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April 2, 2018

CD18-0036

DRC-2018-003164

Mr. Scott T. Anderson
Director
Utah Division of Waste Management and Radiation Control
195 North 1950 West
Salt Lake City, Utah 84114-4880

Subject: Radioactive Material License UT2300249: **Responses to the Amended and New Interrogatories Related to Clive DU PA Modeling Report Version 1.4 Dated November 2015**

Dear Mr. Anderson:

Energy*Solutions* herein submits responses to the Utah Division of Waste Management and Radiation Control's Amended and New Interrogatories Related to Clive Depleted Uranium Performance Assessment Modeling Report Version 1.4 from November 2015 (dated May 11, 2017). With submission of this final set of responses, Energy*Solutions* understands that "*the Division intends to move forward with a second version of the [Safety Evaluation Report] for public comment, after which the Director will be prepared to make a determination.*"[1] Energy*Solutions* herein repeats its request made with the 2015 submission of version 1.4 of the Depleted Uranium Performance Assessment,

> "*Prior to releasing the next [Safety Evaluation Report] draft, EnergySolutions requests that the comments contained in [Clive Depleted Uranium Modeling Report Version 1.4] be addressed and that they have opportunity to consult with the Division on any further issues identified.*"[2]

[1] Anderson, Scott. "Depleted Uranium Performance Assessment (DUPA) Clive Facility; Model Version 1.4 Interrogatories; Radioactive Material License 2300249" Letter from the Division of Waste Management and Radiation Control to Vern Rogers of Energy*Solutions*, May 11, 2017.

[2] Rogers, Vern. "Radioactive Material License UT2300249: Safety Evaluation Report for Condition 35.B Performance Assessment; Response to Issues Raised in the April 2015 Draft Safety Evaluation Report (CD16-0266)." Letter from Energy*Solutions* to Mr. Scott Anderson of the Utah Division of Waste Management and Radiation Control, November 25, 2015.

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As originally reported with Energy*Solutions'* submission of version 1.4 of the Depleted Uranium Performance Assessment, the five categories of deficiencies with the 2015 Safety Evaluation Report included,

1) **The April 2015 draft Safety Evaluation Report goes beyond the scope outlined by the Nuclear Regulatory Commission (NRC) and inappropriately provides policy and legal direction to the Division Director.**

2) **The April 2015 draft Safety Evaluation Report is in conflict with Utah Code Section 19-3-104(7)(a) and Utah Code Ann. 19-5-102(5) as it applies a more stringent standard than R313-25-9(5)(a) requires. Additionally R313-25-9(5)(a) is "more stringent" than the draft corresponding federal regulation 10 C.F.R. 61.13(e).**

3) **The April 2015 draft Safety Evaluation Report inappropriately addresses issues with general data rather than using available site-specific analysis.**

4) **The April 2015 draft Safety Evaluation Report includes several factual errors that require correction.**

5) **The "Unresolved Issues" in the April 2015 draft Safety Evaluation Report have been addressed in version 1.4 of the DU PA Modeling Report.**

Energy*Solutions* recognizes that the 2015 Safety Evaluation Report's first condition prerequisite to any Director approval requires an enforceable agreement be executed between Energy*Solutions*, the State of Utah and the U.S. Department of Energy for transfer, after decommissioning, of ownership of that portion of Energy*Solutions'* Clive facility on which depleted uranium has been land disposed. Legal justification for this requirement was provided in a letter dated August 9, 2017.[3] The justification questions the applicability of Energy*Solutions'* existing land ownership exemption granted by the former Radiation Control Board to disposal of depleted uranium in significant quantities. Holland and Hart's response to the Division's justification, prepared on behalf of Energy*Solutions'*, has been submitted separately.[4]

---

[3] Anderson, Scott. "Response to Question Regarding Tri-Party Agreement for Depleted Uranium Disposal." Letter from the Division of Waste Management and Radiation Control to Vern Rogers of Energy*Solutions*, August 9, 2017.

[4] Smith, Amanda. "Tri-Party Agreement Requirement Response." Letter from Holland and Hart to Scott Anderson of the Division of Waste Division of Waste Management and Radiation Control, April 2, 2018.

Thank you for your thoughtful review of these responses. Please let me know when the Division is available to discuss preparation of the second revision to the Safety Evaluation Report.

Sincerely,

Vern C. Rogers
Mar 23 2018 9:56 AM

CoSign

Vern C. Rogers
Manager, Compliance and Permitting

cc Don Verbica, DWMRC
Helge Galbert, DWMRC

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

RML UT2300249 – CONDITION 35.B: RESPONSES TO INTERROGATORIES RAISED WITH VERSION 1.4 OF THE DEPLETED URANIUM PERFORMANCE ASSESSMENT

MARCH 23, 2018

NAC-0115_R0

Introduction to DU PA Model Version 1.4 Interrogatory Responses

23 February 2018

Prepared by

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ACRONYMS AND ABBREVIATIONS

CSM	Conceptual Site Model
DEQ	(Utah) Department of Environmental Quality
DU	depleted uranium
ET	evapotranspiration
GIGO	garbage in, garbage out
LLRW	low-level radioactive waste
PA	performance assessment
PPA	probabilistic performance assessment
SER	Safety Evaluation Report
UDEQ	Utah Department of Environmental Quality

1.0 Introduction

Beginning in 2009, Energy*Solutions* contracted Neptune and Company, Inc. (Neptune) to create a probabilistic performance assessment (PPA) for the disposal of large quantities of depleted uranium (DU) at their Clive, Utah low-level radioactive waste (LLRW) disposal facility.

The initial model was submitted as version 1.0 on June 1, 2011 (Neptune 2011) and was revised to version 1.2 on June 5, 2014 (Neptune 2014). A Safety Evaluation Report (SER) based on review of version 1.2 was issued by the Utah Department of Environmental Quality (UDEQ) in April 2015 (SC&A 2015).

On November 25, 2015, Energy*Solutions* submitted *Radioactive Material License UT2300249: Safety Evaluation Report for Condition 35.B Performance Assessment; Response to Issues Raised in the April 2015 Draft Safety Evaluation Report* (Energy*Solutions* 2015). This document included version 1.4 of the DU PA (Neptune 2015), prepared in response to open primary and supplemental interrogatories included in Appendix C and Appendix B, respectively, of the SER.

On May 11, 2017, UDEQ provided *Amended and New Interrogatories Related to Clive DU PA Modeling Report Version 1.4 Dated November 2015* (Utah DEQ 2017). This document contains revised and new interrogatories regarding version 1.4 of the DU PA.

UDEQ has arranged the interrogatories and SER comments in the *Amended and New Interrogatories Related to Clive DU PA Modeling Report Version 1.4* (Utah DEQ 2017) into seven general categories. In order to retain focus on each subject area, responses are grouped into individual papers by these seven categories. Each category is addressed within a standalone Neptune response document as follows:

1. NAC_0106: Evapotranspiration (ET) Cover Design
2. NAC_0108: Erosion
3. NAC_0105: Deep Time Supplemental Analysis
4. NAC_0102: Other Wastes
5. NAC_0104: Groundwater Exposure
6. NAC_0103: Recycled Uranium
7. NAC_0101: Federal Cell Design

Note that, in an attempt to improve readability, the complete interrogatory number is cited as each is first introduced and in headings, while the abbreviated number is used during discussion. For example, Interrogatory CR R313-25-7(2)-05/2 is introduced by its full number, then is abbreviated to Interrogatory 05/2, since the interrogatory numbering system employed by UDEQ applies a unique number after the last hyphen in the sequence.

Note also that some interrogatories are linked to more than one section of the Utah Administrative Code; thus, a single interrogatory can appear at first glance to be two. For example, “Interrogatory CR R313-25-3 and R313-25-8-195/1” is a single interrogatory referencing two parts of the Utah Administrative Code related to the subject at hand. The shorthand for this interrogatory becomes “195/1.”

Full text of each interrogatory, with UDEQ images, tables, and references, is available in Utah DEQ (2017). Within these responses, the interrogatory is briefly quoted or paraphrased to identify what is understood to be the issue of concern. When quoting longer passages of interrogatory text, blue font in Arial size 10.5 is used and indented to visually distinguish the interrogatory from the response. An example is shown below:

> Sample format for quoting interrogatory text.

When quoting shorter passages within a paragraph, italics are used to distinguish the interrogatory text being quoted.

The attached responses address issues raised in the interrogatories point by point, providing a defensible basis for closing all open review items.

2.0 Introduction to Probabilistic Modeling

The Clive DU PA Model is a probabilistic model of the potential long-term risk consequences from disposing DU in the Clive facility. This means that the inputs to the Model are specified as probability distributions. The PA results depend not only on the model structure, but also on the model specification (input probability distributions). The Clive DU PA Model structure is a complex fully coupled organization of features, events, processes, and scenarios as described in the Conceptual Site Model (CSM). Each of the inputs to this Model needs to be specified with the same degree of care and attention that is given to the model structure. The PA Model results depend on the probabilistic inputs; consequently, it is critical that the specification addresses underlying statistical principles that relate to such long-term dynamic modeling. Note also that the sensitivity analysis for the PA Model depends on the specific probabilistic input, in which case identification of the appropriate important, or sensitive, parameters also requires correct specification of the input probabilistic distributions.

The input distributions must address uncertainty in the data/information available for specification, and must address spatial and temporal scaling. A well-formed probabilistic model includes distributions that: 1) are based on what is thought to be known (expectation) and the uncertainty about that expectation; 2) address spatial and temporal scaling, and 3) address correlation between inputs where possible.

There is a tendency in PA modeling to ignore all three facets and instead to perform modeling that is based on notions associated with conservatism (often in a deterministic model instead of a probabilistic model), to ignore spatial and temporal scaling, and to ignore correlation. This leads to projected human health risks or doses that are biased high and are far more uncertain than appropriate, which in turn leads to poor decision making.

It is fine to make conservative decisions, but it is not fine to make important decisions based on purposefully erroneous models. This is the same basic message that was attributed to Charles Babbage after his invention of a "difference machine" in the late 1800s. Babbage wrote, "*On two occasions I have been asked 'Pray, Mr. Babbage, if you put into the machine the wrong figures, will the right answers come out' I am not able rightly to comprehend the kind of confusion of ideas that could provoke such a question."* This is the genesis of the term "garbage in, garbage

out" (GIGO), which also applies to today's modeling paradigm if the "*wrong figures*" are used. It is crucial to pay attention to the statistical details of specifying a probabilistic model if reasonable output is desired.

