types of models are characterized by differential equations and multiplicative terms. Averaging is a linear construct that does not translate directly in non-linear systems. Again, care needs to be taken to capture the appropriate systems-level effect when dealing with differential equations and multiplicative terms.

Another important statistical issue that is often overlooked in PA models is correlation between inputs. Many parameters in the Clive DU PA Model are related to one another. One parameter may be physically constrained by the value of another parameter, or they may simply tend to vary together. When joint data are available, a simple approach is to calculate the sample correlation of the parameters in the data and apply the same correlation to the parameters in the model to induce a joint distribution. A simple correlation structure may not fully capture the relationship between two parameters but often provides a reasonable first approximation.

Where data and expertise are available, it is generally preferable to develop joint distributions for the parameters by constructing a marginal distribution for one parameter and *conditional* distributions for the remaining parameters. By fitting a distinct conditional distribution of the second parameter for each possible value of the first parameter, a more realistic relationship might be constructed than can be achieved through simple correlation.

The statistical methods used for appropriate spatio-temporal scaling and correlation effects are described in the *Fitting Probability Distributions* white paper (Neptune 2021e).

5.3   Model Evaluation through Uncertainty and Sensitivity Analysis

The Clive DU PA Model is built as a probabilistic systems-level model. Systems-level modeling is geared towards decision objectives, and is a style of bottom-up modeling for which model refinement and iteration is performed in response to model evaluation. Model evaluation is performed throughout model development, but in the final stages it involves uncertainty analysis and sensitivity analysis. Quantitative assessment of the importance of inputs is necessary when the level of uncertainty in the system response exceeds the acceptable threshold specified in the decision-making framework. One of the goals of sensitivity analysis is to identify which variables have distributions that exert the greatest influence on the response.

Uncertainty is captured directly for probabilistic system-level models. The input probability distributions are used to capture the range of possible parameter values. For probabilistic models, sensitivity analysis is performed simultaneously for all input parameters. This approach is termed global sensitivity analysis. It is a very powerful tool at the disposal of probabilistic modeling for identifying parameters that are important predictors of the model output, and it is not constrained by the user's preconceptions of what may be important. In addition to global sensitivity analysis, probabilistic models can be evaluated numerically in an uncertainty analysis and for value of information. Uncertainty analysis in this context involves comparison of the output distribution to performance metrics. A determination can then be made based on the comparison of the compliance of the disposal system. Value of information analysis can be performed to identify parameters for which uncertainty reduction in the output of interest might best be achieved, if it is necessary to reduce uncertainty. This approach can also be used in the context of ALARA goals, to determine if further uncertainty reduction can reasonably be performed.

Sensitivity analysis is a very important tool for understanding the Model. For those parameters that are deemed important as a result of the analysis, and if the uncertainty analysis indicates, there are options for further model refinement. These options include further data collection, and refinement of the model. Uncertainty and sensitivity analysis are applied to each endpoint (model output) separately. Consequently, it is reasonable to expect that some of the endpoints are sensitive to different inputs. For example, output doses might be sensitive to parameters that are related to radon production and transport, whereas the groundwater concentrations might be sensitive to ^{99}Tc inventory or K_d. Consequently, each endpoint might have different needs regarding further data collection or model refinement.

Sensitivity analysis can be used to help identify those inputs for which uncertainty reduction through further information collection will have the most impact on reducing uncertainty in the model response. However, sensitivity analysis of high dimensional probabilistic models can be computationally challenging. These challenges can be met through machine learning methods applied to probabilistic simulation results. Further details are provided in *Machine Learning for Sensitivity Analysis of Probabilistic Environmental Models* (Neptune 2023f).

Another aspect of uncertainty when running probabilistic simulations is simulation stability. The final statistics of interest might relate to the mean output, or to a percentile of the output, and therefore may require a large number of simulations for stability of the estimate of the statistic. The question is, how large? The number of simulations needed can be determined by running a

different number of simulations for each endpoint and statistic of interest. Otherwise, simulation uncertainty could interfere with the uncertainty and sensitivity analysis.

5.4   Clive DU PA Model Structure

The Clive DU PA Model is written using the GoldSim systems modeling software. Like other such models, its structure is hierarchical, with nested "containers" providing the means to organize the model into different conceptual parts (see Figure 3). This model uses containers to represent basic modeling constructs, such as Materials, and contaminant transport Processes that are global (model-wide) in scope. Other containers are devoted to distinct topics, such as Inventory definitions, Disposal calculations, Exposure and Dose calculations, comparisons to GWPLs, and the development of Deep Time Scenarios. Supplemental containers define dashboards used for running the model and displaying results, collected Results from calculations around the model, Simulation Settings for model controls, and Documentation. The role of each of these is discussed below. For instructions on how to use the model, consult the *User Guide for the Clive DU PA Model* (Neptune 2023d).

The purpose of this model is to simulate, to a degree sufficient for decision making, the fate and transport of radionuclides proposed for disposal in the Federal Cell, and to assess their potential effects on future individuals and populations. This is done in the realm of environmental transport modeling coupled with the modeling of health physics and toxicity to humans.

5.4.1 Materials

Any physical model of an environmental system must contain some sort of materials as a basis for representing the physical environment. Water, air, waste, soils, and other porous media are defined in this container, and are referenced throughout the model. The arrangement of these materials in space, and their interconnectivity, is intended to represent a large block of the environment, including the Clive Facility, or in this case the Federal Cell within that facility, and its surroundings. The spatial definition of the environment is in the Disposal container.
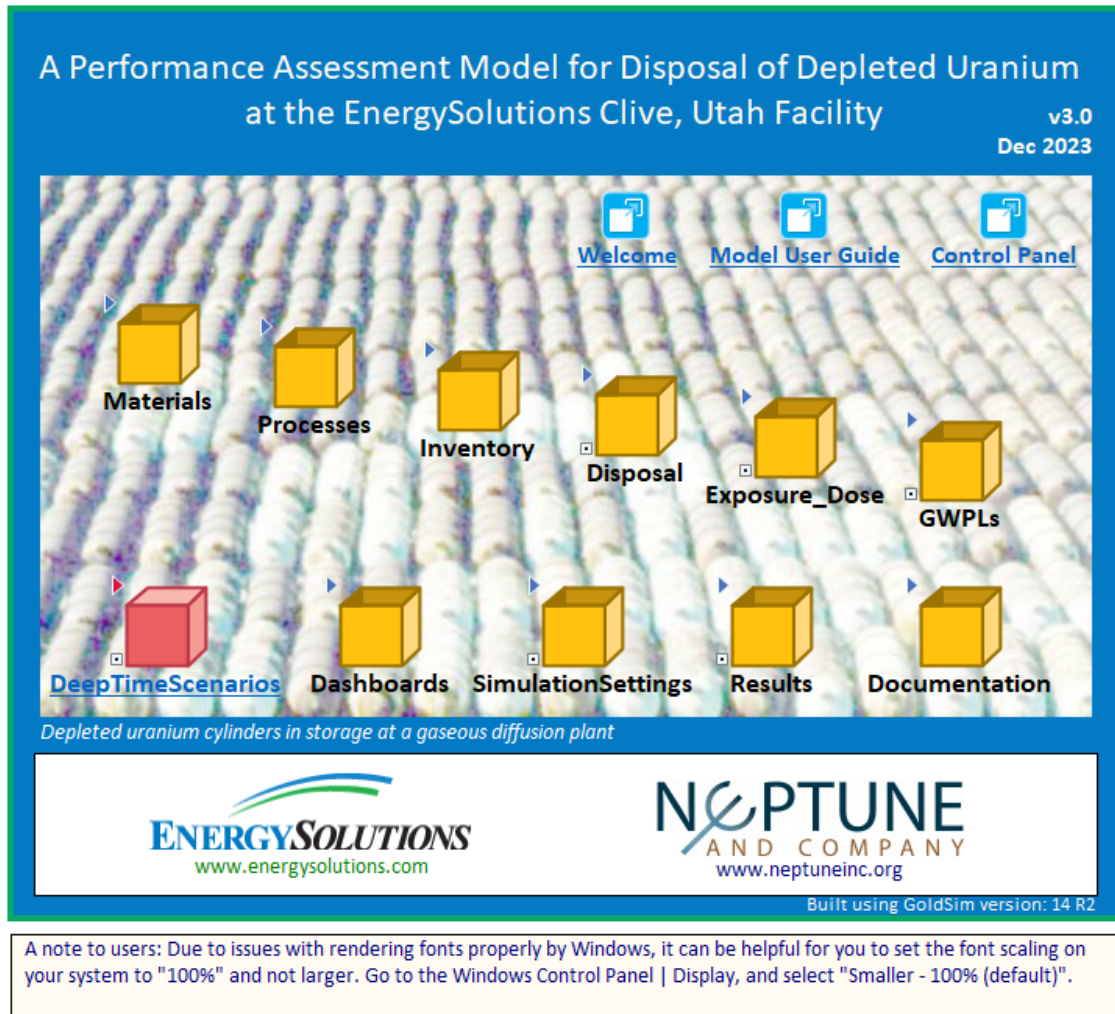
Figure 3. Top level of the Clive DU PA Model v3.0.

5.4.2 Processes

Contaminant transport in the environment is driven by several processes in this model, including advection in water, diffusion in water, diffusion in air, uptake and redistribution by plants, and disturbance by burrowing animals. The parameters defining these processes are global in model scope, and so are defined at this high level. The actual implementation of these processes in moving radionuclides in the environment is done mostly in the Disposal container.

Radioactive decay and ingrowth, chemical solubility in water, soil/water partitioning, and air/water partitioning are also fundamental processes that determine fate and transport of radionuclides, though these are defined in the Materials container since they are directly related to materials.

5.4.3 Inventory

The mass of radionuclides introduced as waste into the model is called the inventory. Inside this container, the total mass of various types of DU waste is defined, as are the concentrations of the radionuclides in each type of waste. These inventories can be selected individually or in combination by the user by using the Control Panel dashboard (see Figure 4), and are then introduced to the modeling cells that represent the waste layers, in the Disposal container.
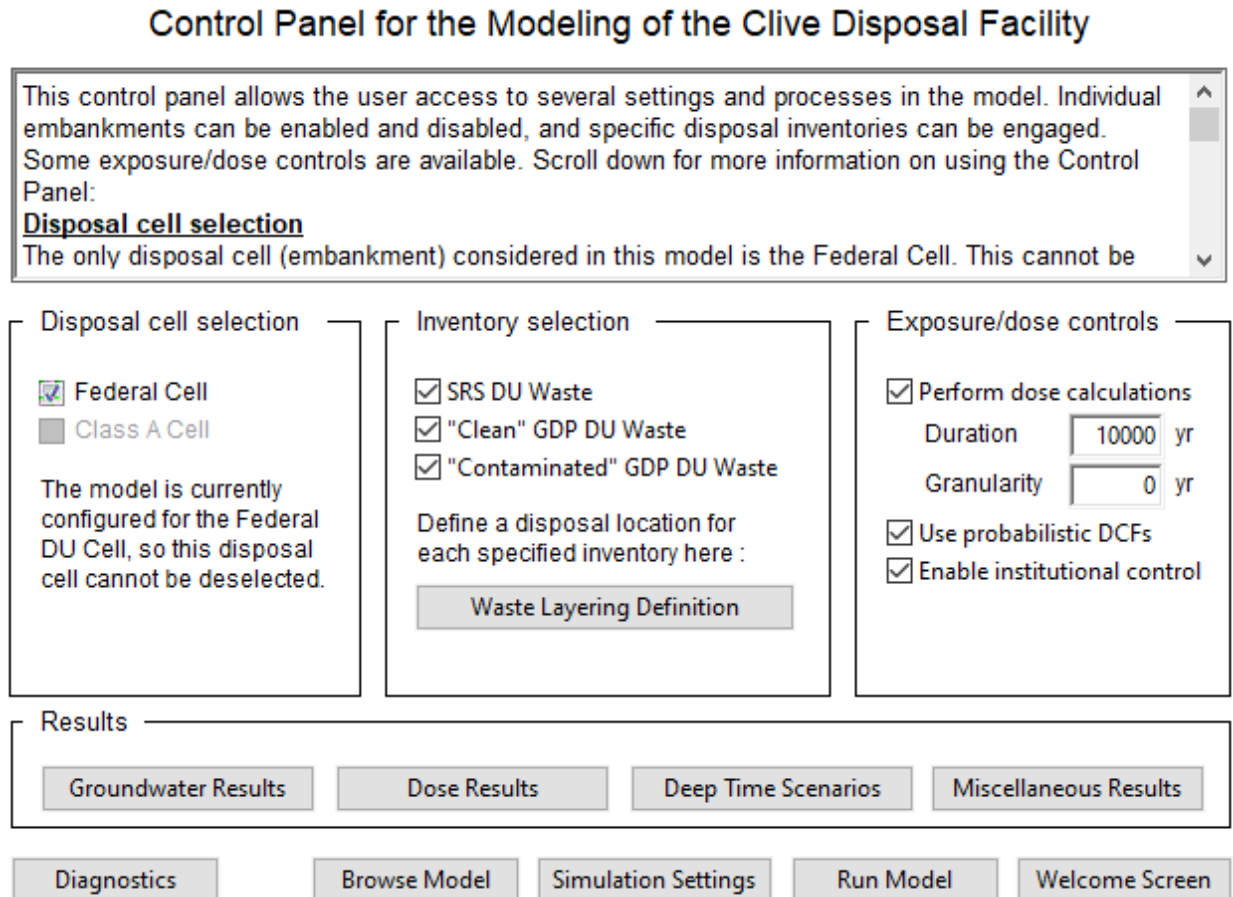

Figure 4. Control Panel for the DU PA Model v3.0.

5.4.4 Disposal

For the first 10,000 yr following disposal, calculations are performed for the fate and transport of radionuclides from the inventory into and throughout the modeled environment, in the Disposal container. Here the physical location of modeling cells is defined, each with materials representing what would be found at that location. For example, modeling cells represent the cover, waste, liner, shallow aquifer, and other porous media, as well as water and air. Cells representing the aquifer contain Unit 2 sediments and water, but no air, since this region is saturated with water by definition. Waste cells contain waste and backfill as porous media, air and water, and are provided a mass of radionuclides from the inventory. As the model progresses through time, these radionuclides migrate into other parts of the physical system, and eventually

are found in environmental media (air, water, soils) that receptors will encounter. The Disposal container performs essentially all of the contaminant transport calculations necessary to estimate future concentrations of radionuclides in these exposure media.

5.4.5 Exposure and Dose

The exposure and dose calculations, which also include estimates of uranium toxicity hazard, are performed in the Exposure_Dose container. Receptors are hypothetical future humans who have behaviors similar to those of people around the site today: There are ranch workers, hunters, and OHV enthusiasts, all of whom are expected to have direct access to the site after institutional control is lost. There are also receptors who travel in the area, using highways, railroads, and access roads. These receptors are represented with a range of attributes and behaviors, from age to time spent on an OHV, and each encounters exposure media. As they breathe dust-laden air and walk on contaminated soils, for example, their exposures result in doses from radionuclides and toxic effects from uranium as a heavy metal. All of these calculations are performed in this container, and provide results that can be compared to performance objectives such as peak dose limits.