The Clive DU PA Model has been built to the extent possible based on expectation and uncertainty. Correlation is included when and if supporting data/information are available. And, considerable effort has been put into ensuring that the spatial and temporal scales of the input distributions used in the PA Model are appropriate. There are several aspects of the supporting data/information, supporting models (process level models such as Hydrus, SIBERIA, and AERMOD, which were used to support the PA Model), and the PA Model itself that must be considered when establishing the correct spatial and temporal domain of the PA Model and the supporting data. Often data that are useful for specifying input distributions for a PA are available at a very small spatial and temporal scale. Process level models need to address scaling at a refined level, and the systems level PA model must address scaling at yet another level.

Statistical scaling must also consider the endpoint of interest. For PA models, an intermediate endpoint is concentration of radionuclides in some media thousands of years (or in the case of the Clive DU PA, millions of years) into the future. Some assumptions are critical, such as that a PA model will project current knowledge into the future, so that changes to many aspects of the environmental system are considered unlikely (for example, the basin contents are silt/clay, and this is assumed to not change throughout time). Scaling can address temporal (or spatial) changes, but the point here is to explain why scaling is needed, and relatively simple examples are used for demonstration purposes. Consequently, for the purpose of this explication, the parameters of interest are assumed stable in time and space (e.g., chemical/physical characteristics).

Other considerations relate to the computational set up and the computational complexity of a PA model. Suppose, for simplicity, that the model looks forwards 1,000 years, and that each time step is one year. In principle a new random number could be drawn from an input distribution every year; however, in practice this adds greatly to the computational complexity. Instead, an approach is taken that draws a random number at the beginning of time, and applies that random number in each of the 1,000 time steps. The trick is to find the appropriate distribution for this approach to mimic pulling a random number every time step. If the response to the input parameter is linear and the system with respect to that input parameter is stationary (or steady state), then the input distribution that is needed at the beginning of time to mimic the effect of drawing new random numbers every year (time step) is the distribution of the average of the distribution that would be used for 1,000 random draws over time. For non-linear responses, and non-stationary systems, the statistical scaling issues are more complex, but they are conceptually the same.

In effect, the spatial and temporal scaling that is needed must address the differences in scale between the data/information available and the models that are used, including the difference in scale of the supporting process level models and the systems level PA model. Scaling in this context is largely an averaging process. If the response is linear and stationary, then pure averaging works directly, and this is the approach that has been taken in the Clive DU PA Model for projecting future concentrations to which human receptors are exposed.

A simple example of scaling considers the proportion of green M&Ms in a packet as a predictor of the proportion of green M&Ms that are produced. The distribution of green M&Ms from many packets might range from near 0% up to about 33%, but that is not the correct distribution to use to predict the proportion of green M&Ms in 1,000 packets. Scaling takes over, and a better estimate for 1,000 packets would be very close to 16% overall (the production rate of green M&Ms is about 16%). One could estimate the number of green M&Ms in 1,000 packets by adding up how many are in each packet (similar to choosing a new random number each time step), or by taking the distribution of the average of the packet specific distribution. To make this more concrete, suppose the proportion of green M&Ms in a packet follows a normal distribution with mean 16% and standard deviation 5%; then, simulating by drawing a new random number from that distribution for each one of the 1,000 packets gives the same result (distributional estimate of overall proportion) as that obtained from simulating directly from a normal distribution with mean 16% and standard deviation 5%/sqrt(1,000), where the 1,000 represents the 1,000 packets. However, the wrong thing to do would be to simulate from the N(16%, 5%) distribution and apply that to the overall proportion of green M&Ms in 1,000 packets. This describes the essence of the scaling problem, which depends on the endpoint of interest for the problem, and the scale of both the data and the model.

The basic approach to developing input probability distributions is described in Appendix 14 of the initial Clive DU PA submittal. Further explanation of some of the details is provided in response to interrogatories concerning the ET Cover, because there are more interrogatories about input distributions for the ET Cover than for other aspects of the Clive DU PA Model. The critical issue is the importance of spatial and temporal scaling so that parameter uncertainties are appropriately captured in the Model.

3.0 References

Energy*Solutions*, 2015. *Radioactive Material License UT2300249: Safety Evaluation Report for Condition 35.B Performance Assessment; Response to Issues Raised in the April 2015 Draft Safety Evaluation Report,* Energy*Solutions* LLC, Salt Lake City UT, November 2015

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Neptune, 2014. *Final Report for the Clive DU PA Model, Clive DU PA Model v1.2,* NAC-0024_R2, Neptune and Company, Inc., Los Alamos NM, August 2014

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SC&A, 2015. *Utah Division of Radiation Control, EnergySolutions Clive LLRW Disposal Facility, License No: UT2300249; RML #UT 2300249, Condition 35 Compliance Report; Appendix A: Final Report for the Clive DU PA Model, Safety Evaluation Report, Volume 1,* SC&A Inc., Vienna VA, April 2015

Utah DEQ, 2017. *Division of Waste Management and Radiation Control, EnergySolutions Clive LLRW Disposal Facility License No: UT2300249; RML #UT 2300249, Amended and New Interrogatories Related to Clive DU PA Modeling Report Version 1.4 Dated November 2015,* Utah Department of Environmental Quality (DEQ), Salt Lake City UT, May 2017

NAC-0106_R0

ET Cover Design Responses for the Clive DU PA Model

23 February 2018

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ACRONYMS AND ABBREVIATIONS

ACAP	Alternative Cover Assessment Program
bgs	below ground surface
BSC	biological soil crust
CCD	complementary cumulative distribution
CSU	Colorado State University
DEQ	(Utah) Department of Environmental Quality
DOE	(United States) Department of Energy
DU	depleted uranium
DWMRC	Division of Waste Management and Radiation Control
DWR	(Utah) Division of Water Rights
ET	evapotranspiration
HAL	Hansen, Allen, and Luce
HSU	hydrostratigraphic unit
LLRW	low-level radioactive waste
LM	DOE's Office of Legacy Management
MAUP	modifiable areal unit problem
NOAA	National Oceanographic and Atmospheric Administration
NRC	(United States) Nuclear Regulatory Commission
NRCS	Natural Resources Conservation Service
PA	performance assessment
PPA	probabilistic performance assessment
PDF	probability density function
PET	potential evapotranspiration
RML	Radioactive Material License
RMSE	root mean squared error
sd	standard deviation
SER	Safety Evaluation Report
SWCC	soil water characteristic curve
UDEQ	Utah Department of Environmental Quality
USDA	United States Department of Agriculture
WSS	(NRCS) Web Soil Survey

1.0 Overview and Conceptual Model

This document begins with three sections that provide necessary background information for the interrogatories and responses on the subject of the proposed evapotranspiration (ET) cover design. Section 1.1 offers a discussion of the basis for the statistical approaches applied to probabilistic PA modeling. This includes fitting distributions to data or elicited information, scaling, and model abstraction. Section 1.2 is a summary of the setting of the Clive Site that includes a description of the cell design, local hydrogeology, climate, and vegetation. Section 1.3 is a brief summary of the features of the variably saturated flow model HYDRUS-1D used to develop models for net infiltration and water content in the GoldSim DU PA model. The implementation of the software for modeling flow in the cover is also summarized in this section.

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 at the Clive Site include climate, soil characteristics, and native vegetation. Engineered barriers are used at the Clive Site 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 (net infiltration).

These processes would be expected to show temporal variability at the Clive Site on the time scale of minutes to hours in the near surface and days to years deeper in the disposal cell. Processes that tend to change cover properties such as plant and animal activity and climate influences (e.g. frost heave, erosion) are expected to be slowed by the effects of eolian deposition.

1.1 Modeling for Probabilistic Performance Assessments

Introduction

The Clive DU PA Model is a probabilistic model; consequently, its inputs are specified as probability distributions. The PA Model results depend on both the model structure and the model specification through the input probability distributions; consequently, it is critical that the specification addresses underlying statistical principles that relate to this type of long-term dynamic modeling. The sensitivity analysis for the PA Model also depends on the specific probabilistic input, in which case identification of the appropriate important, or sensitive, parameters also requires correct specification of the input probabilistic distributions. The

statistical aspects of this type of dynamic probabilistic modeling are critical to the success and defensibility of the model results.

A crucial piece of developing and evaluating distributions is understanding what the values from the distributions should, or do, represent. This understanding is necessarily linked to how values of the input parameters are used in the PA Model, and to the assumptions needed to use available data/information to inform the distributions. A challenge for evaluating and developing distributions is identifying the appropriate temporal and spatial scales that need to be represented. The data/information to support specification are typically available at different scales than those required by the model. The following provides a more detailed discussion of the implications of this "scaling" on the development of input distributions for the Clive DU PA Model, and is intended to supplement the information provided in Appendix 14 of the Clive DU PA Final Report (particularly Section 6.0, titled *Scaling and Model Abstraction*). Appendix 14 of the Clive DU PA Final Report contains supporting information for the probability distributions—and methods to obtain those distributions—used to develop the distributions for the Clive PA.

Probabilistic PA

The probabilistic Clive DU PA Model uses probability distributions to represent the current state of knowledge in the PA Model inputs, with the goal of running the PA Model at many sets of plausible inputs. The approach is designed to provide information regarding the expected performance of the Site. In general, the modeling effort should be focused on running the PA Model under different realistic scenarios defined by different combinations of values of the input parameters. Judging what is realistic is the fundamental challenge, and it depends on the spatial and temporal scale represented by the values of the input in the PA Model.

This is in contrast to testing the potential performance of the Site "deterministically" by using a single value to represent each input parameter. In addition, probabilistic modeling is aimed at modeling what is thought to be known and the uncertainty in that knowledge, whereas deterministic models are often run using extreme, and likely unrealistic, input parameter values that are usually described as a conservative or protective. A problem with so-called conservatism in PA models is that the direction of conservatism is often difficult to justify. Conservative models are also difficult to explain because they are knowingly wrong, and thus use of conservatism leads to poor decision making. If there is a desire to make a conservative (protective) decision, then those value judgments should be separated from the PA model, and should be based on a model that explains the system response as best possible.

The PA model uses time steps to propagate movement of radionuclides through the engineered and environmental system to project concentrations in various media at various future points in time. However, for a single simulation, random numbers are drawn from the input distributions at the beginning of time, and are used throughout time (thousands of years, or more). This means that the input distributions must represent long time periods, and the data/information available must be scaled appropriately to represent those long time periods. The same is the case for the spatial scale of the model; the available data/information often represent small spatial scales, and must be adjusted to represent the large areas or volumes that underlie the PA model. Each simulation is, essentially, a deterministic run of the PA model. Uncertainty in the output is

obtained by running many (thousands of) simulations, each one of which has a distinct set of input values drawn at random from the underlying distributions of the input parameters.

For example, using a value that is extreme at a small temporal scale (such as a daily soil temperature in the summer) implies that it is realistic to hold that input constant at such an extreme for the entire time period represented by a run of the PA model (thousands of years or more). Therefore, it is crucial to question whether a value is "plausible" or "realistic" to represent a constant condition over a long period of time or a large spatial area. A probabilistic PA provides a natural framework for running the model at sets of values that are deemed realistic for representing long-term conditions over the spatial extents represented in the model. If this is accomplished, the model outputs can be interpreted as indicative of expected performance of the entire site under realistic long-term conditions, given the current state of knowledge in input parameters and the assumptions underlying the PA model.

The Importance of Scaling and Its Challenges

All models are approximations of reality, and the assumptions should always be evaluated and discussed. However, given the assumptions of a PA model, the distributions should be developed to explicitly match, as much as possible, the assumptions and design of the model. The use of distributions representing values at a different scale than that represented by the model is not consistent with the fundamental goals underlying probabilistic PA modeling. Therefore, model developers and reviewers must ensure they are considering the problem relative to the same spatial and temporal scales in order to have a meaningful and productive conversation and to ultimately improve the distributions, and hence models, used in a probabilistic PA.

Developing an appropriate distribution for a PA model input parameter is not simply an exercise in approximating a histogram of available data thought to be relevant to the site. It is unlikely that available data, information from the literature, and/or expert knowledge exist at spatial and temporal scales consistent with the design of the PA model. Therefore, an additional step in distribution development is taking the available information and "scaling" it appropriately; this typically means taking available values that are representative of relatively small scales (e.g., locations in space and/or points in time) and combining them to represent larger scales, typically through averaging.

Identifying a scale consistent with the PA model requires in-depth understanding of how the values from the distribution will ultimately be used in the PA model. That is, there should be an explicit connection between what the values are assumed to represent within the PA model and the distribution developed to produce those values. To accomplish this, the values coming from the distribution should be aligned with the spatial and temporal scales upon which the PA model is built; that is, they should represent the spatial and temporal scales represented by a value of the input. Tangible examples are provided later in this discussion. If the scale represented in the distribution does not match that used for the model, then the results from the model cannot be interpreted as representing the performance of the site under realistic conditions consistent with the model assumptions.

The Change-in-Scale Problem

A mismatch in spatial and/or temporal scale between available data and what is needed to inform a model, or to make predictions from a model, is a problem that arises in many disciplines. It is not a new problem or a problem unique to PA work, and it has different names in different disciplines such as change-of-support, change-of-scale, downscaling and/or upscaling, and the modifiable areal unit problem (MAUP) in the geography literature (see Cressie and Wikle (2011)). The need to match the scale of available data to that needed for the model or predictions is fundamental to problems with temporal and/or spatial components. Higgs et al. (2017) offer a general description of the problem within the context of PA work.

Understanding the Scales Represented in the PA Model

The first step in understanding what spatial and temporal scales a distribution should represent is asking questions about how a value drawn from that distribution will ultimately be used in the PA model. In the current implementation of the Clive DU PA Model in GoldSim, volumes of material at the Site are represented as a network of "cells," and the material represented by a single cell is assumed to be completely mixed (homogeneous). For a single realization of the Model, a property of the entire volume of material/soil associated with a cell is represented by the value of input parameter drawn from a distribution for that property. Therefore, a value from a distribution used to specify a property of material within a cell should represent the entire volume of completely mixed materials within the cell. If the value is used to represent properties of multiple cells, then the value should represent the larger spatial scale associated with the volume of the combined cells. What values are appropriate to represent the entire volume of material? How should available information, collected at various scales from the Site or elsewhere, be used to inform the distribution of such values?

A value drawn from a distribution is typically held constant over the entire time period of a PA model run or realization; it is usually not changed over time within a particular realization. Therefore, the distribution should provide plausible values for summarizing the input parameter over thousands of years (or longer), such as a long-term average. For example, even if values of the input parameter may vary seasonally, that does not mean it is reasonable to run the model as if a seasonal extreme is held constant for 1000 years. It is most realistic, and thus informative of expected performance, to run the model at plausible long-term averages, not at short-term extremes. Running the model at values representative of smaller time scales (such as individual seasons) results in many unrealistically extreme realizations that will not adequately characterize expected site performance over the period of interest. Over a long period of time, the input variable is expected to be below average and above average during small periods of time, but the performance is assessed over such large time scales that the extremes should "balance each other out" given the model structure. Data may only be available over short time periods, such as months, but distributions for longer-term averages can be developed using the short-term data and assumptions regarding the future.

The relatively large spatial and temporal scales of input parameters represented in the PA model result in challenges for development and evaluation of distributions. It is often not intuitive how to use the information from available data, or from subject matter knowledge of "possible

values" for an input parameter, to develop a distribution representing the scale consistent with the PA model. For example, it is tempting to assume that any value that could possibly be obtained from a single sample from one location at one point in time should be represented in the distribution. However, such an approach is generally misaligned with the scale of the PA model, as described previously. This idea is further explored in the following discussion, with spatial and temporal dimensions considered separately, and in more detail.

Spatial Scaling Example

Suppose data are collected on material properties from 20 soil cores taken at random locations from around the actual site. The variability in the resulting values from the samples will reflect the heterogeneity across the site. An individual sample represents the spatial scale of a point location (or small core), and a distribution fit directly to the observed values from all the cores could be used to represent possible values that could be obtained from other potential cores taken from the same site. Now, suppose values that reflect the entire volume of soil of the site are of interest, and need to be obtained from the 20 soil cores. Is it reasonable to use a value representing a single core as if it represents the larger volume of soil? In general, it is not reasonable for a value from an individual sample to represent the larger volume; instead, an average (or estimated mean) would typically be used as a representative value of the larger volume. The idea can be thought of in terms of prediction; what value is reasonable to use to predict the same property of a different site of the same size: the value from an individual core or the average over all the cores sampled? Choosing the estimated mean will clearly give better predictions and should have smaller errors on average (uncertainty) and less variability in errors.

A single data set has an associated estimate of the mean, but different estimates would be obtained from different sets of 20 locations sampled. That is, there is uncertainty in the value of the mean because the entire volume of material represented in the PA model will never be sampled. Therefore, a probability distribution is used to incorporate uncertainty in the mean rather than variability among values from different point locations; the distribution should represent plausible means for the entire volume of material, rather than variability among measurements from cores taken from individual locations within a site. Using values from a distribution describing variability among individual small-scale locations to represent the entire volume of material leads to extreme, and unrealistic, model runs. Practically, this often translates into using standard errors for the estimated mean over a larger scale to define distributions, rather than standard deviation of available small-scale measurements.

Another way to think about the problem is through the assumption of complete mixing used in the conceptual construction of the PA model cells. First, envision the 20 samples described in the previous paragraph. Now, suppose a huge mixer is employed to completely mix the entire volume of material/soil before the 20 samples are taken. What would variability among the values from these new 20 samples look like compared to variability among the first 20 samples from the heterogeneous material? Because the soil is thoroughly mixed, the relatively large values and small values are now dispersed through the whole volume so that the samples will now all have values relatively close together (the more completely the material is mixed, the closer they will be). The average value of the 20 samples in both cases (heterogeneous vs. mixed) should be the same (or close to the same), but the variability may be drastically different.

The point estimate of the mean from the original 20 samples can be used as the center for the desired distribution, with the variance adjusted to reflect uncertainty in that mean because it is based on a limited number of samples.

Temporal Scaling Example

The time scale associated with the input parameters in a PA model is the length of time over which a value from a distribution is held constant in a run of the model. The Clive DU PA Model most often uses a single value, drawn from an input distribution at the beginning of a model realization, over the whole time period represented by the Model. Therefore, it must represent the spatial volume (described in the previous section) over thousands of years (or longer). This is obviously challenging because available data exist at much, much smaller temporal scales (less than a day to perhaps 50 years) and an assumption must be made that current knowledge is projected into the future. The lack of knowledge about the future requires making assumptions about future conditions, and typically the assumption is made that the conditions under which data were collected will hold into the future (i.e., stationarity). This implies the mean and associated variance will stay constant into the future represented by the PA Model. Under this assumption, information in the available data and expert knowledge can be used to directly inform the distribution; uncertainty and lack of trust in assumptions can also be incorporated.

As discussed for the spatial scale, the distribution should represent the current state of knowledge about the input at the PA model scale, meaning random draws from the distribution should capture variability among plausible long-term means for the volume of material represented by the PA model cell(s). Using soil temperature as an example, consider the variability among daily average soil temperatures in a region with seasonal variation, with extremes captured by the daily average soil temperatures during the coldest time of the year, and the daily average soil temperatures during the warmest part of the year. Now, contrast that with the extremes expected across different annual average soil temperatures; one extreme is a year that is colder on average over all seasons and the other extreme is a year that is warmer on average over all seasons. The difference between these two annual extremes is expected to be far less than the difference between the two extremes defined on the daily scale. Is it reasonable to use an extreme daily average to represent an extreme annual average soil temperature? Using a daily average as an annual average is equivalent to representing incredibly extreme conditions that are not supported by available data—it amounts to assuming that conditions in the system are going to change so drastically that daily averages become representative of annual averages.

These ideas continue to larger scales, where, at each larger scale, less variability is expected among averages at that scale. In other words, we expect less variability among decadal averages than annual averages, and less variability among 50-year averages than decadal averages, and so on. The degree to which the distributions representing the current state of knowledge in larger and larger scales get narrower does depend on the trust in the assumption of stationarity of conditions into the future. However, regardless of the proposed difference in variance between a distribution of annual averages and a distribution of 100- or 1000-yr averages, it is clear that seasonal variation occurs at a scale much smaller than that represented by the PA model. It is not appropriate to assume that a value measured at a location at one point in time should be represented in the collection of draws from a distribution for that input used for the PA model

when the value drawn from the distribution is held constant over thousands of years (or longer). When evaluating the reasonableness of an input distribution, given the modeling conditions, one should ask "Are these values plausible given they will be held constant in the model over hundreds or thousands of years?"