5.4.6 Groundwater Protection Level Calculations

In addition to the performance objectives provided by the State of Utah and the NRC for dose limits, there are GWPLs to be considered. In the Disposal container, the model provides radionuclide concentrations at a hypothetical monitoring well located about 27 m (90 ft) from the interior of the waste embankment. In the case of the proposed DU waste disposal, only the top slope section of the embankment would contain DU waste, so the effective distance from the DU waste to the well is lengthened by the width of the side slope section, to about 81 m (265 ft). For those radionuclides that have GWPLs defined, the maximum well concentrations within 500 yr are compared to the GWPL values. These comparison calculations are performed in the GWPLs container.

5.4.7 Deep Time

All the calculations described above are aimed at producing results for comparisons to performance objectives that pertain to the first 10,000 yr after disposal. Following that, and out to the time of peak activity, is considered deep time. Peak activity of the DU waste, which is predominantly ^{238}U, is the time at which the decay products of the parent reach secular equilibrium with the parent. In this case, the peak activity is at about 2.1 million years. For the purposes of the model, deep time is that duration from 10,000 y to 2.1 My.

Given the distinct time frame, the deep time calculations are independent of much of the rest of the model, except that the radionuclide mass in the embankment, as calculated in the Disposal container, is used as a source of radionuclides for dispersal in future lakes. The DeepTimeScenarios container produces estimates of radionuclide concentrations in the water of future lakes, and in the sediments that they deposit, as well as radon flux calculations and rancher scenario dose estimates after the first lake recedes.

5.4.8 Supplemental Containers

The Dashboards container is simply a location in the model for storing Dashboard elements, which are dialog-box-like controls for operating the model and for conveniently viewing results. The model can be executed and browsed without using any dashboards, though their convenience makes them quite useful.

The Simulation Settings container hosts a small number of elements that are used simply to control the simulation. Logical switches and values controlled by the dashboards are kept here.

The dashboards provide access to several results of general interest, most of which are collected in the Results container. In addition to those referenced by the dashboards, there are many other results that provide a more detailed look into the model. Also inside this container are the results needed for performing sensitivity analyses, such as those discussed later in this report.

The Documentation container includes records pertinent to model development, such as the Change Log, illustrations about particular model processes, and a large collection of references supporting the model. The sub-container Documentation\References holds reference materials in PDF format.

6.0 Results of Analysis

The Clive DU PA Model was run in order to evaluate the performance of the disposal system and to understand the sensitivity of input parameters on those results. Endpoints of interest include:

- groundwater concentrations of radionuclides for which GWPLs are specified,

- dose and uranium toxicity hazard to various receptors,

- ^{222}Rn flux in the deep time analysis, and

- lake water and sediment concentrations of ^{238}U in the deep time analysis.

Statistical results (e.g., mean, median, 95th percentile) are based on probabilistic simulations of 10,000 realizations. Sensitivity analysis has been performed on each of the model endpoints of interest.

The DU waste is disposed below the grade of the surface soil surrounding the embankment, about 11 m (36 ft) below the surface of the embankment. The disposal volume above the DU waste is assumed to be backfilled with clean material for the purposes of this DU analysis. The waste is arranged as follows: The bottom waste layer contains SRS DU, the four waste layers above that contain Clean GDP DU, and the top waste layer contains Contaminated GDP DU. Details regarding these wastes can be found in the *Waste Inventory* white paper (Neptune 2023g).

Each waste layer is roughly 0.45 m (18 in) in thickness. In general, the effect of the layer is that the higher the waste is emplaced in the volume, the greater influence it has on doses, which are derived from surface soils. The lower the waste, the greater its influence on groundwater concentrations. For this reason, the contaminated GDP DU wastes are placed above the clean GDP DU wastes, in order to position the ^{99}Tc that is present in contaminated wastes as far from

the groundwater as possible. Details on this modeling can be found in the *Embankment Modeling* white paper (Neptune 2021a). This arrangement allows exploration of the Clive DU PA Model and hence the performance of the system.

Groundwater protection levels are defined in the Clive Facility's groundwater discharge permit (Utah 2014). Radionuclides with GWPLs and for which concentrations are evaluated include ^{90}Sr, ^{99}Tc, ^{129}I, ^{230}Th, ^{232}Th, ^{237}Np, ^{233}U, ^{234}U, ^{235}U, ^{236}U, and ^{238}U (see Section 4.1.2.12). The Clive DU PA Model estimates contributions to groundwater concentrations from the DU wastes for 500 yr, assuming transport to a hypothetical monitoring well. Details on the groundwater transport calculations are provided in the *Unsaturated Zone Modeling* and *Saturated Zone Modeling* white papers (Neptune 2021c, 2021l).

Possible human receptors are of the following basic types, and details are available in the *Dose Assessment* white paper (Neptune 2021b):

- Ranch workers, hunters, and OHV enthusiasts are expected to be present on and near the embankment after the institutional control period.

- Other receptors have doses evaluated at specific locations, including the nearby highway (Interstate-80), the Knolls OHV Recreations Area (Knolls), the nearby rail road (Railroad), the Grassy Mountain Rest Area on I-80 (Rest Area), and the Utah Test and Training Range access road (UTTR).

- All receptors are considered in population dose calculations.

Erosion and the formation of gullies in the embankment cap are modeled using SIBERIA as discussed in Section 4.1.2.9 above. The model may be run with or without inclusion of gully formation, so that their effect on modeled doses may be explored. In the following presentation of results, gully calculations are included. Details on the erosion calculations are provided in the *Erosion Modeling* white paper (Neptune 2023h).

Endpoints related to the deep time assessment include lake sediment concentrations of ^{238}U, ^{230}Th, and ^{226}Ra, and concentrations of ^{238}U, ^{230}Th, and ^{226}Ra in lake water, when lakes are present, as well as ^{222}Rn flux and corresponding rancher dose after the first lake recedes. Lake and sediment concentrations are presented in graphical format to illustrate effects with lakes coming and going with time. Summary statistics of these results are presented at 82,500 years, which is the timestep at which the greatest percentage of lakes is present in the 1000 realizations that were run. Details on the deep time calculation methods are provided in the *Deep Time Assessment* white paper (Neptune 2021h).

Results for all of these endpoints are summarized in tables below. The means and 95th percentiles are used for comparison with performance objectives. Graphs of time histories and sensitivity analysis results are also shown, although, in cases where results are qualitatively similar, only a single representative graph is presented. The results presented below in tables, sensitivity analysis results, and figures are primarily from the Clive DU PA Model v3.0 run for 10,000 realizations with seed 1. Where noted, the results presented in other figures and tables with 1000 realizations are from the Clive DU PA Model v3.0 run for 1000 realizations with seed 1. In both cases, Latin Hypercube Sampling is enabled using mid-points of strata, and Repeat Sampling Sequences is enabled. GoldSim solution precision is set to High.

Some output distributions are positively skewed, with a long tail. The long tails are probably due to a combination of factors that include skewed input distributions that reflect uncertainty in upper values of a parameter, multiplicative effects in the model, and missing correlations between some input parameters. This can lead to implausible combinations of input values. Consequently, results that are far into the tail of the output distributions might be unreliable.

6.1 Groundwater Concentrations

Peak groundwater activity concentrations within 500 yr resulting from the proposed waste disposal are calculated for all radionuclides at a hypothetical monitoring well placed about 27 m (90 ft) from the toe of the waste in the Federal Cell. In the case of the proposed DU waste disposal, only the top slope section of the embankment would contain DU waste, so the effective distance from the DU waste to the well is lengthened by the width of the side slope section to about 81 m (265 ft).

6.1.1 Summary of Results for Groundwater

For those radionuclides for which GWPLs exist, as specified in the facility's permit (Utah 2014), results are shown in Table 2. It should be noted that these statistics summarize the concentrations at 500 yrs. In general, concentrations increase with time, in which case the statistics presented are of the concentrations at 500 yrs. Because all modeled estimates are of mean concentrations, the statistics represent the mean, median, and 95th percentile of the (peak of the) mean concentration. As such, the 95th percentile is analogous to a 95% upper confidence limit on the mean. The large difference between the mean and median concentrations, when values are reported for each, indicates that these output distributions are markedly positively skewed.

Table 2. Summary statistics for peak mean groundwater activity concentrations within 500 yr, compared to GWPLs.

radionuclide	GWPL[1] (pCi/L)	activity concentration at 500 yr (pCi/L)		
		mean	median (50th %ile)	95th %ile
^{90}Sr	42	0	0	0
^{99}Tc	3790	24	3.1E-1	135
^{129}I	21	9.9E-3	5.7E-9	6.2E-2
^{230}Th	83	1.8E-28	0	9.1E-33
^{232}Th	92	1.4E-34	0	0
^{237}Np	7	8.6E-21	0	7.1E-27
^{233}U	26	1.6E-23	0	3.1E-27
^{234}U	26	1.0E-22	0	4.8E-27
^{235}U	27	8.0E-24	0	4.1E-28
^{236}U	27	1.5E-23	0	6.6E-28
^{238}U	26	7.6E-22	0	3.9E-26

[1]GWPLs are from Utah (2014), Table 1A.
Results are based on 10,000 realizations, seed 1.

Since the DU waste is emplaced below grade in the embankment, modeled monitoring well concentrations are greater than they would be if the DU were emplaced at a higher elevation within the embankment for two reasons: 1) The waste is closer to the groundwater, and so has a shorter travel distance, bringing the peak closer in time, and 2) the waste is more concentrated if it is arranged into a smaller volume, thereby decreasing the duration of breakthrough at the well, while increasing its amplitude.
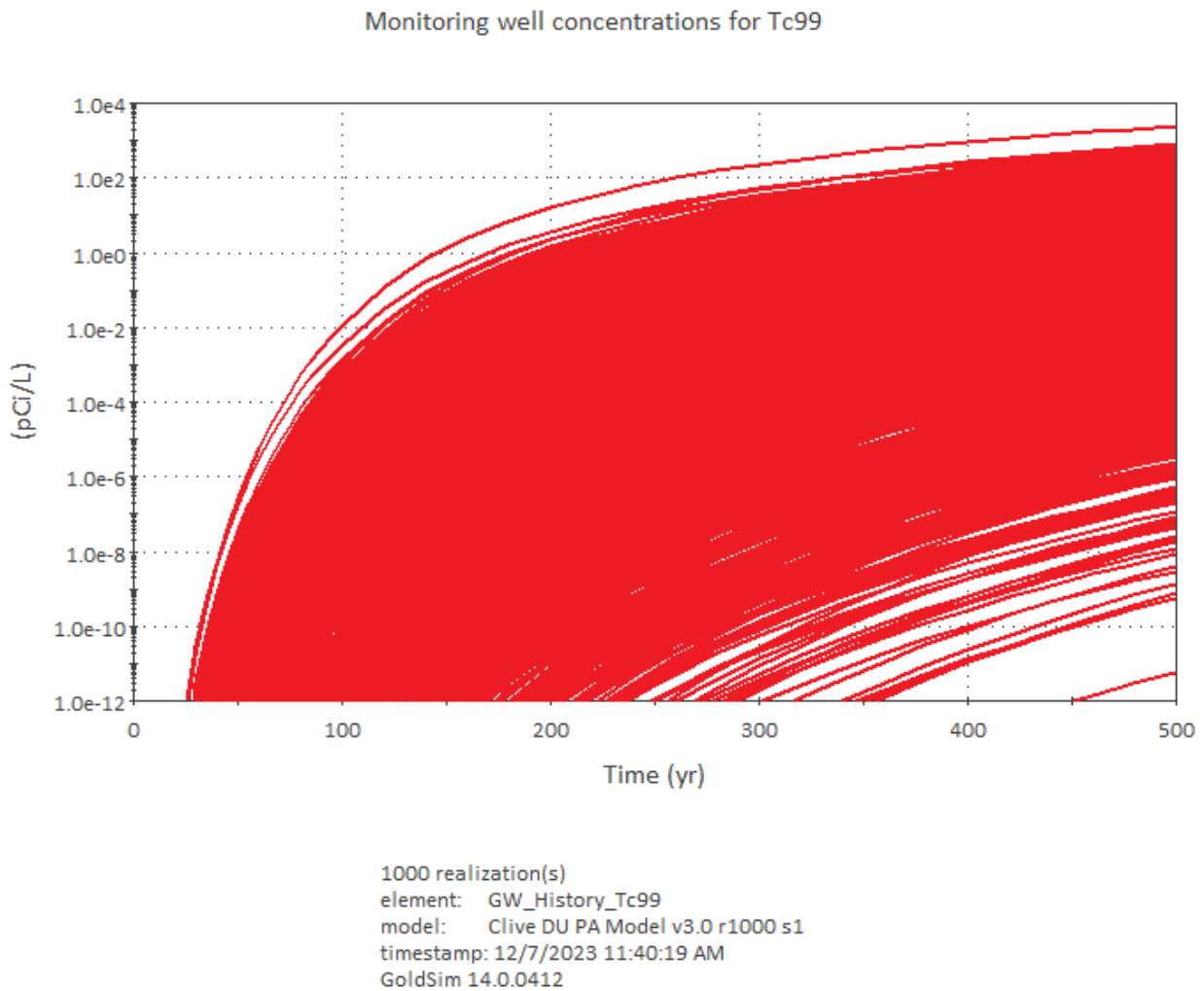
For most radionuclides in Table 2 the groundwater concentrations are negligible compared to the GWPLs. The exceptions are ^{99}Tc and ^{129}I, although the 95th percentile values for these radionuclides are still more than an order of magnitude below the respective GWPLs. The distributions of these concentrations are highly skewed, largely because of the skew in some of the input distributions. For example, the distributions for K_d for ^{99}Tc and ^{129}I are expressed as left-truncated normal distributions, which is a skewed distribution.