Combining Spatial and Temporal Scaling

As described above, from a temporal perspective the values captured in a distribution should be judged reasonable in the context of being held constant over long time periods, and therefore should not reflect extremes that are only realistic at smaller time scales. Thinking about plausible long-term averages for the values representing the spatial volumes of the PA model is the easiest way to judge reasonableness of the distribution relative to time. However, this is challenging because it is clearly impossible to collect data over hundreds or thousands of years into the future to inform the distribution of a long-term average.

Therefore, temporal scaling is often more abstract than the methods discussed for spatial scaling, and often must actually use mainly spatial variability as a surrogate for variability that might be observed over time. For example, using data from different locations and regions captures conditions in different materials that may be observed at one location over time. Therefore, the heterogeneity over space is used as a surrogate for heterogeneity over time for the volumes represented by the PA model.

This is necessary if distributions are to be based on empirical information because it is not possible to collect the data needed to capture the heterogeneity over time into the future. While the scaling does appear to be simply "spatial scaling" on the surface, it is not a misnomer to call it spatio-temporal scaling because both scales are always simultaneously considered even if most of the information available is spatial. The resulting distributions should be evaluated relative to both dimensions by asking "does the distribution provide values that are plausible when applied to the spatial volumes of PA cells over long periods of time?"

Choice of Statistical Methods

There are many statistical methods that can be used to estimate a mean, along with associated uncertainty; the choice depends on the method of data collection (e.g., sampling design) and characteristics of the data such as dependence (e.g., correlation) among values from different samples. The average (arithmetic mean) is the simplest, and is often appropriate, as long as samples do not severely violate underlying linearity and stationarity assumptions.

If direct averaging applies, then the scaled distribution can often be represented by a normal distribution (depending on the nature of the underlying data). This is because sampling distributions of averages tend to be approximately normally distributed, even when the population of values from which the samples are taken are not normal, and normality improves with increasing sampled sizes. The t-distribution is also an option to account for uncertainty in estimating the standard deviation of the population, but the t-distribution is barely distinguishable from the normal distribution for sample sizes greater than 30, and the normal distribution is simpler to implement and communicate about for a PA model.

The data distribution has a mean and a standard deviation, whereas the scaled distribution obtained as the distribution of the average has the same mean and a standard deviation of the mean, which is usually called the standard error of the mean.

Scaling Challenges Related to Sources of Information

If samples are available directly from the volume of material of interest (represented by a PA model cell), then the development of the distribution at the appropriate scale based on smaller-scale measurements is a straightforward statistical exercise. However, if the information available to inform the distribution is composed of measurements from other sites, under different experimental conditions, representing predictions from other estimated relationships, from expert judgment, etc., then distribution development becomes much more challenging and must rely on professional and expert judgment decisions to factor in uncertainty regarding what measurements might be from the site of interest and to gauge how different sources of information should be weighted against each other in the distribution development process.

In such cases, assumptions and decisions should be explicitly stated, and it is not reasonable that every rational expert would provide the same distribution. It is rare that many samples are taken from the site to inform a distribution, and the variety of types of information and "data" available certainly add to the challenges of representing current state of knowledge in the mean of a spatial volume at the site. Different values and summaries presented in the literature may represent different spatial scales, and this information should be used, if possible and if available. Additionally, development of distributions is often complicated by limited site-specific information over space and over time. This limited information must be transformed to represent the scales consistent with the model, after taking into account the quality of the different data sources and their relevancy to the site, and the assumptions of the PA model.

Conclusions

While all rational experts may not develop the exact same distribution, they should all be critically examining the distributions with the same spatial and temporal scales in mind, given the PA model in question. The relevant question to ask is not "Does the distribution cover all plausible values of the input variable that could be observed from a single sample?" but instead "Does the distribution cover all plausible values of the input variable that could be representative of the large volume of material represented by the PA model cell over long periods of time?" These questions have different answers because they are tied to different spatial scales, and answers depend on the current state of knowledge regarding site conditions, including linearity and stationarity.

Development of distributions for PA model inputs would certainly be easier if each distribution could simply represent possible values that have been observed in data collected from single locations and single points in time. However, running the PA model with such distributions would result in many of the realizations of a PA model capturing unrealistically extreme scenarios (e.g., an extreme daily average temperature of 90 degrees assumed to be held constant over not only a year, but thousands of years). The problem as described for a single distribution magnifies as the number of distributions with spatial and temporal scales misaligned with the PA

model increases, possibly to the point where only a small proportion of the PA model realizations represent realistic and useful outcomes.

The goal of a probabilistic PA is to represent expected outcomes of the site. Using distributions at temporal and spatial scales misaligned with the representations built into the PA model makes this goal unattainable.

If there is interest in running the model at extreme, unrealistic scenarios to test hypothetical limits of the model and the associated performance of the site, then this can be done in a separate investigation, but this should not be built into the distributions meant to capture the current state of knowledge at a scale consistent with the current PA model. Distributional goals are necessarily tied to spatial and temporal scale, and therefore developers and reviewers must ensure they are considering the problem relative to the same spatial and temporal scales in order to have a meaningful and productive conversation about the input distributions. This leads to a defensible model, and a sensitivity analysis that yields meaningful results that can ultimately be used to direct further data/information collection to improve, or refine, the distributions used in a probabilistic PA.

Further examples of scaling in the Clive DU PA are provided in Appendix 14 to the Clive DU PA Final Report.

1.2 Setting

1.2.1 Disposal Cell Design

The design of the Federal DU Cell is a covered embankment, with relatively steeper sloping sides nearer the edges. The upper part of the embankment, known as the top slope, has a moderate slope (2.4%), while the side slope is markedly steeper (20%). The embankment is also constructed such that a portion of it lies below-grade. The overall length of the embankment is 1317.8 ft and the overall width is 1775.0 ft. A detailed description of embankment dimensions and a discussion of the representation of the Federal DU Cell in the GoldSim model are provided in *Embankment Modeling for the Clive DU PA Model* (Neptune 2015g).

Disposal involves placing waste on a prepared clay liner that is approximately 8 ft below the ground surface. For the Federal DU Cell design, the depth of the waste below the top slope is a maximum of 47.5 ft (14.5 m). A cover system is constructed above the waste. The objective of the cover system is to limit contact of water with the waste, limit biointrusion, and protect the lower layers of the cover from freezing. The cover is sloped to promote runoff and is designed to limit water flow by increasing evapotranspiration (ET). The arrangement of the layers used for the ET cover design is shown in Figure 1. Beginning at the top of the cover, the layers above the waste used for the ET cover design are:

- **Surface Layer**: This layer is composed of native vegetated Unit 4 silty clay material with 15 percent gravel mixture on the top slope and 50 percent gravel mixture for the side slope. This layer is 6 inches thick. The functions of this layer are to control runoff, minimize erosion, and maximize water loss from ET. This layer provides storage for water accumulating from precipitation events, enhances losses due to evaporation, and

provides a rooting zone for plants that will further decrease the water available for downward movement.

- **Evaporative Zone Layer**: This layer is composed of Unit 4 material. The thickness of this layer is 12 inches. The purpose of this layer is to provide additional storage for precipitation and additional depth for the plant rooting zone to maximize ET.
- **Frost Protection Layer**: This material ranges in size from 16-inch cobbles to clay-size particles. This layer is 18 inches thick. The purpose of this layer is to protect layers below it from freeze/thaw cycles and wetting/drying cycles, and to inhibit plant, animal, or human intrusion.
- **Upper Radon Barrier Layer**: This layer consists of 12 inches of compacted clay with a low hydraulic conductivity. This layer has the lowest conductivity of any layer in the cover system. This is a barrier layer that reduces the downward movement of water to the waste and the upward movement of gas out of the disposal cell. The design specification for saturated hydraulic conductivity (K_s) of this layer is 5.00×10^{-8} cm/s (Whetstone Associates (2011), Table 15).
- **Lower Radon Barrier Layer**: This layer consists of 12 inches of compacted clay with a low hydraulic conductivity. This is a barrier layer placed directly above the waste that reduces the downward movement of water and the upward movement of gas out of the disposal cell. The design specification for K_s of this layer is 1.00×10^{-6} cm/s, from Table 15 of Whetstone Associates (2011).

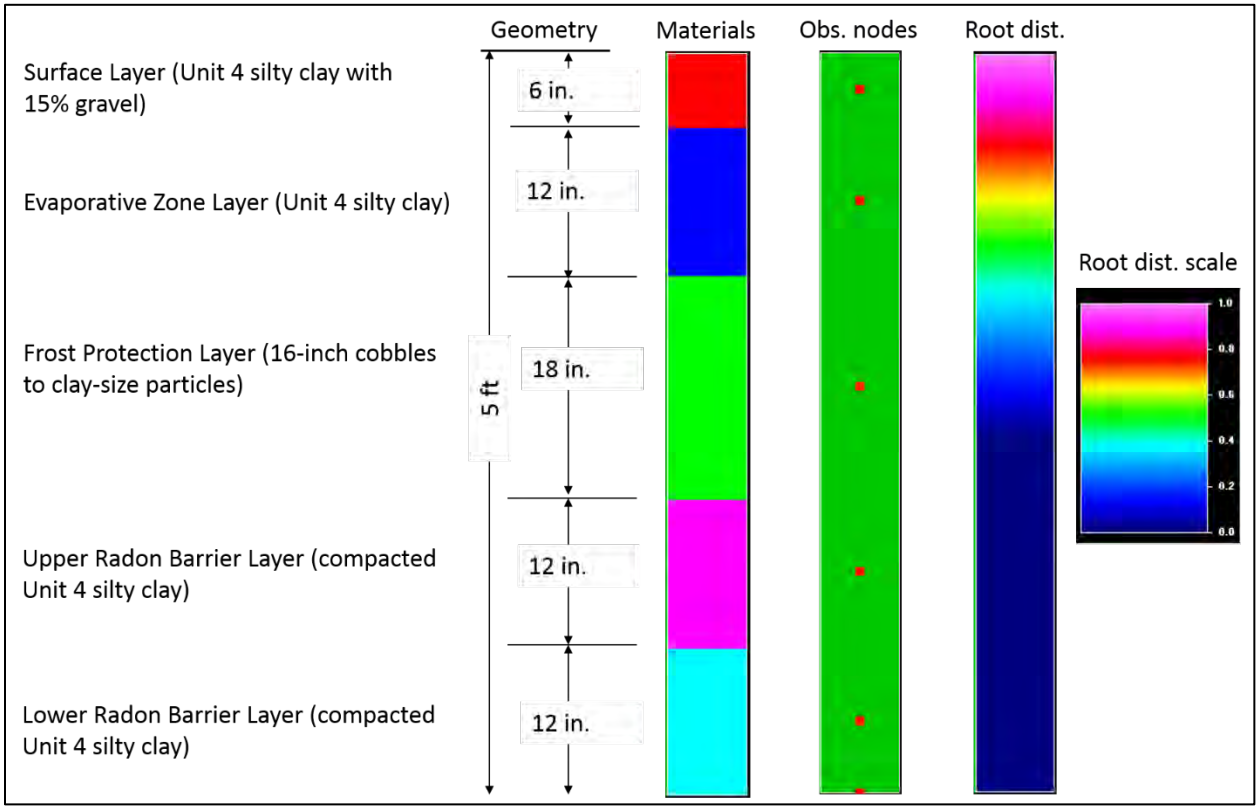

Figure 1. Evapotranspiration (ET) cover profile showing materials, observation nodes, and root distribution used in the HYDRUS-1D models.

1.2.2 Unsaturated Zone and Shallow Aquifer

The following description of the Clive Site hydrology is taken from the review prepared by Envirocare (2004). The Site is described as being located on lacustrine (lake bed) deposits associated with the former Lake Bonneville. The sediments underlying the facility are principally interbedded silt, sand, and clay. Sediments at the Site are described by Bingham Environmental (1991, 1994) and Envirocare (2000, 2004) as being classified into four hydrostratigraphic units (HSU). Predominant sediment textural class, layer thickness range, and average layer thickness for each unit are listed in Table 1. A diagram of the unsaturated zone is shown in Figure 2.

Unit 4: This unit begins at the ground surface and extends to between 6 ft and 16.5 ft below the ground surface (bgs). The average thickness of this unit is 10 ft. This unit is composed of finer grained low permeability silty clay and clay silt.

Unit 3: Unit 3 underlies Unit 4 and ranges from 7 ft to 25 ft in thickness. The average thickness of this unit is 15 ft. Unit 3 is described as consisting of silty sand with occasional lenses of silty to sandy clay.

Unit 2: Unit 2 underlies Unit 3 and ranges from 2.5 ft to 25 ft in thickness. The average thickness of this unit is 15 ft. Unit 2 is described as being composed of clay with occasional silty

sand interbeds. A structure map was prepared by Envirocare (2004) (their Figure 5) with contours representing the elevations of the top of the unit. This map shows that the top surface of Unit 2 slopes downward gradually from east to west in the vicinity of the Class A South cell.

Unit 1: Unit 1 underlies Unit 2 and is saturated beneath the facility, containing a locally confined aquifer. Unit 1 extends from approximately 45 ft bgs and contains the deep aquifer. The deep aquifer is reported to be made up of lacustrine deposits consisting of deposits of silty sand with some silty clay layers. One or possibly more silty clay layers overlie the aquifer (Bingham Environmental 1994).

Table 1. Texture class, thickness range, and average thickness for the hydrostratigraphic units underlying the Clive site.

Unit	Sediment Texture Class	Thickness Range (ft)	Average Thickness (ft)
4	silt and clay	6–16.5	10
3	silty sand with interbedded silt and clay layers	7–25	15
2	clay with occasional silty sand interbeds	2.5–25	15
1	silty sand with interbedded clay and silt layers	>620	>620

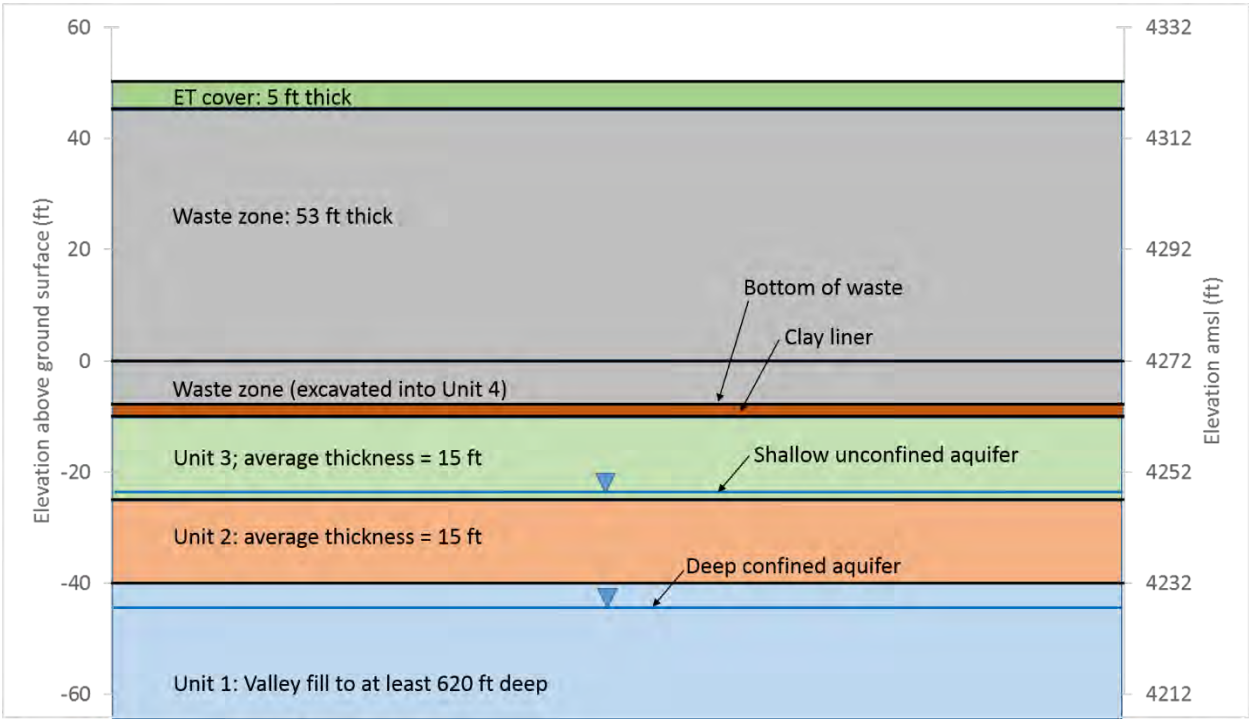

Figure 2. Stratigraphic profile showing ET cover, waste zone, and stratigraphy below the Federal DU Cell.

The aquifer system in the vicinity of the Clive Site is described by Bingham Environmental (1991, 1994) and Envirocare (2000, 2004) as consisting of unconsolidated basin-fill and alluvial fan aquifers. Characterization of the aquifer system is based on subsurface stratigraphy observations from borehole logs and from potentiometric measurements. The aquifer system is described as being composed of two aquifers: a shallow, unconfined aquifer and a deep confined aquifer. The shallow unconfined aquifer extends from the water table to a depth of approximately 40 ft to 45 ft bgs. The water table in the shallow aquifer is reported to be located in Unit 3 on the west side of the Site and in Unit 2 on the east side.

The deep confined aquifer is encountered at approximately 45 ft bgs and extends through the valley fill (Bingham Environmental 1994). The boring log from a water supply well drilled in adjoining Section 29 indicates continuous sediments to a depth of 620 ft bgs as described in Utah Division of Water Rights water right number 16-816 and associated well log 11293 (DWR 2014).The deepest portion of the basin in the Clive area is believed to be north of Clive in Ripple Valley, where the basin fill was estimated to be 3,000 ft thick (Baer and Benson as cited in Black et al. (1999)).

Deeper saturated zones in Unit 1 below approximately 45 ft bgs are reported to show higher potentiometric levels than the shallow unconfined aquifer. Differences in potentiometric levels are attributed to the presence of the Unit 2 clays. These observations are interpreted as indicating that the shallow unconfined aquifer below the Site does not extend into Unit 1 but is contained within Units 2 and 3 (Bingham Environmental 1994). The aquifer systems are described in more detail in the *Saturated Zone Modeling* white paper (Neptune 2015a).

Recharge to the shallow aquifer in the vicinity of Clive is thought to consist of three components: a small amount is due to vertical infiltration from the surface, some small amount of lateral flow is from recharge areas to the east of the Site, and the majority of recharge is believed to be from upward vertical leakage from the deeper confined aquifer (Bingham Environmental 1994). Average annual groundwater recharge from the surface in the southern Great Salt Lake Desert in the precipitation zone typical of Clive was estimated by Gates and Kruer (1981). An estimated 300 acre-feet per year were recharged to lacustrine deposits and other unconsolidated sediments over an area of 47,100 acres. This is a recharge rate of approximately 0.08 in/yr (2 mm/yr).

Groundwater recharge from lateral flow occurs due to infiltration at bedrock and alluvial fan deposits away from the Site, which moves laterally through the unconfined and confined aquifers (Bingham Environmental 1994). This is evidenced by the increasing salinity of the groundwater due to dissolution of evaporate minerals as water moves from the recharge area to the aquifers below the Site facility (Bingham Environmental 1994). The majority of recharge to the shallow aquifer is believed by Bingham Environmental (1994) to be due to vertical leakage upward from the deep confined aquifer due to the presence of upward hydraulic gradients.

The higher potentiometric levels in the deeper saturated zones in Unit 1 described previously are attributed to the presence of the Unit 2 clays (Bingham Environmental 1994). Vertical gradients between shallow and deeper screened intervals in the monitor well clusters were calculated by Bingham Environmental (1994). An upward vertical gradient was observed ranging in magnitude from 0.02 to 0.04 based on the distance between the screen centers. For a vertical hydraulic

conductivity of 1×10^{-6} cm/s (Bingham Environmental 1994), this corresponds to a recharge range from 0.25 in/yr to 0.5 in/yr (6.35 mm/yr to 12.7 mm/yr).