In the case of ^{129}I, this radionuclide was not detected in any samples collected from the SRS drums (see the *Waste Inventory* white paper (Neptune 2023g)). Not only was ^{129}I not detected, but it was not identified in any sample. However, because ^{129}I may be present at concentrations below the detection limits, these limits were used directly for creating the input distribution for inventory of ^{129}I. This probably greatly overestimates the inventory of ^{129}I in the DU waste.
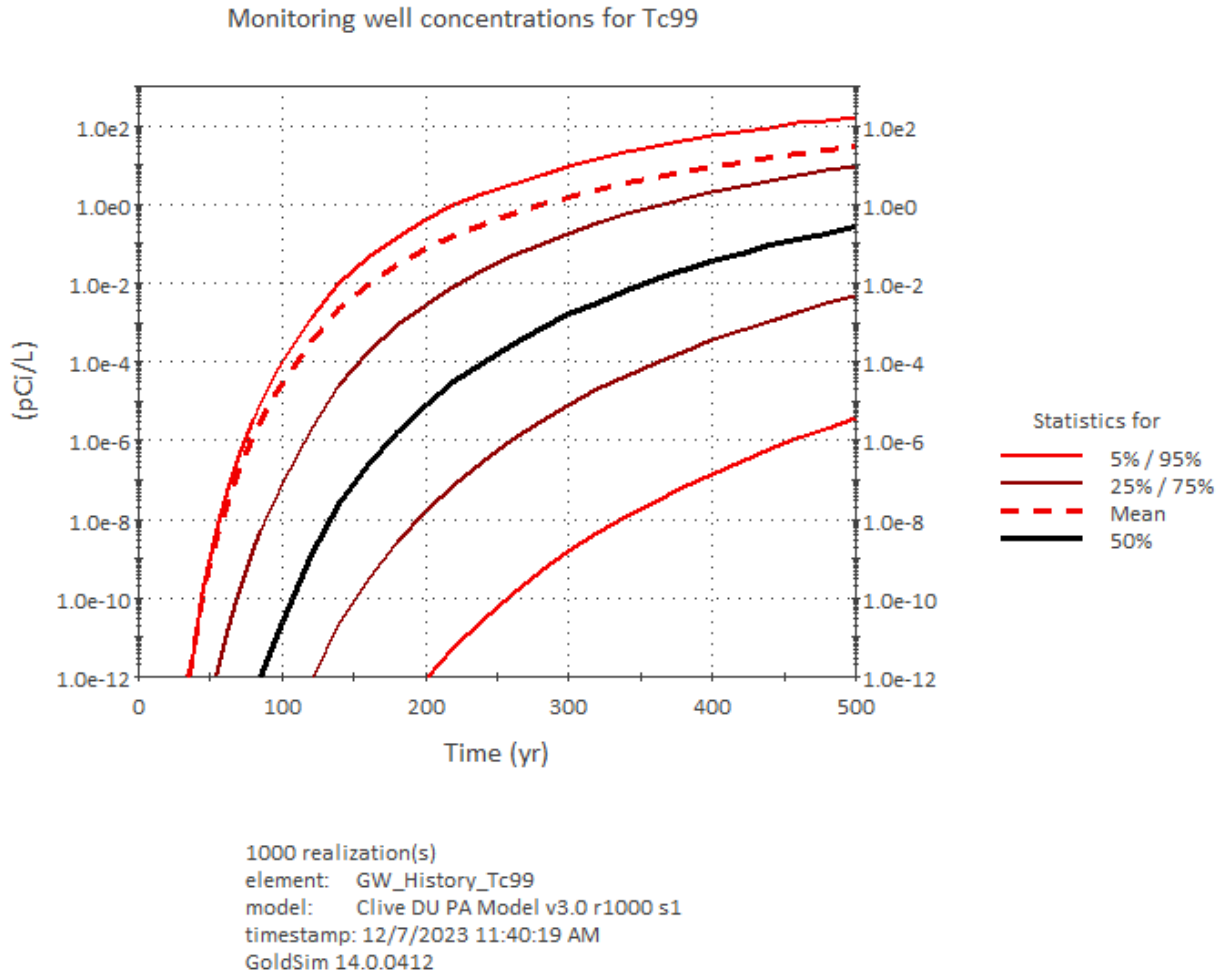
The ^{99}Tc inventory concentration distribution is derived from four datasets that suggest very different potential waste concentrations, with particular uncertainty in the concentration of ^{99}Tc in the GDP waste. Consequently, the input distribution covers more than one order of magnitude of

possible ^{99}Tc concentrations. With more data or better information, it is reasonable to expect that this uncertainty could be reduced.

Technetium-99 is selected to represent a time history of monitoring well concentrations, as shown in Figure 5. Figure 5 shows each of the 1000 realizations, and Figure 6 shows a statistical summary of those realizations. Note that the model results are based on 10,000 realizations, on which the summary statistics in Table 2 are based. Subsequent time histories will show only the statistical summaries. Of particular interest is that the concentrations of ^{99}Tc are considerably less than the GWPL, and concentrations of ^{99}Tc increase over time up to the 500-yr compliance period.

1000 realization(s)
element: GW_History_Tc99
model: Clive DU PA Model v3.0 r1000 s1
timestamp: 12/7/2023 11:40:19 AM
GoldSim 14.0.0412

Figure 5. Time history of ^{99}Tc well concentrations; 1000 realizations shown.

Figure 6. Time history of ^{99}Tc well concentrations: statistical summary of the 1000 realizations shown in Figure 5.

6.1.2 Sensitivity Analysis for Groundwater

A sensitivity analysis of the ^{99}Tc and ^{129}I groundwater concentrations was performed in order to determine which modeling parameters are most significant in predicting its value. As seen in Figure 7 and tabulated in Table 3, the most sensitive parameter for both ^{99}Tc and ^{129}I groundwater concentrations was net infiltration. This parameter is included in the output table from HYDRUS and affects advection of radionuclides to groundwater. The next most sensitive parameter for both radionuclide concentrations was molecular diffusivity in water, which controls diffusion. The soil-water partition coefficient (K_d) was the third most sensitive parameter for both radionuclides. K_d controls sorption to the solid phase, with higher K_d resulting in increased sorption which retards migration of the radionuclides.

Overall, the controlling mechanism is infiltration. The infiltration rate is sufficiently small that waste inventory and K_d are not the primary drivers. Note also that the sensitivity indices are not very large. It is typical in a model that is well structured and specified that a few input variables

have sensitivity indices that are quite large collectively. Otherwise, the model might not be well formed, or the signal is very low. The latter appears to be the case here. Consider that the 50th percentile is essentially zero, in which case the ability of an input variable to differentiate signal responses is a challenge.

Sensitivity analyses for other results are presented in Neptune (2023c).

Table 3. Sensitivity Indices of select peak groundwater concentrations within 500 years.

Radionuclide	SI rank	input parameter	sensitivity index (SI)
waste emplaced below grade			
^{99}Tc	1	Net infiltration	0.41
	2	Molecular Diffusivity in Water	0.19
	3	K_d for Tc [1]	0.14
	4	Meat Preparation Loss	0.05
^{129}I	1	Net infiltration	0.40
	2	Molecular Diffusivity in Water	0.30
	3	K_d for I [1]	0.23

[1] For iodine and for technetium, the same K_d value was used for all materials.
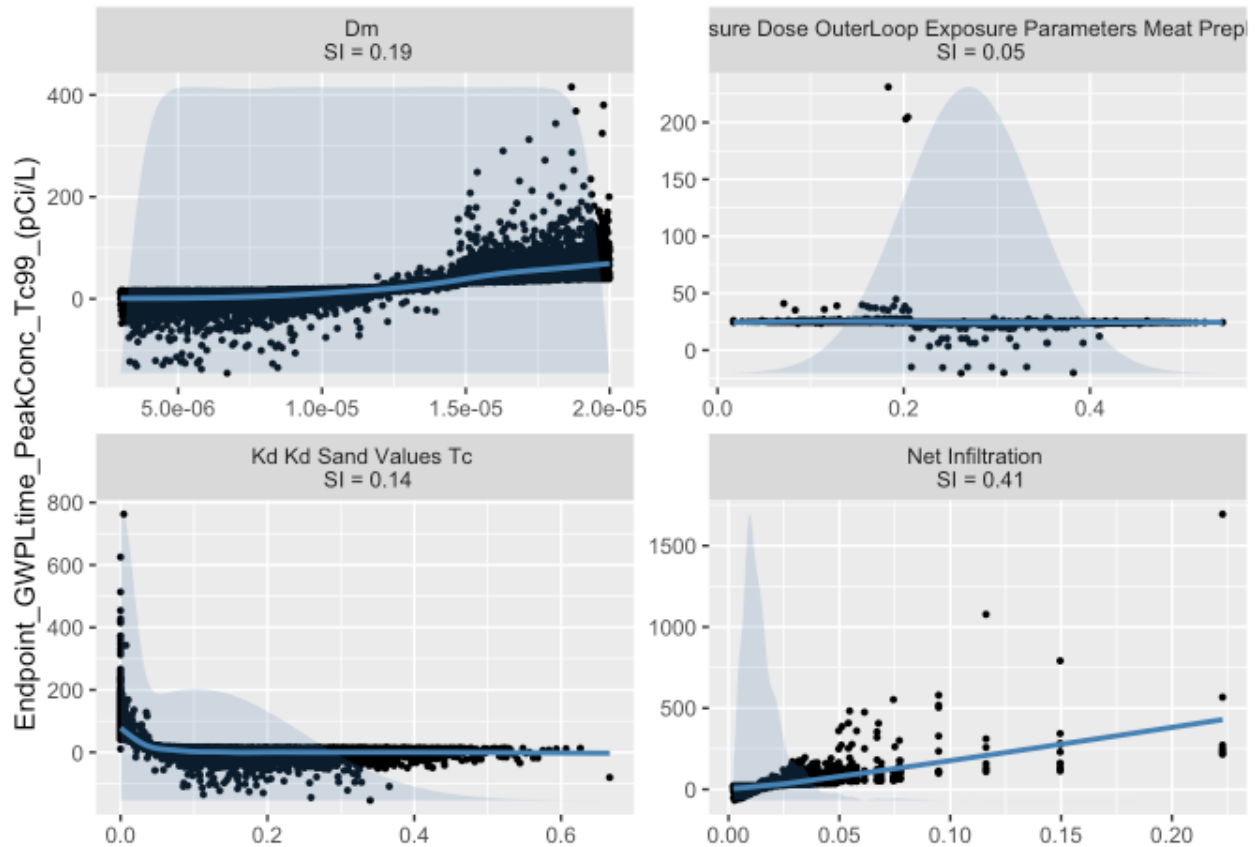
Figure 7. SHAP plot for peak ⁹⁹Tc groundwater concentration in 500 years.

6.2 Receptor Doses

Radiation doses to receptors are calculated as the total effective dose equivalent (TEDE), and are compared to the performance objective of a peak dose of 0.25 mSv (25 mrem) in a year within 10,000 yr (UAC 2018). Comparison with the inadvertent intrusion standard of 5 mSv (500 mrem) in a year is also considered in relation to human-induced gully erosion.

6.2.1 Summary of Results for Doses

The dose results are summarized in Table 4, which shows the statistics for peak TEDE for all receptors for DU waste emplaced below surface grade. These results include consideration of dose related to gully erosion. The greatest doses occur at or near 10,000 years. The peak mean dose results are presented in Table 4 at 10,000 years, along with median and 95th percentile values of the doses at 10,000 years.

Table 4. Peak of the mean TEDE: statistical summary within 10,000 yr.

receptor	TEDE (mrem/yr) at 10,000 yr		
	mean	median (50th %ile)	95th %ile
ranch worker	3.1E-2	2.5E-2	7.3E-2
hunter	2.7E-3	2.1E-3	6.8E-3
OHV enthusiast	4.0E-3	3.5E-3	8.7E-3
I-80 receptor	7.3E-7	5.6E-7	1.9E-6
Knolls receptor	2.1E-6	8.2E-7	8.3E-6
rail road receptor	1.1E-6	8.8E-7	3.0E-6
rest area receptor	1.8E-5	1.5E-5	4.5E-5
UTTR access road receptor	4.1E-4	3.3E-4	1.0E-3

Results are based on 10,000 realizations, seed 1.

Note that the doses to the offsite receptors are very small relative to the doses for receptors that may be exposed on the embankment. Consequently, the attributes of the dose results for offsite receptors are not explored in this discussion. Of greater interest are the doses to the ranchers, hunters, and OHVers. These three classes of receptors are modeled with the intent of capturing dose to each hypothetical individual in the relevant populations (see the *Dose Assessment* white paper (Neptune 2021b)). The data presented hence represent summary statistics for the peak of the mean dose to a diverse set of hypothetical individuals within each group of receptors. The peak of the mean doses occurs at 10,000 years in the Clive DU PA Model, because dose increases with time for DU. Consequently, the 95th percentile is analogous to a 95% upper confidence limit of the mean dose at 10,000 years that might be used under CERCLA, for example.

The greatest doses are to ranch workers; these doses are greater than the doses to hunters and OHV enthusiasts by about an order of magnitude. In all cases the summary statistics present values that are several orders of magnitude below the IHI performance objective of 5 mSv (500 mrem) in a year. Although the model results include consideration of dose that may occur subsequent to gully formation initiated by inadvertent intrusion, these values are also orders of magnitude below the MOP performance objective of 0.25 mSv (25 mrem) in a year.

An evaluation of pathway-specific doses for the three onsite receptors indicates that effectively 100% of the dose is associated with the inhalation exposure pathway. There is practically zero dose related to external radiation from soil or inadvertent soil ingestion, which is because virtually no radionuclides have been transported to surface soil on the cap through the overlying 11 m (36 ft) of embankment within 10,000 years. Even in gullies, soil concentrations of ^{210}Pb, deposited as the progeny of ^{222}Rn subsequent to air-phase diffusion, only reach concentrations of approximately 0.001 pCi/g. Because surface soil particulate radionuclide concentrations and associated dose pathways are so low, the inhalation pathway doses are necessarily related to inhalation of gas-phase radionuclides; namely ^{222}Rn.

6.2.2 Sensitivity Analysis for Doses

Sensitivity analysis was performed on the results for the mean TEDE at 10 ky to ranch workers, hunters, and to OHV enthusiasts. Sensitive parameters are summarized in Table 5, and the partial dependence plot for the ranch worker is shown in Figure 8.

Table 5. Sensitivities of peak TEDE within 10,000 yr.

receptor	SI rank	input parameter	sensitivity index (SI)
waste emplaced below grade			
ranch worker	1	Radon Escape/Production Ratio for Waste	0.38
	2	K_d for Ra in sand	0.11
	3	Molecular Diffusivity in Water	0.08
hunter	1	Radon Escape/Production Ratio for Waste	0.21
	2	Molecular Diffusivity in Water	0.14
	3	K_d for Tc [1]	0.13
	4	Plant Concentration Ratio for Tc	0.07
	5	K_d for Ra in sand	0.07
OHV enthusiast	1	Radon Escape/Production Ratio for Waste	0.60
	2	K_d for Ra in sand	0.16
	3	Molecular Diffusivity in Water	0.09

[1] For technetium, the same K_d value was used for all materials.