1.2.3 Climate

Precipitation measurements taken at the Site over the 17-year period 1992 to 2009 show a mean annual value of 8.53 inches (21.7 cm) (Whetstone Associates 2011). Precipitation exceeds the annual average from January through June and again in October and is below average for the remaining months. The nearest National Oceanographic and Atmospheric Administration (NOAA) station with a long-term record is located in Dugway, Utah, approximately 40 miles to the south. The mean annual precipitation for the same 17-year period measured at the Dugway station is 8.24 inches (20.9 cm). A comparison of the Dugway precipitation data for the 17-year period 1992 to 2009 with the long-term average for Dugway was made by Whetstone Associates (2011). This comparison indicated that annual average precipitation at the Site during this 17-year period has been greater than the long-term average at Dugway by 8 percent. Whetstone Associates (2011) concluded that simulations of cover performance using precipitation data from this 17-year period might be overestimating this component of the site water balance.

The HYDRUS-1D modeling performed is based on the 17-year record for consistency with the modeling results reported in Whetstone Associates (2011). However, an additional 2 years of monthly precipitation data are available from MSI (2012). The 19-year average precipitation is 8.62 inches (21.9 cm). This difference is driven primarily by the 4.28 inches of rainfall in May 2011. The small change in the overall average suggests that the modeling results presented for this analysis would not change significantly if the 19-year precipitation record had been used instead of the 17-year record.

The close correspondence between mean monthly temperatures measured at the Clive Site and the Dugway NOAA station was demonstrated by Whetstone Associates (2011). Average monthly temperatures measured at the Clive Site over the 17-year period 1992–2009 ranged from 27.7 °F in December to 79.5 °F in July.

1.2.4 Vegetation

Actual transpiration is dependent on the characteristics of the plant communities at the Site. Vegetation cover at the Site is less than 20 percent, with soils supporting a range of native and invasive shrubs. Excavations at the Site have shown plant rooting depths extending to approximately 31 inches (80 cm) below the ground surface, with root density decreasing with depth (SWCA 2011).

Vegetation surveys of three field plots on or adjacent to the Clive Site were conducted by SWCA (2011). The three low desert vegetation associations were characterized as: black greasewood, Plot 3; halogeton-disturbed, Plot 4; and shadscale-gray-molly, Plot 5. The dominant shrub in Plot 3 was black greasewood with a percent cover of 4.5% and the dominant forb was halogeton with a percent cover of 0.7%. In Plot 4, the dominant shrub was shadscale saltbush with a percent cover of 2.3%, and the dominant forb was halogeton with a percent cover of 3.3%. In Plot 5, the

dominant shrub was shadscale saltbush with a percent cover of 12.5%, and the dominant forb was halogeton with percent cover of 0.9%.

Black greasewood, shadscale saltbush, and halogeton are all classified as facultative halophytes (Anderson 2004; Pavek 1992; Simonin 2001). Facultative halophytes are known to benefit from high salt concentrations in their growth media (Shabala 2013). Halophytes are able to adjust to saline environments through various physiological adaptations such as compartmentalization of ions in cell vacuoles, succulence, and the elimination of salt through salt-secreting glands and bladders (Shabala 2013). Optimal growth for halophytes has been demonstrated by Shabala (2013) to occur in media with a concentration of approximately 50 mM NaCl for monocots, and between 100 and 200 mM for dicots. For the optimum range for dicots of 100 to 200 millimoles per liter (mM), the corresponding range of electrical conductivity for a NaCl solution is 9.5 to 18.4 mmho/cm (https://www.wolframalpha.com/).

Depending on the extent of the area defined on and adjacent to the Clive Site, approximately 80 to 90 percent of the soils are mapped by the Natural Resources Conservation Service (NRCS) as the Skumpah on 0 to 2 percent slopes (NRCS 2016). This Unit is characterized as having maximum salinity ranging from 8.0 to 16.0 mmhos/cm. The top end of this range of maximum salinity does not exceed the maximum of the range of salinity considered optimum for halophyte growth of 18.4 mmho/cm. Given the similarity in ranges of salinity in the surface soils at the Clive Site and that needed for optimum halophyte growth, the influence of the osmotic head reduction in the root-water uptake water stress response function is considered negligible and was, consequently, not included in the model.

1.3 HYDRUS-1D Software Package

HYDRUS-1D (Šimůnek et al. 2013) was selected for simulating the performance of the ET cover proposed for the DU waste cell. The HYDRUS-1D platform was selected for this project because of its ability to simulate processes known to have a significant role in water flow in landfill covers in arid regions. HYDRUS includes the capabilities to simulate:

- water flow in variably saturated porous media,
- material hydraulic property functions,
- atmospheric surface boundary conditions including precipitation and evapotranspiration,
- root water uptake, and
- free-drainage boundary conditions.

The flow component of unsaturated flow and transport software packages with atmospheric boundary conditions such as HYDRUS solves modified forms of the Richards equation for variably saturated water flow. The flow equation incorporates a sink term to account for water uptake by plant roots. HYDRUS can be applied to one-, two-, and three-dimensional problems. The HYDRUS software includes grid generators for structured and unstructured finite element meshes. Programs such as HYDRUS require detailed data to represent the atmospheric boundary conditions and plant responses that are the dominant influences on flow in the cover in arid and semi-arid conditions. These programs use the infiltration capacity of the soil at any time as calculated in the model to partition precipitation into infiltration and overland flow. HYDRUS

has been used for many applications for unsaturated zone modeling and has received numerous favorable reviews such as Scanlon's (Scanlon et al. 2002) review of HYDRUS-1D, Diodato's (Diodato 2000) review of HYDRUS-2D, and McCray's (McCray 2007) review of the most recent program, HYDRUS (2D/3D).

HYDRUS-1D was selected for simulating flow in the Federal DU 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. 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.

HYDRUS-1D models were developed for the evapotranspiration cover design for the Federal DU Cell (Figure 1). 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 are available from previous studies at the Site or can be estimated from site-specific measurements such as particle size distributions. 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 were available from the literature.

HYDRUS implements the soil-hydraulic functions of van Genuchten (1980), who used the statistical pore-size distribution model of Mualem (1976) to obtain a predictive equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters. The expressions of van Genuchten (1980) are given by

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_S - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_S & h \geq 0 \end{cases} \tag{1}$$

$$K(h) = K_s S_e^l [1 - \left(1 - S_e^{\frac{1}{m}}\right)^m]^2 \tag{2}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{3}$$

where

θ	is volumetric water content (–),
h	is the matric potential (l),
θ_r	is residual volumetric water content (–),
θ_s	is saturated volumetric water content (–),
α	is a van Genuchten fitting parameter (l^{-1}),
n	is a van Genuchten fitting parameter (–),
m	is 1-1/n with n > 1,
K	is hydraulic conductivity (l/t), and
K_s	is the saturated hydraulic conductivity l/t.

The above equations contain five independent parameters: θ_r, θ_s, α, n, and K_s. The pore-connectivity parameter "*l*" (lower-case L) in the hydraulic conductivity function was estimated (Mualem, 1976) to be about 0.5 as an average for many soils. The value for *l* is commonly taken to be 0.5, and this value was used for all simulations for all soil types.

2.0 UDEQ Interrogatory Responses

UDEQ has arranged the interrogatories and SER comments in the *Amended and New Interrogatories; Clive DU PA Modeling Report Version 1.4* (Utah DEQ 2017) into seven groups. The first group named by UDEQ as ET Cover Design will be addressed in this document. This includes Open Interrogatories CR R313-25-7(2)-05/2, CR R313-22-32(2)-10/3, CR R317-6-2.1-20/2, CR R313-25-8(4)(d)-21/2, CR R313-25-8(4)(a)-28/3, CR R313-25-7(2)-59/2, CR R313-25-7(3)-60/2, CR R313-25-7(1–2)-90/2, CR R313-25-7(2)-150/3, CR R313-25-8(4)(d)-153/2, CR R313-25-7(2)-175/1, CR R313-25-8(5)(a)-176/1, CR R313-25-7(2)-189/3, and CR R313-25-7(2)-192/3, and Supplemental Comments from Appendix B of the SER (SC&A 2015) 1, 2, 3, 4, 5, 6, 7, 8, 9, and 11.

2.1 Interrogatory CR R313-25-7(2)-05/2: Radon Barriers

DEQ Conclusion from April 2015 SER, Appendix C:

Based on several unresolved issues related to the evapotranspiration (ET) cover, DEQ indicated in the DU PA SER that the cover design was deficient. Therefore, this interrogatory remains open. The unresolved issues are as follows:

Evapotranspiration Cover—There are still a number of unresolved issues with respect to the selection of parameter ranges, distributions, and correlations, as well as the modeling approach and predicted sensitivities. These concerns are detailed in Appendix B. Further, because the model-predicted infiltration rates will be sensitive to the hydraulic properties assigned to each ET layer, DEQ recommends that Energy*Solutions* develop hydraulic properties for the cover system based on the approach outlined by Dr. Craig H. Benson in Appendix F to this SER. Issues related to this portion of the performance assessment cannot be closed until these concerns have been resolved. (All references in prior interrogatories to Appendices of "the SER" refer to the April 2015 SER (SC&A 2015)).

Clay Liner—As with the ET cover, there is still an unresolved concern that K_{sat} values will increase greatly over time, and that the α and K_{sat} values assumed for modeling flow through the liner must either be correlated or a sensitivity analysis be conducted to demonstrate that the lack of correlation assumed does not adversely affect the modeling results. In addition, there are problems with assumed liner hydraulic conductivity values. Furthermore, the DU PA Model v1.2 does not account for liner degradation over time. These issues must be resolved before DEQ can determine the adequacy of this portion of the DU PA.

DEQ Critique of DU PA v1.4, Appendix 21:

Modeling conducted for the clay liner beneath the waste should employ hydraulic parameters representative of a compacted clay liner. Typical α, n, and Θ_S for compacted clays can be found in Tinjum et al. (1997). Typical saturated hydraulic conductivities for clay liners can be found in Benson et al. (1994).

Infiltration—Before the adequacy of the DU PA can be determined, additional modeling of the ET cover infiltration rates must be conducted based on in-service hydraulic properties and correlated log(α) and log(K_{sat}) values as described in Appendix E. Without this information, DEQ is unable to conclude if the infiltration rates predicted by the DU GoldSim model are reliable or representative of future conditions (i.e., ≥ 10,000 years).

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatories 21, 175, 176, and 189 for discussions regarding the relationship between infiltration and the in-service hydraulic properties.

Erosion of Cover—Before the adequacy of the DU PA can be determined, Energy*Solutions* needs to clarify certain issues relating to Appendix 10 to the DU PA Model v1.2 (June 5, 2014; Neptune 2014g) as described in Section 4.4.2 of the SER. The Division of Waste Management and Radiation Control (DWMRC) is currently reviewing a proposed ET cover test request as part of a Stipulation and Consent Agreement to use a cover of similar design to that proposed for the Federal Cell in the DU PA. Any recommendations and conclusions from that review will need to be applied to the proposed Federal Cell as well.

DEQ Critique, v1.4, Appendix 21: See Interrogatories 20, 28, 160, and 191 for discussions regarding cover erosion.

Effect of Biologicals on Radionuclide Transport—Energy*Solutions* has not shown that the cover system is sufficiently thick or designed with adequate materials to protect the cover system or the underlying bulk waste in the embankments against deep rooting by indigenous greasewood (a species known to penetrate soils at other sites down to 60 feet) or other plants, or against biointrusion by indigenous ants or mammals (e.g., with maximum documented burrowing depths greater than the proposed cover thickness). Higher rates of infiltration are typically associated with higher contaminant transport rates. Under Utah rules, infiltration should be minimized [see UAC Rule R313-25-25(3) and (4)]. DEQ cannot determine the adequacy of the DU PA until Energy*Solutions* accounts for greater infiltration through the cover system at the proposed Federal Cell embankment due to biointrusion by plant roots and by animals.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatories 10, 20, 28, and 71 for discussions regarding enhanced transport due to biological processes.

Frost Damage—With the current proposed Federal Cell design, Energy*Solutions* should account in modeling for substantial disruption of near-surface layers above and within the radon barriers by frost, with accompanying decreases in ET and increases for initially low-permeability soil in

both hydraulic conductivity and correlated α values, which could affect modeled infiltration rates and radon release rates. UAC R313-25-25(3) and (4) require a licensee to minimize infiltration; therefore, Energy*Solutions* must model infiltration under realistic long-term assumed site conditions before DEQ can determine that this requirement has been met.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 192 for discussions regarding depth of potential frost impacts.

2.1.1 Interrogatory Response

Evapotranspiration Cover (ET Cover)

UDEQ argues that modeling of infiltration rates "must be conducted based on in-service hydraulic properties and correlated log(α) and log(K_{sat}) values" as described by Dr. Craig Benson in Volume 2, Appendix E, of the safety evaluation report (SER) prepared by SC&A (SC&A 2015a) [see interrogatories and comments 05/2, 21/2, 60/2, 90/2, 176/1 and B.4].

However, the hydraulic property recommendations and cover material naturalization presented in Benson et al. (2011) and in Appendix E of SC&A (2015a) are inappropriate for the Clive Site. When included in the model, they produce a model inconsistent with the observed site conditions of Clive. This model can be considered "conservative" in terms of modeling groundwater concentrations but dose results are lower for this model implementation than for the Clive DU PA Model v1.4 (Neptune 2015d), which does not imply "conservative." The rationale for not using these naturalized or in-service cover properties in the Clive DU PA Model v1.4 (Neptune 2015d) are presented in this section.

The hydraulic property recommendations provided in Benson et al. (2011) are based on measurements for samples from in-service covers made at 12 sites throughout the continental United States. One element of the characterization of a site's climate is the ratio of mean annual precipitation to mean annual potential evapotranspiration. The magnitude of this ratio is estimated to be 0.17 for Clive. Only one of the sites sampled by Benson et al. (2011) was considered to be arid, having a ratio of 0.06. The mean value of this ratio for all sites sampled was 0.51, with a highest value of 1.10. At two of the sites rainfall exceeded potential evaporation, which is completely inappropriate for the arid conditions at Clive. All but one of the sites that form the basis for the hydraulic property recommendations have much wetter conditions than Clive.

The conceptual model of cover material "naturalization" for Clive based on the work of Benson et al. (2011) is described in Appendix E of SC&A (2015a) as including changes in the hydraulic behavior of the material following construction. These changes are characterized by increasing values of hydraulic properties such as K_s and the hydraulic function α parameter (see Equation (1)) that begin soon after cover completion. These changes are commonly attributed to soil forming processes including wet-dry and freeze-thaw cycles, activity of roots and soil animals, decomposition of organic matter by microbes producing compounds that tend to bind soil particles into aggregates, and changes in cations adsorbed onto soil particle surfaces. In this conceptual model these processes lead to the development of soil structure but not soil horizons.

Under the wetter conditions considered by Benson et al. (2011), plant and animal activity are greater than in an arid setting. These wetter conditions promote a faster rate of disruptive processes due to plant and animal activity and in some cases freeze-thaw activity that were shown by Benson et al. (2011) to lead to formation of an aggregated soil structure and natural mixing of soil layers within a 5 to 10 year period at their study sites. Most importantly, the sites considered by Benson et al. (2011) also lack significant eolian deposition.

This is not the case for a site like Clive. Recent field studies (Neptune 2015b) provide evidence for a site-specific conceptual model of weak development of soil profiles (limited soil formation) in a setting influenced by deposition of eolian silt in Holocene history. The Site is within a region of significant eolian activity evidenced by locally thick accumulation of gypsum dunes west and southwest of the Site and a laterally continuous layer of suspension fallout silts preserved beneath the modern surface throughout the Clive Site. Clive quarry exposures examined in a field study (Neptune 2015b) showed sections of eolian silts immediately below a modern vegetated surface (Figure 3). The bottom of the eolian silt formed a gradational but definable contact with the lake muds and marl below. The upper vegetated surface at the top of the eolian section was distinct and noted as being partially indurated. In addition, buried soils were found in the eolian and lake sediments below the Lake Bonneville lacustrine sequence.

The eolian deposits in the upper part of the stratigraphic section shown in Figure 3 represent a 10,000-year-old record of deposition and soil formation (Neptune 2015b). Primary soil features developed over this time interval include an indurated Av-zone, and slight reddening of the silt profile with local platy structure from formation of clays (Figure 4). These observations are consistent with slow processes of soil formation in a high elevation semi-arid setting and continuing suppression and burial of developing soils by a relatively low rate of deposition of eolian silt. There is no evidence of soil structure development extensive enough to influence soil hydraulic properties.

Observations of Holocene eolian silt throughout the Clive Site support a conceptual model of long-term eolian deposition on a stable surface that promotes and preserves concurrent eolian deposits which are only slightly modified by slow processes of soil formation. The past Holocene depositional conditions at the Clive Site are promoted by a combination of extensive wet playa sources of eolian source material to the west and southwest of the Clive Site and the extremely low gradient paleo-Lake Bonneville surface surrounding the Site with sparse surface vegetation and limited surface erosion. These conditions will persist at the Clive Site as long as the lake levels remain below the site elevation. Rates of eolian deposition would be expected to increase as future lakes approach the Site with increased formation of dunes (deposition of eolian sands). Recurring lakes during ice ages (climate cycles) will rework and mix the eolian deposits with aggrading clastic lake sediments. The expectation is that eolian deposits will drape and slightly stabilize closure covers until future lakes return to the Clive Site. These studies at the Clive Site were conducted by two highly experienced Ph.D. geologists, one of whom, Dr. Jack Oviatt (https://www.k-state.edu/geology/faculty-staff/Oviatt.html), has decades of experience working in the Lake Bonneville region.

Climate conditions and soil formation processes at the Clive Site contradict the assumptions of rapid soil structure formation in the cover layers observed by Benson et al. (2011) at other sites

and demonstrate the inapplicability of the conceptual model to the Clive Site. The one-size-fits-all generalization of hydraulic properties does not appropriately represent the unique conditions at the Clive Site. As described by Neuman et al. (2003) in NUREG/CR-6805:

> Hydrogeologic models are by nature site-specific. Though there is an established (and evolving) set of general hydrogeologic principles that apply to many sites on many scales, they are insufficient to either describe (conceptualize) or quantify (model) the hydrogeology of a particular site over a given range of scales. Because each site is unique, general principles must always be supplemented by regional and site-specific data to be useful for conceptualizing and modeling subsurface flow and transport at a site, regardless of purpose.

The soils at the Clive Site used for construction of the cover have been mapped, described, sampled, and their properties measured. These soils have hydraulic properties that derive from their origin and their environment, which are unique to the Clive Site. These properties are therefore already "naturalized."

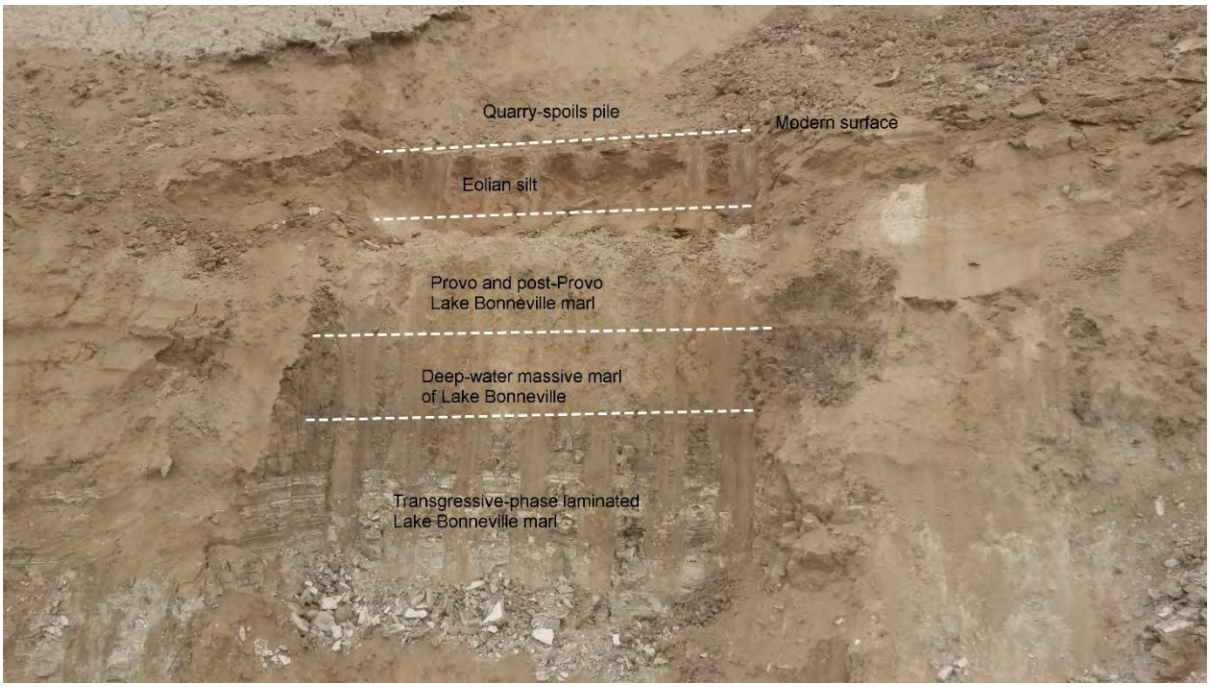

Figure 3. Eolian silt in trench located at Clive Pit 29 overlying Lake Bonneville sedimentary deposits (Neptune 2015b).