Results are based on 10,000 realizations, seed 1.
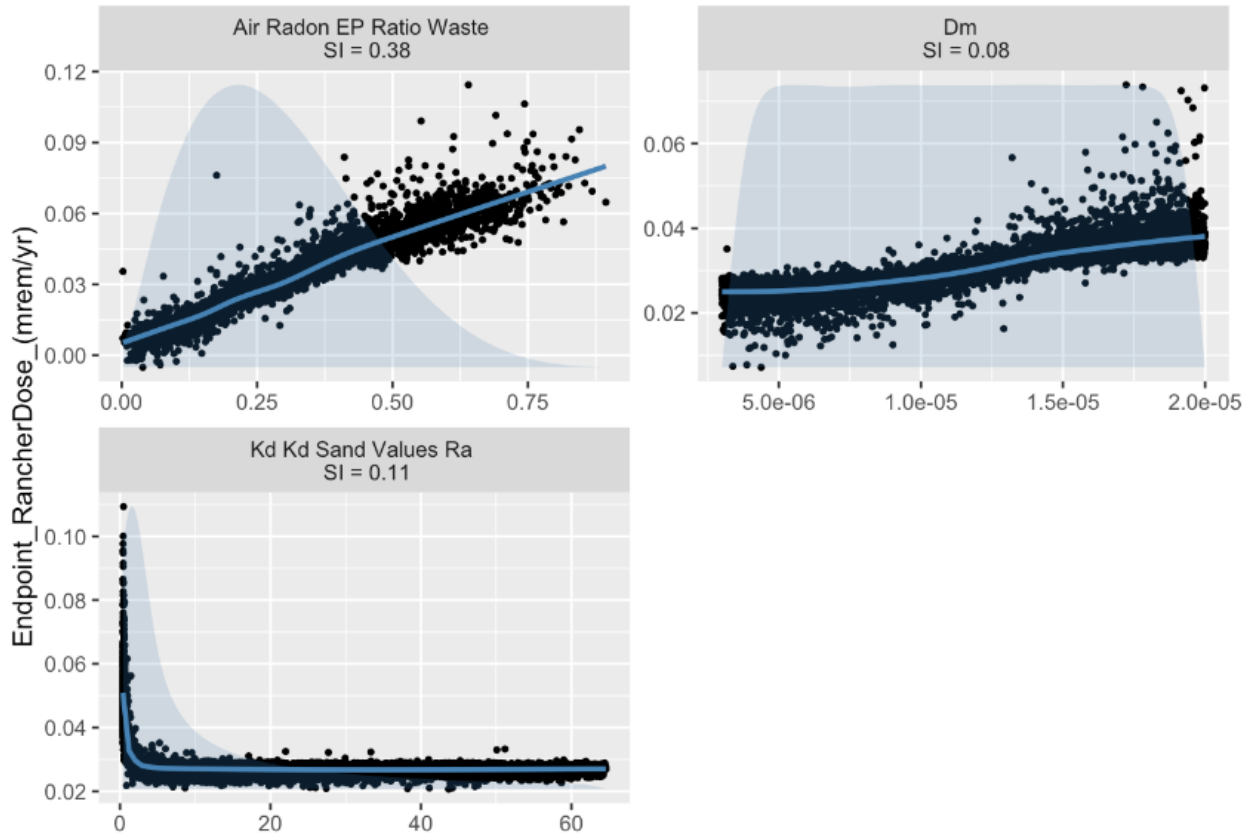
Figure 8. SHAP plots for the mean ranch worker dose, assuming waste below grade.

As shown in Table 5, the most sensitive input parameter for all receptors is the radon E/P ratio, which defines the fraction of ^{222}Rn that escapes into the mobile environment when formed by radioactive decay from its parent, ^{226}Ra. Radon that does not escape but remains within the matrix of the radium-containing waste material stays in place and decays to polonium and then to ^{210}Pb. Note that the higher the E/P ratio, the higher the dose.

The next most sensitive input for the Ranch Worker is the soil/water partition coefficient (K_d) for radium in sand, the parent radionuclide of radon. Radon gas inhalation is an important dose pathway for all receptors at the ground surface. Increased radium partitioning to the solid phase tends to hinder migration of dissolved radium, which reduces surface radon flux and thus doses, as can be seen in the partial dependence plot in Figure 8. Molecular diffusivity in water is the next most important input; increased diffusion of radionuclides through the unsaturated zone tends to increase doses.

The sensitivity analysis confirms that radon is the greatest dose driver in the Model. The sensitive parameters for radiation dose are associated with the release and transport of radon. Diffusivity and K_d affect transport to the ground surface, while higher values of the radon E/P ratio are associated with higher radon doses. As described in the *Dose Assessment* white paper (Neptune 2021b), radon dose is not often calculated in a PA. Instead, radon flux at the surface of a disposal system is commonly calculated and compared to a radon-specific flux criterion. This example perhaps indicates the importance of considering the impact of radon in a dose calculation. If dose

due to radon inhalation was not included in the results, the rancher doses shown in Table 4 would be orders of magnitude lower than those shown.

6.2.3 Screening Groundwater Ingestion Dose

Future potential ranch hands, hunters, and OHV users may come near the Clive site on rare occasions with only transitory exposure to the site. These future receptors may drill a well for routine water ingestion while in the area and drink the groundwater. While that scenario is not likely given the low yield and excessive salinity of the upper aquifer, the dose from groundwater ingestion can be evaluated. The calculations in the Model can be used to assess potential radiological dose to people from future ingestion of potentially impacted groundwater near the Clive site.

Total dissolved solids (TDS) levels in the upper aquifer in the vicinity of the Clive site are approximately 41,000 mg/L, a concentration far in excess of potable levels. Any future routine ingestion of radiologically impacted upper-aquifer groundwater must therefore presume desalinization. Desalinization technologies involving evaporation or condensation would result in complete removal of solutes, including site-related radionuclides of concern, and render groundwater ingestion of radionuclides an incomplete exposure pathway. Therefore, an evaluation of potential radiological dose from groundwater ingestion is performed assuming the use of a filtration technology such as reverse osmosis to generate potable water.

Model results of 10,000 realizations for peak groundwater ingestion dose show a mean dose of 0.4 mrem/yr, a median dose of 0.2 mrem/yr, and a 95th percentile of 1.2 mrem/yr. As expected, ^{99}Tc is the dominant radionuclide contributing to the groundwater ingestion dose.

6.3 Receptor Uranium Hazard Indices

Uranium hazard indices (HIs) within 10,000 yr are calculated for each receptor scenario as the sum of hazard quotients (HQs) for the ingestion exposure pathways defined in Table 1. An HQ is the ratio of the average daily dose (i.e., chemical intake) of a chemical to the corresponding reference dose for that chemical, where a reference dose is an estimate of daily exposure likely to be without appreciable risk of adverse health effects. The uranium HI values are compared to EPA's standard HI threshold of 1.0, a level that indicates that the average daily dose is below the dose associated with health effects.

6.3.1 Summary of Results for Uranium Hazard

The uranium HI results are summarized in Table 6, which shows the statistics for the peak of the mean uranium HI for all receptors.

The HIs for uranium are extremely small relative to the threshold of 1.0, indicating essentially no possibility of observing health effects from uranium toxicity. Similar to the dose results presented above, this indicates that disposal of DU waste below grade, at the bottom of the embankment, is protective of human health and the environment. These values are in compliance with the regulatory standards. Peak mean uranium HI results, across time, occur essentially at 10,000 years since concentrations at the ground surface increase with time within 10,000 years.

Table 6. Peak of the mean uranium hazard index within 10,000 years.

receptor	uranium hazard index at 10,000 yr		
	mean	median (50th %ile)	95th %ile
ranch worker	7.0E-8	1.3E-17	3.4E-8
hunter	4.6E-9	1.1E-18	2.8E-9
OHV enthusiast	6.2E-9	1.5E-18	3.9E-9

Results are based on 10,000 realizations, seed 1.

6.3.2 Sensitivity Analysis for Uranium Hazard Index

Sensitivity analysis was performed on the results for the mean uranium hazard index to ranch workers, hunters, and to OHV enthusiasts, summarized in Table 7. The most sensitive input parameter for the ranch worker uranium HI is the water ingestion rate of cattle. This is a relatively low sensitivity index, but it may indicate that a small amount of uranium transport occurs upward into a region where plants and animals could move small amounts to the surface, at which point beef cattle ingest the uranium and a ranch worker ingests the beef. For the hunter and OHV receptors, all inputs exhibited relatively low sensitivity indices, suggesting that the absolute uranium HI are so low that the model signal is too small to find differentiating factors that explain the results.

Table 7. Sensitivities of uranium hazard index within 10,000 yr.

receptor	SI rank	input parameter	sensitivity index (SI)
waste emplaced below grade			
ranch worker	1	Water Ingestion Rate of Cattle	0.13
	2	UO$_3$ Solubility	0.08
	3	Molecular Diffusivity in Water	0.08
	4	Activity Concentration of Ra-226 in SRS DU Waste	0.06
	5	Porosity of Unit 4 Compacted	0.06
	6	I Solubility	0.05
hunter	1	Mammal Mound Density of Plot 4	0.08
	2	Tracer Element Influence on Soil Ingestion Rate	0.08
	3	Molecular Diffusivity in Water	0.08
	4	I Solubility	0.07
	5	Activity Concentration of Ra-226 in SRS DU Waste	0.07
OHV enthusiast	1	Mammal Mound Density of Plot 4	0.12
	2	Tracer Element Influence on Soil Ingestion Rate	0.12
	3	Molecular Diffusivity in Water	0.11
	4	Activity Concentration of Ra-226 in SRS DU Waste	0.07
	5	Np Solubility	0.05

6.4   ALARA

The focus of the assessment for establishing doses as low as reasonably achievable (ALARA) is an evaluation of potential doses to the entire population of hypothetical individuals. This calculation addresses the cumulative dose to all ranch workers, hunters, and OHV enthusiasts, summed across all individuals and all years of the 10,000-yr simulation. These cumulative population doses, expressed as the TEDE, are shown in Table 8.

Table 8. Cumulative population TEDE: statistical summary.

receptor type	population TEDE (person-rem) within 10,000 yr		
	mean	median (50th %ile)	95th %ile
total population	5.5	4.9	11
ranch worker	1.2	1.1	2.6
hunter	0.76	0.64	1.8
OHV enthusiast	3.5	3.1	7.3

These population doses represent the sum of the doses to all hypothetical individuals in each year over the 10,000-yr simulation. Table 9 shows statistics of the average number of cumulative individuals at 10,000 years for the total population as well as the different receptor types.

Table 9. Cumulative receptor population: statistical summary.

receptor type	population at 10,000 yr		
	mean	median (50th %ile)	95th %ile
total population	3.2E6	3.2E6	3.3E6
ranch worker	1.0E5	1.0E5	1.1E5
hunter	7.6E5	7.6E5	7.9E5
OHV enthusiast	2.3E6	2.3E6	2.4E6

One measure for evaluating the population dose levels shown in Table 8 is by comparing these doses with radiation doses related to natural sources. Average annual individual background dose related to ubiquitous natural background radiation in the United States is approximately 3.1 mSv (310 mrem) (NCRP 2009). For the total population of about 3 million individuals, natural background radiation dose is therefore approximately 930,000 rem, a level that is many orders of magnitude higher than the population doses shown in Table 8.

A second measure for these population doses can be obtained by considering the person-rem costs suggested by NRC (see the *Decision Analysis* white paper (Neptune 2021d)). Prior to 1995, NRC suggested a flat $1,000 per person-rem cost. Subsequent to 1995, NRC suggested a value of $2,000 with a discounting factor of 7% for the first 100 years, and 3% thereafter. NRC also suggested that a range of $1,000 to $6,000 might be reasonable, with a best estimate of $2,000. NRC noted that the intent of raising the person-rem costs from $1,000 to $2,000 was to accommodate discounting in an economic analysis. Note that the intent of the NRC approach is to capture the societal effects of added dose to the public. However, more recently, NRC (2015) suggests a value of $5,100 per person-rem. Further discussion is provided in Neptune (2021d). If a flat rate of $5,100 is applied to the population dose estimates provided above in Table 8, then the costs associated with these scenarios are provided in Table 10.

Table 10. Statistical summary of the flat rate ALARA costs.

simulation scenario	population ALARA costs over 10,000 yr		
	mean	median (50th %ile)	95th %ile
total population	$28.050	$24,990	$56,100
ranch worker	$6,120	$5,610	$13,260
hunter	$3,876	$3,264	$9,180
OHV enthusiast	$17,850	$15,810	$37,230

Note that discounting could also be applied, but this would simply result in lower costs. This analysis shows that the ALARA costs involved are small (for the total population, about $6 per year, or considerably less than $1 per day) and that the estimated population dose is a fraction of natural background radiation dose. The reasons for this are that there are few receptors in the model that are involved in ranching, hunting, or OHV activities at the site at any particular time, the concentrations are low, and, hence, the individual doses are also low.

6.5   Deep Time Results

The deep time model addresses in a heuristic fashion the fate of the Federal Cell from 10 ky to 2.1 My, the time at which DU reaches secular equilibrium. The model addresses the needs identified in Section 5(a) of R313-25-9 of the UAC to perform additional simulations for the period where peak dose occurs, for which the results are to be analyzed qualitatively. Even though the deep time model runs to 2.1 My and there is huge uncertainty in predicting human society and evolution that far into the future, rancher doses are calculated to provide a context for radon fluxes which are calculated when no lake is present. The output of the deep time model is also presented in terms of concentrations of radionuclides in relevant environmental media.

The deep time model considers the return of lakes in the Bonneville Basin that reach or exceed the elevation of Clive. Two classes of lakes are considered. The first is a deep lake similar to Lake Bonneville that inundates the Clive Facility. It is deep and adds to materials that are currently on the Bonneville Basin floor. This type of lake is assumed to occur once every 100 ky in line with the 100-ky climate cycles that have occurred for the past 1 My or so. The second type of lake is shallower and is termed an intermediate lake. It is also assumed to inundate the Clive Facility and to add sediment materials but is not a deep lake like Lake Bonneville. It is more similar to the Gilbert Lake that occurred at the end of the last ice age. This type of lake is assumed to occur several times in each climate cycle in response to colder, wetter conditions.

Return of a lake at or above the elevation of Clive is assumed to result in the destruction of the Federal Cell. The above-grade embankment material and radionuclides are assumed to be dispersed through wave action. The dispersal area forms the basis for the lake volume in which radionuclides are dissolved and ultimately settle back to the basin floor through precipitation or through evaporation as the lake recedes. The lake cycle involves movement of the radionuclides, subject to continuing decay and ingrowth, from the sediment into lake water and back to sediment as the lake forms and recedes. The dispersed radionuclides are assumed to be fully mixed with the accumulated sediment. Sediment accumulates on average at the rate of about

16.5 m per 100-ky climate cycle. The current Unit 3 layer of sediment at Clive, which is derived from Lake Bonneville, is assumed to be a confining layer.

The lake cycle effects on transport processes are complex. Sediment core records show significant mixing of sediment, but also can be used to identify significant lake events in the past several hundred thousand years. The extent of sediment mixing is not well understood. The mechanisms for dispersal of a relatively soft pile of material in the middle of a desert flat are not well understood. The extent of mixing of dissolved materials in a deep lake is also not well understood. The model, consequently, is simplified to the point of acknowledging lake return, destruction of the Federal Cell, and cycling of radionuclides between periodic lakes and basin sediments.

In particular, the model overly simplifies the lake cycle processes and the effect of those processes on the transport of radionuclides. It limits the dispersal of radionuclides through time. Destruction of the Federal Cell is assumed to occur with a lake that at least reaches the elevation of Clive. This means that even a very shallow lake is assumed to destroy the embankment. With the sediment acting as one large mixing cell, lake water diffusion can occur across the entire depth of the sediment, no matter how deep. The simplified model ignores increased precipitation and cooler conditions as the time of lake return approaches, which would move radionuclides downwards in the sediment. With these simplifying assumptions, some (perhaps unreasonably) high lake water and sediment concentrations are predicted by the model.

The area of dispersal of the Federal Cell is captured with a simple distribution that reflects the area of an intermediate lake. This fixes a dispersal area. Dissolution into the lake is assumed to occur and to be mixed in the entire lake. The same dispersal area is used for both intermediate and deep lakes, limiting both the volume of water within which dissolved materials might mix and the area in which precipitates and evaporates can return.

Although the embankment material is dispersed within a specified dispersal area, isolation of any part of the sediment profile is assumed not to occur. That is, the sediment is assumed to completely mix with previous sediment for every lake event. Lake sedimentation does not allow burial or isolation of previously formed sediment layers. Since different lakes can be identified in sediment cores, this again limits the dispersal of the radionuclides.

The model therefore represents a closed system that cycles radionuclides from lake water to sediment and back again. Decreased concentrations in sediment are obtained because of the increased sediment load, but the mass of radionuclides available to diffuse into each lake is not different in time, except from decay and ingrowth.

Deep time model results such as radon flux are considered in the context of gauging system performance and may provide limited insight into the behavior of the disposal system in deep time. Based on potential future radon fluxes, a rancher dose is calculated in deep time to provide a context for the radon flux results, consistent with the rancher scenario from the first 10,000 years of the model.

Conceptually, deep time will result in a combination of repeated isolation of sediment layers and more dispersal than modeled. This will cause mixing over ever-increasing areas and volumes, rather than mixing within a closed system. Consequently, concentrations of radionuclides will

decrease with each lake cycle and with each climate cycle. However, the constraints of the model do not allow lake water concentrations to decrease with each cycle, and sediment concentrations decrease only because of the additional mass of sediment within which the DU waste is mixed.

In light of the simplifications in the model, the results for the deep time scenario are presented primarily within the first 100-ky cycle, in which the first intermediate or deep lake will return and the Federal Cell will be obliterated. Consideration of model assumptions should be used when interpreting results beyond the first 100-ky cycle. Summary statistics concentrations are presented at 82,500 years, which is the timestep at which the greatest percentage of lakes is present on average in the first 100-ky cycle across 1000 realizations. The focus of the deep time results is, consequently, on the effects of dispersal on concentrations of ^{238}U and its progeny in lake water and sediments within the first 100-ky climate cycle, as well as on ^{222}Rn flux and rancher dose after the first lake recedes. Progeny of ^{238}U presented include ^{230}Th and ^{226}Ra. Unless otherwise noted, deep time results are presented for 1000 realizations in order to capture the temporal changes in these results most clearly.

6.5.1 Sedimentation and Lake Timing Results

Thickness of the sediment above the DU waste is shown in Figure 9. The next lake to reach the elevation of Clive is assumed to occur no sooner than 50 ky into the future, so only aeolian deposition, at a constant (uncertain) rate, contributes to accumulation of sediments in the vicinity of Clive. Note that the embankment exists until the advent of the first lake, so the aeolian deposition thickness up to 50 ky is the only sediment accumulation in the vicinity of Clive. When a lake reaches the Clive elevation, aeolian deposition is augmented by the deposition of lake-derived sediments. Because the number and timing of such lakes and the depth of deposited sediments are uncertain, the variability in sediment thickness after 50 ky is considerably greater than in the initial 50-ky modeling period. The change in the slope of the sediment thickness curve at approximately 75 ky reflects the deposition of sediment from deep lakes that often appear at this time within the 100-ky climate cycle. Based on variable depositional rates, sediment thickness increases with time at a mean rate of approximately 16.5 m per 100 ky climate cycle.

The increasing depth of material covering the disposed DU waste over time will result in attenuation of radon flux. However, this rate of attenuation will be partly offset by the slowly increasing activity of the radioactive progeny of ^{238}U. Modeling results indicate that sediment accumulation overwhelms the influence of progeny ingrowth. This is revealed by inspection of the results of individual model realizations, where radon flux is always highest at the model time when the first intermediate lake recedes and then decreases over time to the end of the modeling period. Hence, the time of peak radon flux is equivalent to the time when the first lake to reach the elevation of Clive (and to destroy the embankment by wave action) has just receded from the location of the below-grade disposed DU waste.

The time when the first intermediate lake returns after 50 ky is modeled as a Poisson process and varies with each model realization. 100% of intermediate lakes occur within the first 80 ky of the 1000 realization simulation. Deep lake start times are modeled as a log-normal distribution which occurs before 100 ky. As shown in Figure 10, the likelihood that the first lake to reach Clive has appeared increases with time from 50 ky such that there is approximately an 80% probability that
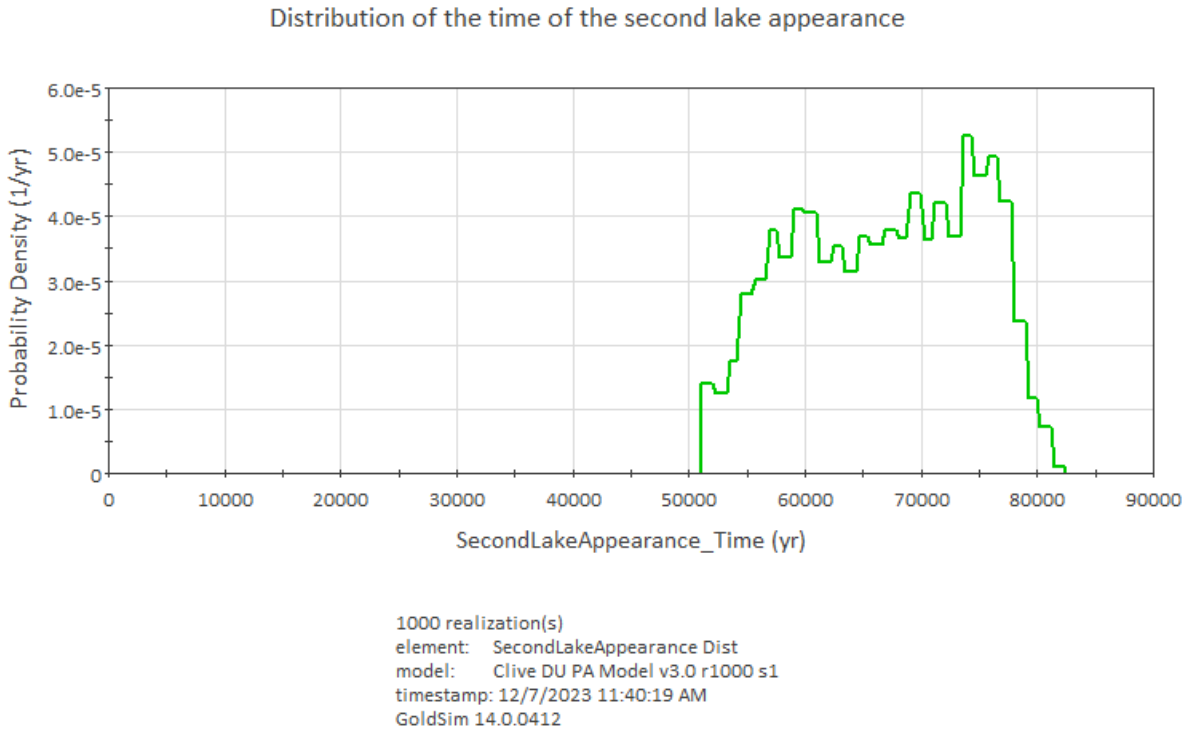
a lake will have appeared by approximately 66 ky. At that time the advent of an intermediate lake is overtaken by the probability that a deep lake will begin within this 100-ky climate cycle.
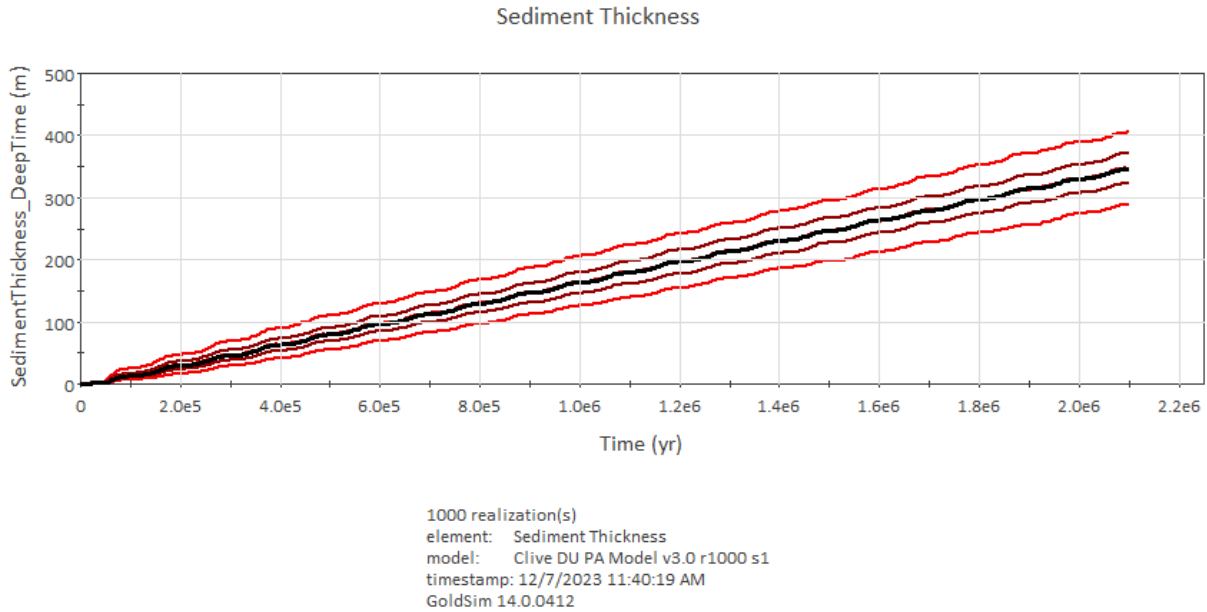
Figure 9. Evolution of sediment thickness in deep time.
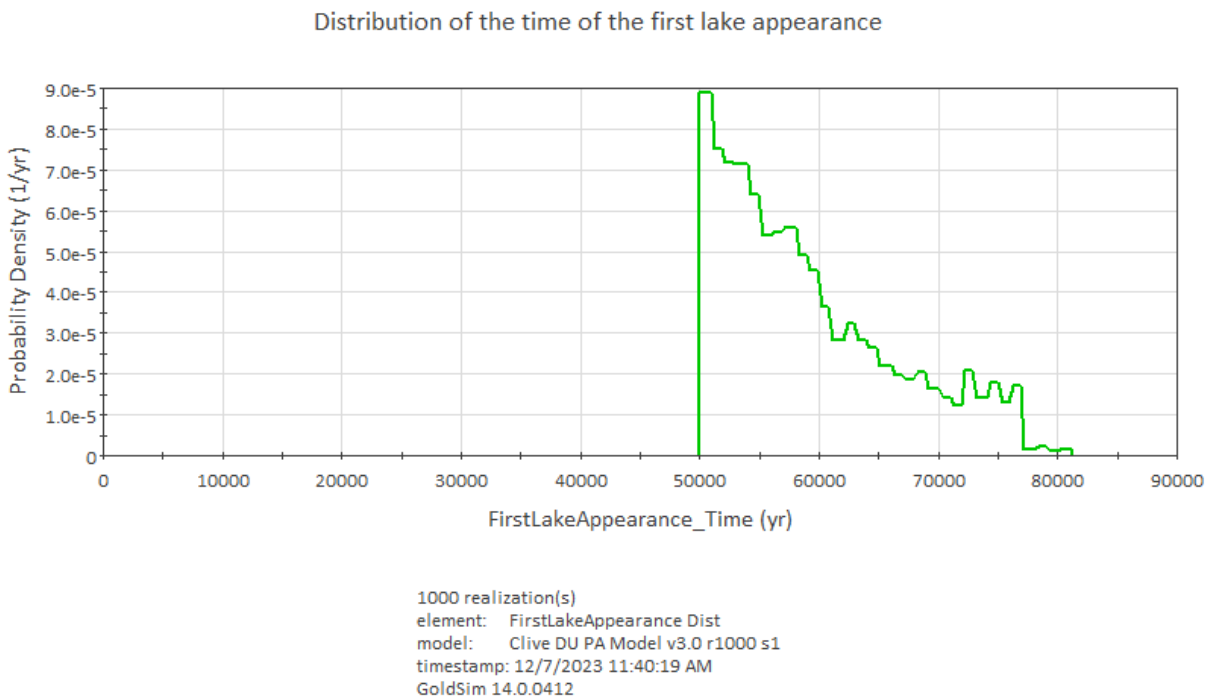
Figure 10. Time of appearance of first intermediate lake to reach the Clive elevation.

Figure 11. Time of appearance of second lake (intermediate or deep) to reach the Clive elevation.
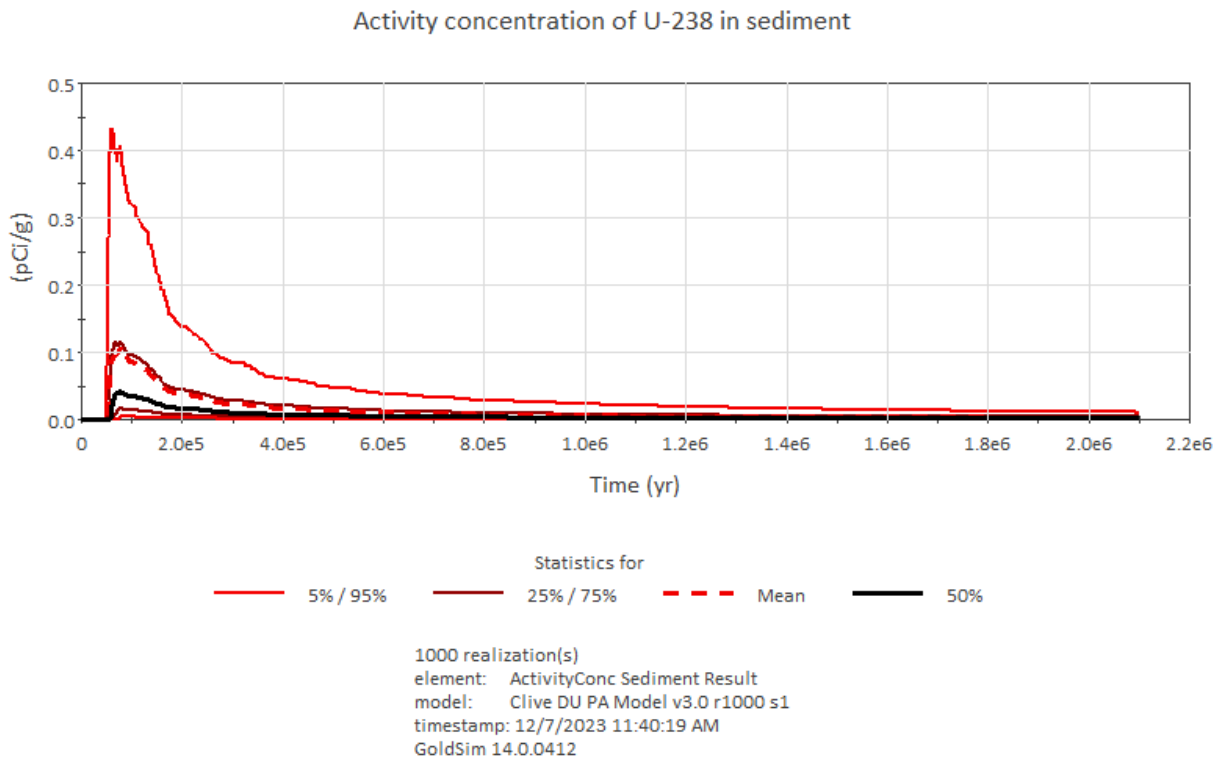
6.5.2 Lake Sediment Concentrations

Results are presented similarly in Table 11 for concentrations of ^{238}U and its progeny in sediment derived from successive lakes. These results are statistical summaries of lake concentrations at 82.5 ky. Lake sediment concentrations are presented at 82,500 years, which is the timestep at which the greatest percentage of lakes is present on average in the first 100-ky cycle across 1000 realizations. By that point in time, ^{230}Th and ^{226}Ra have ingrown sufficiently to be present in computable concentrations.

Table 11. Statistical summary of deep time sediment concentrations at model year 82,500. Based on 1000 realizations, seed 1.

	25th Percentile	Median	Mean	95th Percentile
U-238 sediment concentration (pCi/g)	0.015	0.039	0.10	0.38
Ra-226 sediment concentration (pCi/g)	2.2E-3	6.2E-3	0.014	0.050
Th-230 sediment concentration (pCi/g)	2.3E-3	6.3E-3	0.014	0.051

Time history plots of radionuclide concentrations in future lake sediments for [238]U and its progeny, [230]Th and [226]Ra, are presented in Figure 12, Figure 13, and Figure 14, respectively, over 2.1 My. These plots show a large increase in concentrations as a consequence of the first lake event, with subsequent decreases as the sediment load increases.

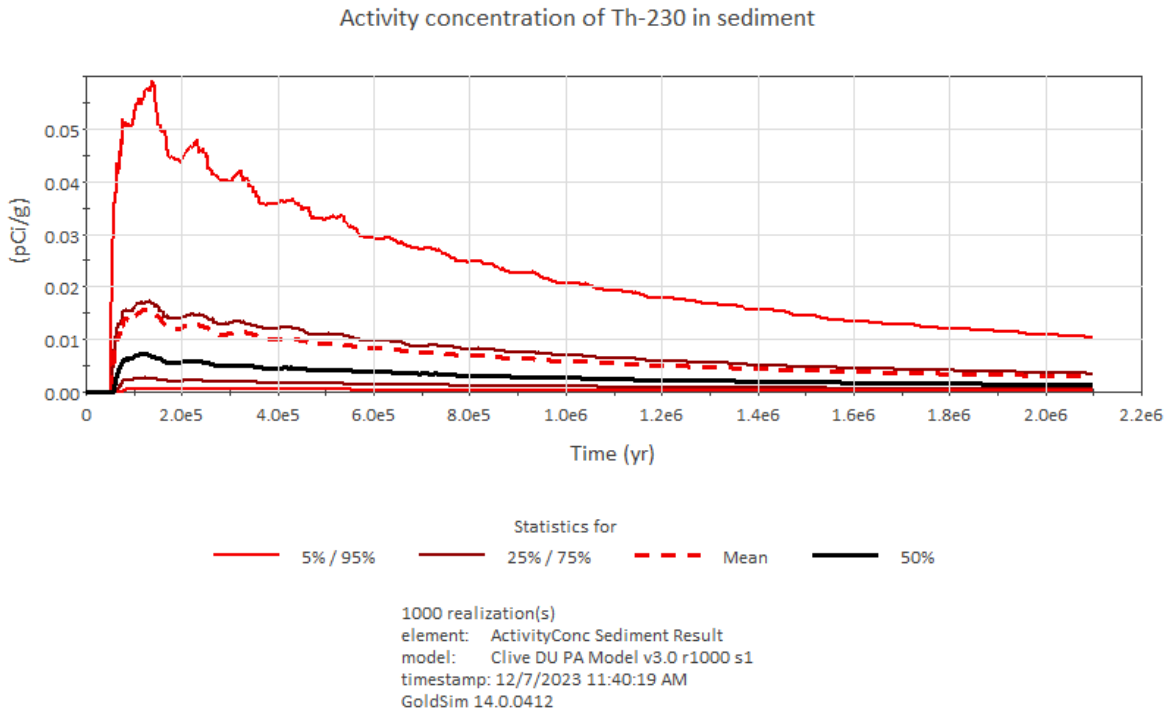**Figure 12. Time history of concentrations of uranium-238 in sediments.**

Figure 13. Time history of concentrations of thorium-230 in sediments.
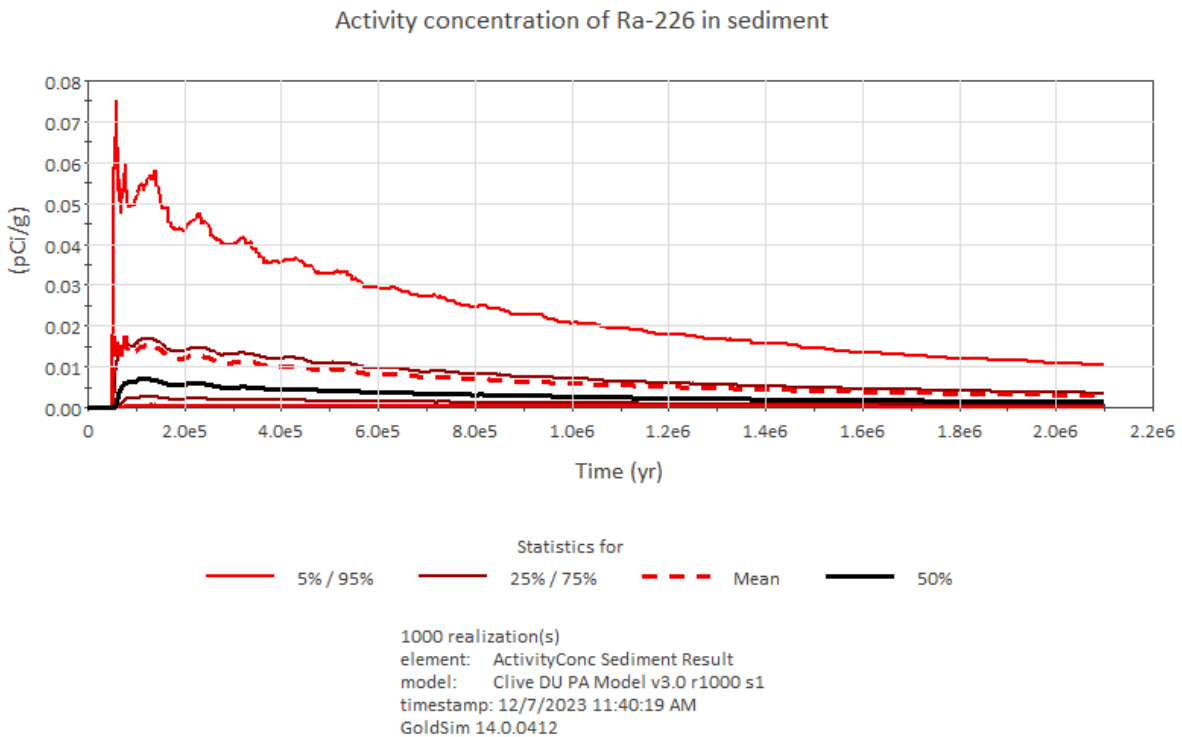

Figure 14. Time history of concentrations of radium-226 in sediments.

6.5.3 Lake Water Concentrations

A summary of lake water concentrations of ^{238}U and some of its progeny are presented in Table 12. Lake water concentrations are presented at 82,500 years, which is the timestep at which the greatest percentage of lakes is present on average in the first 100-ky cycle across 1000 realizations. By that point in time, ^{230}Th and ^{226}Ra have ingrown sufficiently to be present in computable concentrations.

Table 12. Statistical summary of deep time lake concentrations at model year 82,500. Based on 1000 realizations, seed 1.

	25th Percentile	**Median**	**Mean**	**95th Percentile**
U-238 lake concentration (pCi/L)	5.6E-7	2.4E-05	4.6E-3	2.3E-02
Ra-226 lake concentration (pCi/L)	0.26	0.74	1.5	5.3
Th-230 lake concentration (pCi/L)	0.26	0.76	1.5	5.4

Time history plots of lake water concentration statistics for ^{238}U and its progeny, ^{230}Th and ^{226}Ra, are presented in Figure 15, Figure 16, and Figure 17, respectively, across 2.1 My. These are presented on a log scale to capture the full concentration range. The jagged nature of the plots is due to the fact that lake water concentrations are zero when there is no lake present, and intermediate lakes only occur on average four times per 100 ky. Lake water concentrations tend to peak near the end of the period of the deep lake, which provides time for the radionuclides to dissolve into the lake.

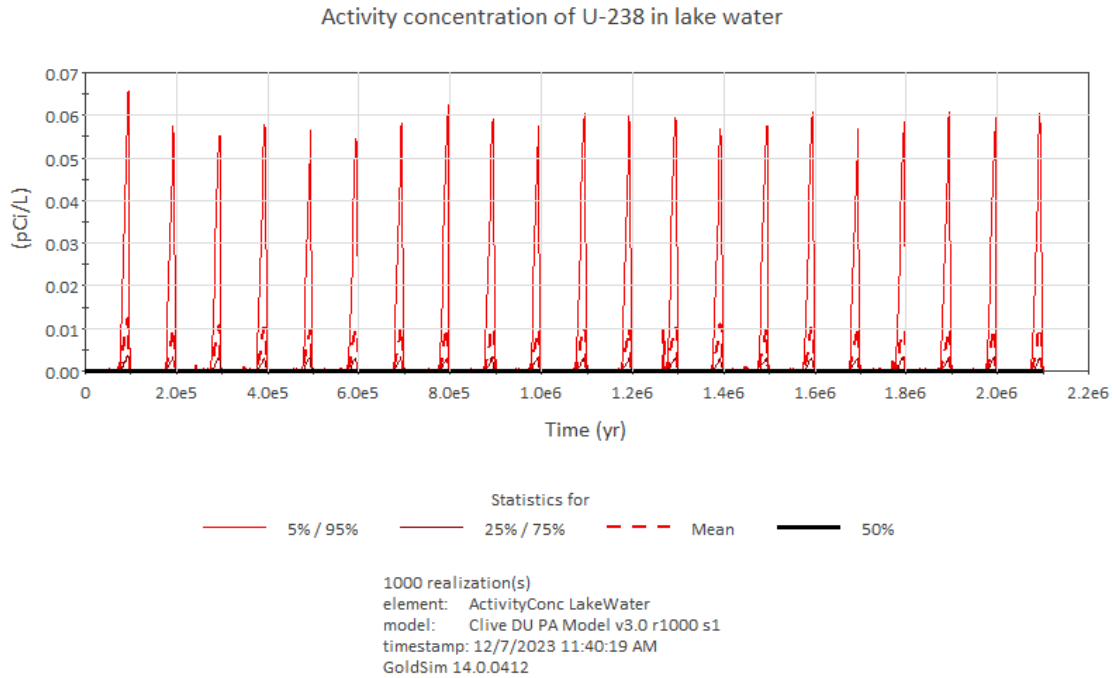Activity concentration of U-238 in lake water

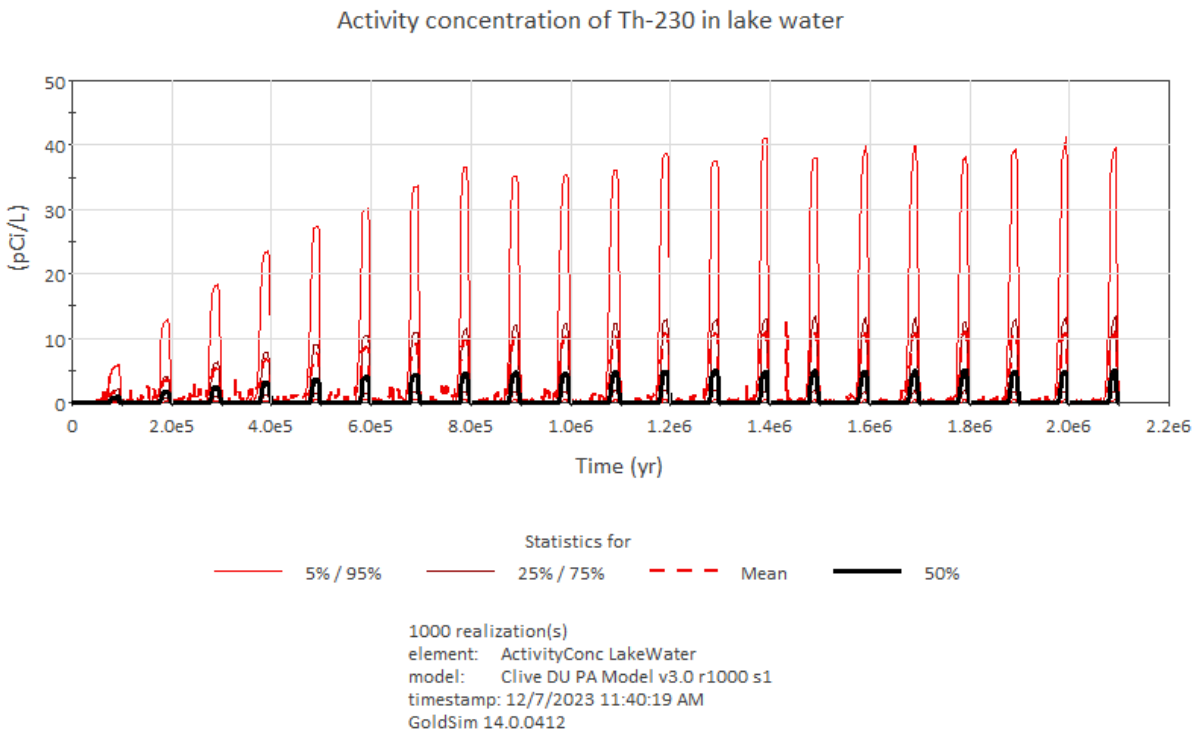**Figure 15. Time history of concentrations of uranium-238 in lake water.**

Activity concentration of Th-230 in lake water

Figure 16. Time history of concentrations of thorium-230 in lake water.

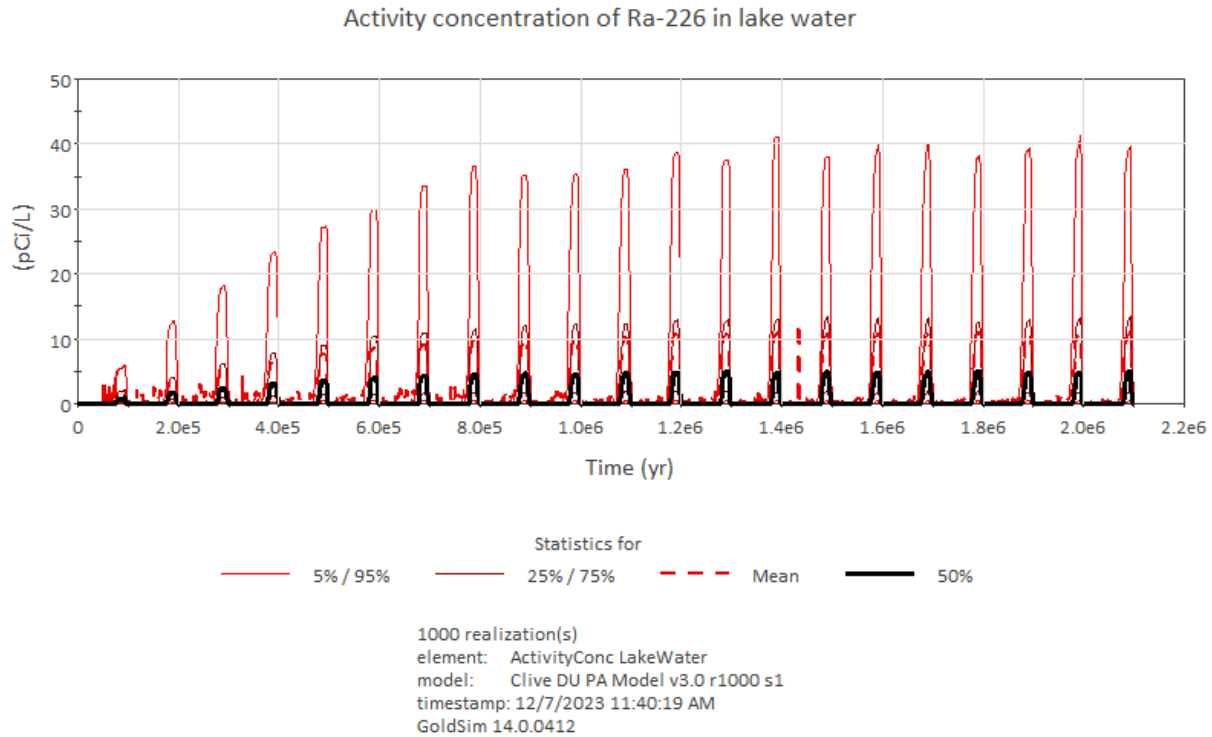Activity concentration of Ra-226 in lake water

Figure 17. Time history of concentrations of radium-226 in lake water.

6.5.4 Radon Flux Results (10,000 Realizations)

A statistical summary of radon flux results after the first lake recedes are presented in Table 13. The time when the first intermediate lake returns after 50 ky is modeled as a Poisson process and varies with each model realization. Therefore, the time of peak radon flux also varies with each realization. Median values are below the 10,000-yr time frame regulatory limit of 20 pCi/m^{2}s.

Table 13. Statistical summary of radon-222 flux concentrations. Based on 10,000 realizations, seed 1.

result	Radon-222 flux (pCi/m2-s)		
	mean	median (50th %ile)	95th %ile
After 1st lake	24	9.0	100
Before 2nd lake	30	11	120

By comparison, peak radon flux over the 10,000-year time frame is orders of magnitude lower. Mean and median radon peak flux within 10,000 years is 0.013 and 0.011 pCi/m^2-s. The 95th percentile radon flux within 10,000 years is 0.027 pCi/m^2-s.

Radon flux over time is shown in Figure 18. Although radon flux will be highest at times closest to 50 ky, in most realizations a lake will not have occurred until closer to 60 ky. The change in the slope of radon flux curve before 100 ky in Figure 18 reflects the deposition of sediment from a deep lake that appears by this time within the 100-ky climate cycle.

The peak of the mean radon flux shown in Figure 18 is approximately 13 pCi/m²-s across 1,000 realizations. The peak occurs at about 60,500 yr. This value is lower than the mean radon flux after the first lake recedes (above) since that value occurs at various points in time and the mean flux in Figure 18 is calculated for each point in time.

Although the median and mean sediment thickness track closely (Figure 9), the mean radon ground surface flux is much larger than the median. This strongly skewed result for radon flux is a consequence of the nonlinearities inherent in the NRC radon ground surface flux calculation. These are equations (9) through (12) in NRC (1989), here reproduced without detailed explanation:

$$J_t = 10^4 R_t \rho_t E_t \sqrt{\lambda D_t} \tanh\left(x_t \sqrt{\lambda / D_t}\right)$$

$$b_t = \sqrt{\lambda / D_t}, \quad b_c = \sqrt{\lambda / D_c}$$

$$a_t = n_t^2 D_t [1 - (1-k)m_t]^2, \quad a_c = n_c^2 D_c [1 - (1-k)m_c]^2$$

$$J_c = \frac{2 J_t e^{(-b_c x_c)}}{1 + \sqrt{a_t / a_c} \tanh(b_t x_t) + \left[1 - \sqrt{a_t / a_c} \tanh(b_t x_t)\right] e^{(-2 b_c x_c)}}$$

The definitions of variables are available in the NRC Regulatory Guide (NRC 1989), but it is clear that these equations will produce a highly nonlinear result, J_c, which is the ground surface flux of radon. So, even though all the inputs to the calculation are essentially normal distributions, the complexity of dividing one by another and involving powers (e.g., e^x) and hyperbolic tangent produces a nonlinear result.
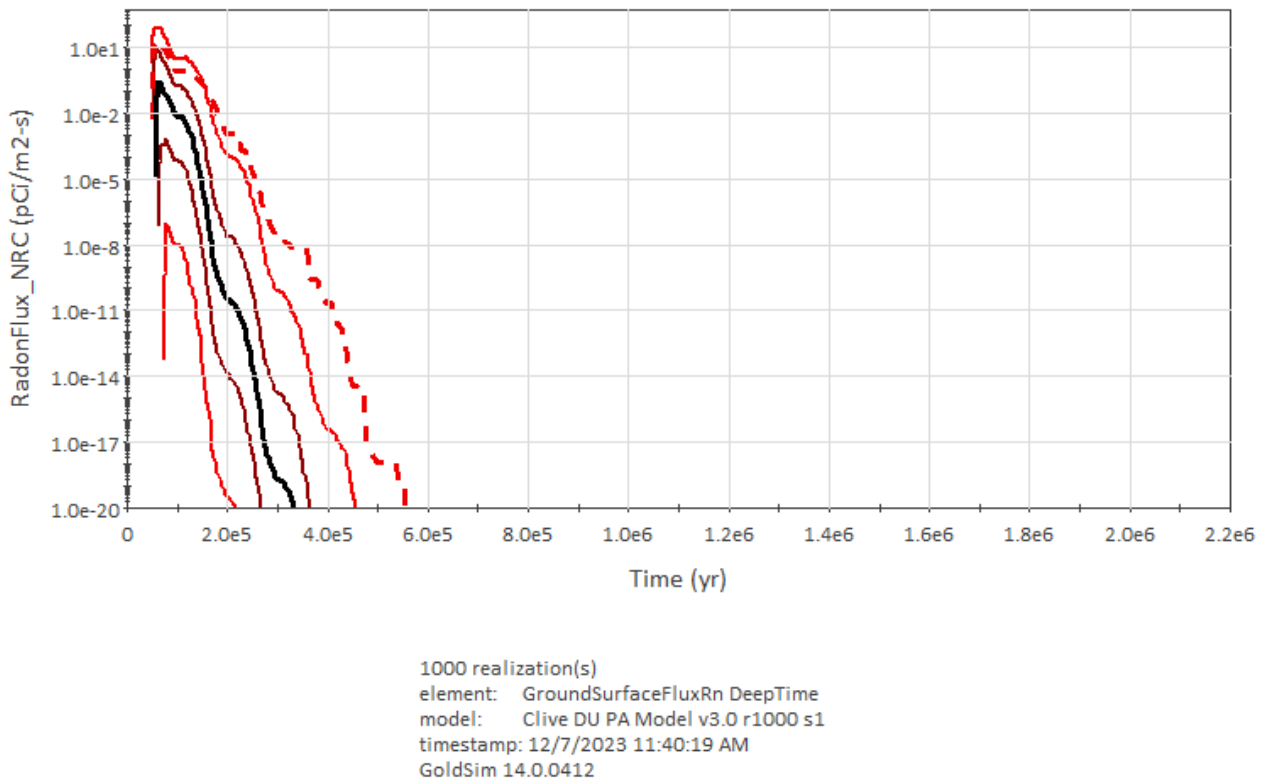
Deep time ground surface flux of Rn-222

1000 realization(s)
element: GroundSurfaceFluxRn DeepTime
model: Clive DU PA Model v3.0 r1000 s1
timestamp: 12/7/2023 11:40:19 AM
GoldSim 14.0.0412

Figure 18. Radon-222 ground surface flux in deep time.

6.5.5 Rancher Radon Results (10,000 Realizations)

Doses to a rancher receptor are calculated to provide a context for the radon flux calculations, using radon flux after the first lake recedes and before the second lake (Table 14). The rancher exposure scenario provided the greatest dose to a receptor in the Model from 10,000 years, so it was used here for comparison. Rancher dose is less than 1 mrem/yr even at the 95th percentile of the results.

Table 14. Statistical summary of doses to ranchers. Based on 10,000 realizations, seed 1.

	Rancher dose (mrem/yr)		
result	mean	median (50th %ile)	95th %ile
After 1st lake	0.18	0.059	0.72
Before 2nd lake	0.22	0.071	0.90

One of the objectives of a PA, as defined in the UAC R313-25-9, is site stability. The performance standard for stability requires that the facility must be sited, designed, and closed to achieve long-term stability and to eliminate to the extent practicable the need for ongoing active

maintenance of the site following closure. If the intent is to minimize the need for ongoing active maintenance, as stated, then obliteration of the Federal Cell in deep time achieves this goal, since concentrations are low and the need to maintain the site disappears completely. In addition, continued deposition through aeolian processes in inter-glacial periods, or through lake deposition otherwise, will continue to affect the site, either by providing additional cover, or through continued mixing with newly formed sediment layers.

7.0 Summary

This report lays out the approach taken to developing the PA model for DU waste disposal in the Federal Cell at the Clive Facility, and presents results of the updated Model (Clive DU PA Model v3.0) with accompanying sensitivity analyses. The purpose of this section is to summarize the results, to provide additional interpretation of the results, and to compare the results more directly to performance objectives in a compliance evaluation.

7.1 Interpretation of Results

Important results of the quantitative Clive DU PA Model can be summarized, given the compliance time frames of interest, in terms of doses to receptors, groundwater concentrations of soluble radionuclides, and disposal system evolution in deep time. The DU waste disposal configuration evaluated in the Model assumes burial below the grade of the area surrounding the embankment. The Model is run assuming that gullies are static in the simulation period, forming immediately in the first year.

Doses to all receptors are driven primarily by inhalation exposure to radon. Groundwater concentrations of ^{99}Tc would be expected to increase as the ^{99}Tc-containing waste is emplaced lower in the disposal facility. These concentrations are driven by infiltration and molecular diffusion. Transport mechanisms move waste either up into the accessible environment or down towards groundwater. The modeling results indicate that the groundwater performance objectives can still be satisfied when DU waste is placed below grade, which also minimizes dose to receptors on the ground surface.

For the configuration used in the Clive DU PA Model v3.0, erosion is included in the Model, but has only minimal impact on dose results since the waste is buried much deeper (11 m) than the gully maximum depth (into erosion model layer 4, between 0.46 and 0.61 m). The impact of gullies has not been fully developed in terms of their effect on biotic activity, radon transport, or infiltration.

The ALARA analysis results indicate that population doses are small compared to natural background radiation dose, and costs are low compared to disposal and other costs. The population doses are small because the population itself is small, and the doses to any hypothetical individual in the population are also small. Taking this ALARA approach to site performance would suggest that this is a good site for disposal of DU waste. There is room for improvement in this simple ALARA decision analysis. For example, other factors could be included in the analysis such as transportation and worker safety factors, and the cost per person rem could be reevaluated. However, the small population doses, because of the remoteness of the

facility and the low individual doses, suggests that the disposal system meets ALARA-based performance objectives.

The deep time model should be regarded as heuristic or highly stylized. Nevertheless, it models the basic concepts of the return of lakes in the Bonneville Basin at or above the elevation of the Clive Facility. A sufficiently deep lake destroys the DU disposal facility, redistributes radionuclides that have moved above ground into the lake sediment, and repeats the cycles of radionuclides moving into lake water and settling back into sediment. Sedimentation rates are about 16.5 m per 100 ky, and the DU waste is assumed to mix with the sediment across time. There are several components of this heuristic model that could be regarded as conservative in the sense of over-predicting concentration in both lake water and lake sediment. For example:

1. In version 3.0 of the Model, all DU waste is disposed below grade. With this waste disposal configuration, none of the waste is dispersed directly. Waste material that would be dispersed under this scenario only includes radionuclides that have transported into the above-grade volume of the disposal system. Note also that eolian deposition occurs until the first lake returns, in which case the site will be more stable than at present and the below-grade waste will be further below grade. Dispersal of the waste occurs for the small fraction of waste that has migrated into the above-ground component of the disposal system. The model does not account for increased wetter and cooler conditions that occur before the first lake returns and that would be expected to move radionuclides downward from the embankment.

2. In the model a lake is assumed to destroy the site when it reaches the Clive elevation, which can cause mixing of waste in a very shallow lake—a lake that perhaps does not have sufficient power to destroy the facility. Research into the power needed for a lake to destroy the facility might indicate the minimum elevation needed for such an event.

3. Sediment mixing is assumed to occur with every lake cycle, even though some lake cycles might result only in burial with new sediments. The resulting concentrations reflect concentrations associated with the first lake event, consistent with the timing of the maximum lake water and lake sediment concentrations.

Peak lake water concentrations of ^{238}U at 82,500 years average about 0.005 pCi/L, even given the conservatism in the model, with a 95th percentile of about 0.02 pCi/L. The peak of the mean concentrations of ^{238}U in sediment average about 0.1 pCi/g, with a 95th percentile of about 0.4 pCi/g. Given the simplified and biased model structure, these lake water and sediment concentrations are substantial overestimates.

7.2   Comparison to Performance Objectives

Comparisons to performance objectives are presented for doses to ranch workers (since doses to other receptors are smaller), and for groundwater concentration for ^{99}Tc, the radionuclide with concentrations closest to the GWPL. The evaluations are for waste disposed below grade and they include erosion. Quantitative performance objectives do not exist for the ALARA analysis or for the deep-time concentration endpoints.

The concentrations reported by the Clive DU PA Model represent estimates of the concentration in each year, or the peak concentration within the 500-yr period of groundwater compliance. The

peaks of those concentrations are collected. Because the groundwater concentration of ^{99}Tc increases with time, the peak concentrations occur at 500 yr. Since the timing of these peaks in different realizations is the same, the peak of the mean concentrations is identical to the mean of the peak concentrations. The 10,000 model realizations provide 10,000 estimates of the peak concentrations. Summary statistics for the distribution of the peak of the mean ^{99}Tc concentrations are presented in Table 15. The mean, median, and 95th percentile values are below the GWPL.

Table 15. Summary statistics for peak mean groundwater activity concentration of ^{99}Tc within 500 yr.

radionuclide	GWPL (pCi/L)	activity concentration at 500 yr (pCi/L)		
		mean	median (50th %ile)	95th %ile
^{99}Tc	3790	24	0.31	135

The results of the analyses depend critically on the Model structure, specification, and underlying assumptions. For example, the release of ^{99}Tc to the environment in the early modeling period would be restricted if waste containerization were taken into account, and ^{99}Tc inventory concentrations might be overestimated.

The dose results for ranch workers are presented in Table 16. The statistics represent summaries of the peak mean doses achieved within 10,000 yr. The 95th percentile is analogous to the 95% upper confidence interval of the mean that is commonly used to represent reasonable maximum exposure conditions in CERCLA risk assessments. Both the mean and the 95th percentile are orders of magnitude lower than the MOP performance objective of 25 mrem/yr.

Table 16. Peak mean TEDE for ranch worker: statistical summary.

receptor	TEDE (mrem/yr) at 10,000 yr		
	mean	median (50th %ile)	95th %ile
ranch worker	0.031	0.025	0.073

8.0 Conclusions

Model results are dependent on the model structure, the model specification, and the assumptions upon which they are based. All conclusions also depend on the model structure, specification, and assumptions. Changes in any aspect of the Model could cause different results. Within this context the Clive DU PA Model v3.0 demonstrates that the below-surface-grade configuration option for the subject DU waste in the Federal Cell is adequately protective of human health and the environment as projected for the next 10,000 years. Protectiveness is assessed under Utah Administrative Code R313-25-9 Section 5(a) by consideration in this PA Model of:

- dose to site-specific receptors,
- concentrations in groundwater,

- ALARA, and
- consideration of deep-time scenarios.

The Model was run with the waste buried below grade under the top slope, beneath extra fill material. It was also run with gully formation assumed to occur near the beginning of the simulation period. Simplified summary results for these scenarios are presented in Table 17.

Table 17. Summary of results of the Clive DU PA Model.

performance objective	meets performance objective?
Dose to MOP below regulatory threshold of 25 mrem in a year	Yes
Dose to IHI below regulatory threshold of 500 mrem in a year	Yes
Groundwater maximum concentration of ^{99}Tc in 500 years < 3790 pCi/L [1]	Yes
ALARA average total population cost equivalent over 10,000 years	$28,050

[1]Groundwater concentrations of all other radionuclides are significantly less than their respective GWPLs.

The configuration evaluated for the Clive DU PA Model v2.0, including erosion, demonstrates that the disposal facility can adequately protect human health and the environment when disposing of the subject DU waste:

- all disposal options evaluated exhibit doses that are less than the inadvertent intrusion performance objective,

- there are clearly disposal configurations for which the predicted doses are less than the MOP performance objective, and

- there are disposal options for which groundwater concentrations do not exceed GWPLs.

In addition, the ALARA analysis indicates that ALARA costs from population doses that might be realized for the duration of the 10 ky model are small. On a per year basis, the ALARA costs are less than $6 per year at the 95th percentile of total population dose.

The Federal Cell is assumed to be destroyed by the return of a deep lake. The deep time model indicates that concentrations in media such as lake water and sediment will continue to decrease with each lake and climate cycle and that destruction of the site will lead to dispersal of radionuclides in the Bonneville Basin.

9.0 References

AdrianBrown, 1997. *Volume 1. LARW Infiltration Modeling Input Parameters and Results,* Report 3101B.970515, prepared for Envirocare of Utah Inc., AdrianBrown, Denver CO, May 1997

Baird, R.D., et al., 1990. *Evaluation of the Potential Public Health Impacts Associated with Radioactive Waste Disposal at a Site Near Clive, Utah,* RAE-9004/2-1, Rogers and Associates Engineering Corporation, Salt Lake City UT, June 1990

Benson, C.H., et al., 2011. *Engineered Covers for Waste Containment: Changes in Engineering Properties and Implications for Long-Term Performance Assessment,* NUREG/CR-7028, Volume 1, United States Nuclear Regulatory Commission, Washington DC, December 2011

Berger, A., and M.F. Loutre, 2002. An Exceptionally Long Interglacial Ahead?, *Science* 297 (23 August 2002) 1287–1288

CFR, 1993. *10 CFR 834, Radiation Protection of the Public and the Environment*, United States Code of Federal Regulations, United States Government Printing Office, Washington DC, 1993

CFR, 2014. *10 CFR 61, Licensing Requirements for Land Disposal of Radioactive Waste*, United States Code of Federal Regulations, United States Government Printing Office, Washington DC, January 2014

CRWQCB, 1990. *Water and Sediment Quality Survey of Selected Inland Saline Lakes,* California Regional Water Quality Control Board, Sacramento CA, October 1990

DOE, 1993. *DOE Order 5400.5 Chg 2, Radiation Protection of the Public and the Environment,* United States Department of Energy, Washington DC, January 1993

DOE, 1997. *Applying the ALARA Process for Radiation Protection of the Public and Environmental Compliance with 10 CFR 834 and DOE 5400.5 ALARA Program Requirements,* DOE-STD-ALARA1draft, United States Department of Energy, Washington DC, April 1997

Energy*Solutions*, 2012. *Utah Low-Level Radioactive Material License (RML UT2300249) Updated Site-Specific Performance Assessment,* prepared for Utah Division of Radiation Control, Energy*Solutions* LLC, Salt Lake City UT, October 2012

GTG, 2021. *GoldSim User's Guide, Version 14.0*, GoldSim Technology Group LLC, available from https://media.goldsim.com/Documents/Manuals/GoldSim.pdf

Hays, J.D., et al., 1976. Variations in the Earth's Orbit: Pacemaker of the Ice Ages, *Science* 194 (4270) 1121–1132

ICRP, 1979. Limits for Intakes of Radionuclides by Workers, ICRP Publication 30 (Part 1), *Annals of the ICRP* 2 (3/4)

ICRP, 1989. Age-dependent Doses to Members of the Public from Intake of Radionuclides—Part 1. ICRP Publication 56, *Annals of the ICRP* 20 (2)

Myrick, T.E., et al., 1981. *State Background-Radiation Levels: Results of Measurements Taken During 1975–1979,* ORNL/TM-7343, Oak Ridge National Laboratory, Oak Ridge TN, November 1981

NCRP, 2009. *Ionizing Radiation Exposure of the Population of the United States,* NCRP Report No. 160, National Council on Radiation Protection and Measurements, Bethesda MD, 2009

Neptune, 2006. *Ant Parameter Specifications for the Area 5 and Area 3 RWMS Models,* Neptune and Company Inc., Los Alamos NM, September 2006

Neptune, 2011. *Final Report for the Clive DU PA Model version 1.0,* Neptune and Company Inc., Los Alamos NM, June 2011

Neptune, 2021a. *Embankment Modeling for the Clive DU PA, Clive DU PA Model v2.0,* NAC-0019_R5, Neptune and Company Inc., Los Alamos NM, June 2021

Neptune, 2021b. *Dose Assessment for the Clive DU PA, Clive DU PA Model v2.0,* NAC-0027_R3, Neptune and Company Inc., Los Alamos NM, August 2021

Neptune, 2021c. *Unsaturated Zone Modeling for the Clive DU PA, Clive DU PA Model v2.0,* NAC-0015_R5, prepared for Energy*Solutions*, Neptune and Company Inc., Los Alamos NM, September 2021

Neptune, 2021d. *Decision Analysis Methodology for Assessing ALARA Collective Radiation Doses and Risks, Clive DU PA Model v2.0,* NAC-0028_R3, Neptune and Company Inc., Los Alamos NM, September 2021

Neptune, 2021e. *Fitting Probability Distributions, Clive DU PA Model v2.0,* NAC-0031_R2, Neptune and Company Inc., Los Alamos NM, August 2021

Neptune, 2021f. *Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility, Clive DU PA Model v2.0,* NAC-0018_R5, Neptune and Company Inc., Los Alamos NM, August 2021

Neptune, 2021g. *Biologically Induced Transport Modeling for the Clive DU PA, Clive DU PA Model v2.0,* NAC-0022_R3, Neptune and Company Inc., Los Alamos NM, September 2021

Neptune, 2021h. *Deep Time Assessment for the Clive DU PA, Deep Time Assessment for the Clive DU PA Model v2.0,* NAC-0032_R6, Neptune and Company Inc., Los Alamos NM, August 2021

Neptune, 2021i. *Atmospheric Transport Modeling for the Clive DU PA, Clive DU PA Model v2.0,* NAC-0021_R3, Neptune and Company Inc., Los Alamos NM, September 2021

Neptune, 2021j. *Radon Diffusion Modeling for the Clive DU PA, Clive DU PA Model v2.0,* NAC-0033_R2, Neptune and Company Inc., Los Alamos NM, September 2021

Neptune, 2021k. *FEP Analysis for Disposal of Depleted Uranium at the Clive Facility,* NAC-0020_R3, Neptune and Company Inc., Los Alamos NM, June 2021

Neptune, 2021l. *Saturated Zone Modeling for the Clive DU PA, Clive DU PA Model v2.0,* NAC-0016_R5, Neptune and Company Inc., Los Alamos NM, August 2021

Neptune, 2023a. *Geochemical Modeling for the Clive DU PA, Clive DU PA Model v3.0,* NAC-0025_R5, Neptune and Company Inc., Los Alamos NM, December 2023

Neptune, 2023b. *Model Parameters for the Clive DU PA Model, Clive DU PA Model v3.0,* NAC-0026_R6, Neptune and Company Inc., Los Alamos NM, December 2023

Neptune, 2023c. *Sensitivity Analysis Results for the Clive DU PA, Clive DU PA Model v3.0,* NAC-0030_R3, Neptune and Company Inc., Los Alamos NM, December 2023

Neptune, 2023d. *User Guide for the Clive DU PA Model, Clive DU PA Model v3.0,* NAC-0171_R2, Neptune and Company Inc., Los Alamos NM, December 2023

Neptune, 2023e. *Quality Assurance Project Plan, Clive DU PA Model v3.0,* NAC-0055_R4, Neptune and Company Inc., Los Alamos NM, December 2023

Neptune, 2023f. *Machine Learning for Sensitivity Analysis of Probabilistic Environmental Models,* NAC-0029_R4, Neptune and Company Inc., Los Alamos NM, December 2023

Neptune, 2023g. *Radioactive Waste Inventory for the Clive DU PA, Clive DU PA Model v3.0,* NAC-0023_R6, Neptune and Company Inc., Los Alamos NM, December 2023

Neptune, 2023h. *Erosion Modeling for the Clive DU PA, Clive DU PA Model v3.0,* NAC-0017_R6, Neptune and Company Inc., Lakewood CO, December 2023

NRC, 1989. *Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers,* Regulatory Guide 3.64, United States Nuclear Regulatory Commission, Washington DC, June 1989

NRC, 1993. *Final Environmental Impact Statement to Construct and Operate a Facility to Receive, Store, and Dispose of 11e.(2) Byproduct Material Near Clive, Utah,* NUREG-1476, United States Nuclear Regulatory Commission, Washington DC, August 1993

NRC, 1995. *Reassessment of NRC's Dollar Per Person-Rem Conversion Factor Policy,* NUREG-1530, United States Nuclear Regulatory Commission, Washington DC, December 1995

NRC, 2000. *A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities: Recommendations of NRC's Performance Assessment Working Group,* NUREG-1573, United States Nuclear Regulatory Commission, Washington DC, June 2000

NRC, 2004. *Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission,* NUREG/BR-0058, Revision 4, United States Nuclear Regulatory Commission, Washington DC, September 2004

NRC, 2006. *Consolidated Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Criteria,* NUREG-1757, Vol. 2, Rev. 1, United States Nuclear Regulatory Commission, Washington DC, September 2006

NRC, 2010. *Proceedings of the Workshop on Engineered Barrier Performance Related to Low-Level Radioactive Waste, Decommissioning, and Uranium Mill Tailings Facilities, Held at the U.S. Nuclear Regulatory Commission Headquarters, Rockville, MD, August 3–5, 2010,* NUREG/CP-0195, United States Nuclear Regulatory Commission, 2010

NRC, 2015. *Reassessment of NRC's Dollar Per Person-Rem Conversion Factor Policy, Draft Report for Comment,* NUREG-1530, Rev. 1, United States Nuclear Regulatory Commission, Washington DC, August 2015

OMB, 2003. *Circular A-4*, Office of Management and Budget, available from https://obamawhitehouse.archives.gov/omb/circulars_a004_a-4/

Shackleton, N.J., 2000. The 100,000-Year Ice-Age Cycle Identified and Found to Lag Temperature, Carbon Dioxide, and Orbital Eccentricity, *Science* 289 (5486) 1897–1902

Šimůnek, J., et al., 2018. *The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media, Version 4.17,* University of California Riverside, Riverside CA, July 2018

SWCA, 2011. *Field Sampling of Biotic Turbation of Soils at the Clive Site, Tooele County, Utah,* prepared for Energy*Solutions*, SWCA Environmental Consultants, Salt Lake City UT, January 2011

SWCA, 2013. *EnergySolutions Updated Performance Assessment—SWCA's Response to First Round DRC Interrogatories,* SWCA Environmental Consultants, September 2013

Trinity Consultants, 2021. *Summary Report of Meteorological Data Collected at EnergySolutions' Clive, Utah Facility, January 2020 through December 2020 and January 1993 through December 2020,* Trinity Consultants, Salt Lake City UT, February 2021

UAC, 2018. *Rule R313-25. License Requirements for Land Disposal of Radioactive Waste— General Provisions*, Utah Administrative Code, 2018

Utah, 2014. *Ground Water Quality Discharge Permit,* Permit No. UGW450005, State of Utah, Division of Water Quality, Salt Lake City UT, 2014

Whetstone Associates, 2006. *EnergySolutions Class A Combined (CAC) Disposal Cell Infiltration and Transport Modeling Report,* prepared for Energy*Solutions* LLC, Whetstone Associates Inc., La Veta CO, May 2006

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Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility, Clive DU PA Model v2.0 (Neptune 2021f)

Embankment Modeling for the Clive DU PA, Clive DU PA Model v2.0 (Neptune 2021a)

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Sensitivity Analysis Results for the Clive DU PA, Clive DU PA Model v3.0 (Neptune 2023c)

User Guide for the Clive DU PA Model, Clive DU PA Model v3.0 (Neptune 2023d)

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[2] Regulatory review of DU PA v2.0 led to revision of some but not all white papers when preparing DU PA v3.0. Those that are unchanged retain "v2.0" in the title.