Figure 4. An example of upper soil-modified eolian silt in Pit 29. Basal contact of the silt is approximately located at the middle of the pick handle. It is a gradational contact between eolian silt intermixed with regressive Lake Bonneville marl (bottom of the pick handle).

UDEQ asserts that "the photographs in Figures 4 and 5 of Appendix 21 [reproduced herein as Figure 3 and Figure 4] are inconclusive and provide no quantitative basis to support inferences that structural development and alterations in hydraulic properties do not occur at Clive. Structural development that occurs in covers due to pedogenesis generally is not visible at the scale represented in these photographs. Moreover, the smearing that occurs in test pits can obscure structure that is present." The interpretation of the expert geologists that recent soil formation is minimal at the Site was based on their direct field observation of the exposures, not on examination of the photographs.

UDEQ states further, "If Energy*Solutions* wishes to use these analogs as evidence to support hydraulic properties representing long-term conditions significantly different from NUREG/CR-7028 (Benson et al. 2011), Energy*Solutions* should conduct appropriate measurements on these in-place materials to demonstrate that the hydraulic properties are indeed different from the abundance of data in NUREG/CR-7028." The profiles excavated and examined by the geologists were not analogs but observations of the Unit 4 material at the Clive Site while the "abundance of data" referred to by UDEQ was acquired from other (nearly all wetter) sites throughout the continental United States.

Correlation Between Saturated Hydraulic Conductivity, K_s, and the van Genuchten α Parameter

The hydraulic parameters α and K_s used in the Clive DU PA Model v1.4 are considered to be statistically independent, implying they are theoretically uncorrelated and distributions can be developed separately for each parameter. UDEQ believes this assumption is not valid based on summaries of data presented by Benson and Gurdal (2013) as presented in Appendix E of the Safety Evaluation Report (SER) (SC&A 2015a), Sections 4.1.1.1 and 4.4.1. Both references examine data aggregated over soil textural classes, while the Clive DU PA Model v1.4 (Neptune 2015c) focuses on a single primary texture class (silty clay), and distributions for α and K_s are developed specifically for that soil textural class. In this response, Energy*Solutions* provides new analysis of data associated with Benson and Gurdal (2013) to demonstrate the importance of considering soil textural class when attempting to quantify correlation between α and K_s.

In addition to providing detail on the different patterns seen in aggregated data versus subpopulations defined by soil textural classes, several other fundamental statistical concepts support a lack of evidence for building strong positive correlation into the distribution development for α and K_s. There are several fundamental statistical concepts that should be taken into account when considering generalization of a correlation observed in a particular data set to a larger population or context: (1) correlation is designed as a summary of the *linear* association between two random variables, and therefore linearity should be assessed before relying too heavily on correlation as a summary of a relationship, (2) data aggregated over many subpopulations with different ranges for the variables may exhibit a drastically different correlation from the correlations observed within the subpopulations, (3) even when random variables are statistically independent, random realizations of data will have estimated correlations that are different from zero, and (4) points with extreme values for both variables have high leverage and can be very influential on estimated correlations and estimated slopes.

Investigations into observed correlations between α and K_s are typically carried out on the logarithmic scale because the relationship is expected to be more linear on the log scale than the original scale. All plots and correlations provided in this response are based on the $\log_{10}$ scale for both α and K_s.

A closer look at the Benson and Gurdal (2013) data

The data from the Benson and Gurdal (2013) paper are used to investigate the evidence of a correlation. Benson (C. Benson, personal communication, October 11, 2017) supplied Energy*Solutions* with the 253 pairs of K_s and α values presented in the 2013 paper, along with information regarding the percent sand/clay/silt, as measured for the material for each sample.

The plot provided in Benson and Gurdal (2013), and included here as Figure 5, does not display or take into account the soil texture associated with the measurements (i.e., data are aggregated over soil textural classes). They reported a sample correlation coefficient for the aggregated data of 0.462 and did not provide a measure of uncertainty or information about what correlation type was calculated.

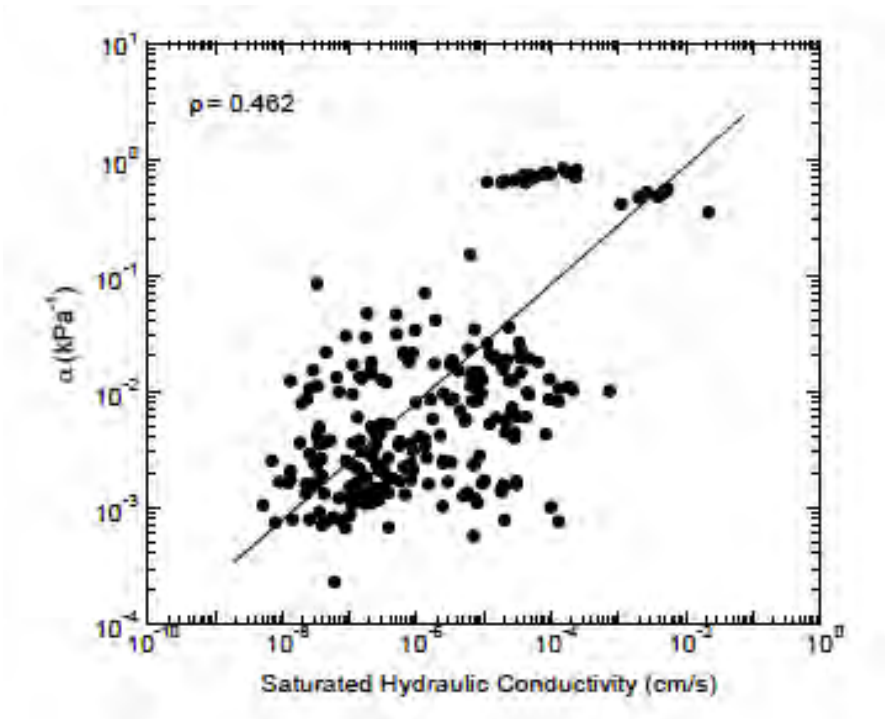

Figure 5. Figure 3 from Benson and Gurdal (2013) showing the data requested by Energy*Solutions.*

Using the USDA soil classification system (Jury and Horton 2004), each data point in the data provided by Benson (2017) was assigned a soil textural class. This information is then used to re-visualize the data (see Figure 6 and Figure 7) and to further investigate estimated correlation coefficients. Pearson's correlation coefficients are used unless otherwise stated.

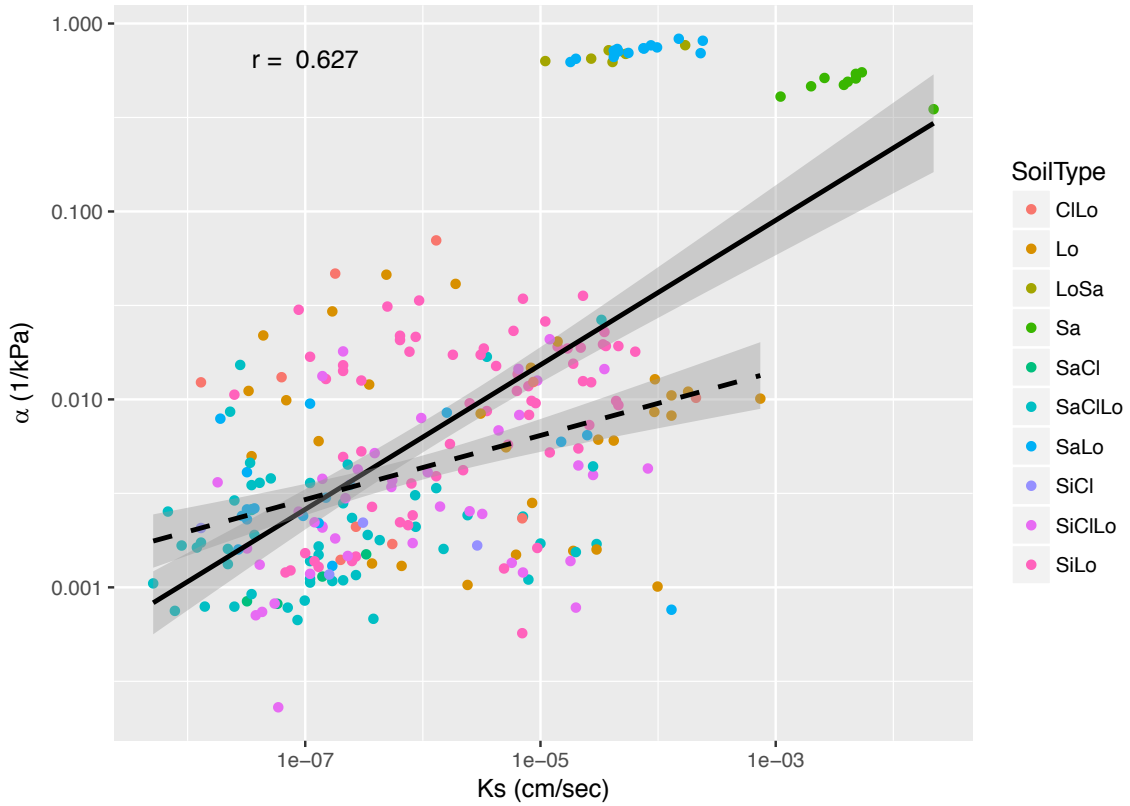

Figure 6. Estimated linear relationships between α and K_s for all observations (solid line) and without the high-leverage points making up the clusters of points in the upper right half of the plot with α greater than 0.10 kPa^{-1} (dotted line). The estimated correlation changes from 0.627 for all the data to 0.384 for the restricted range.

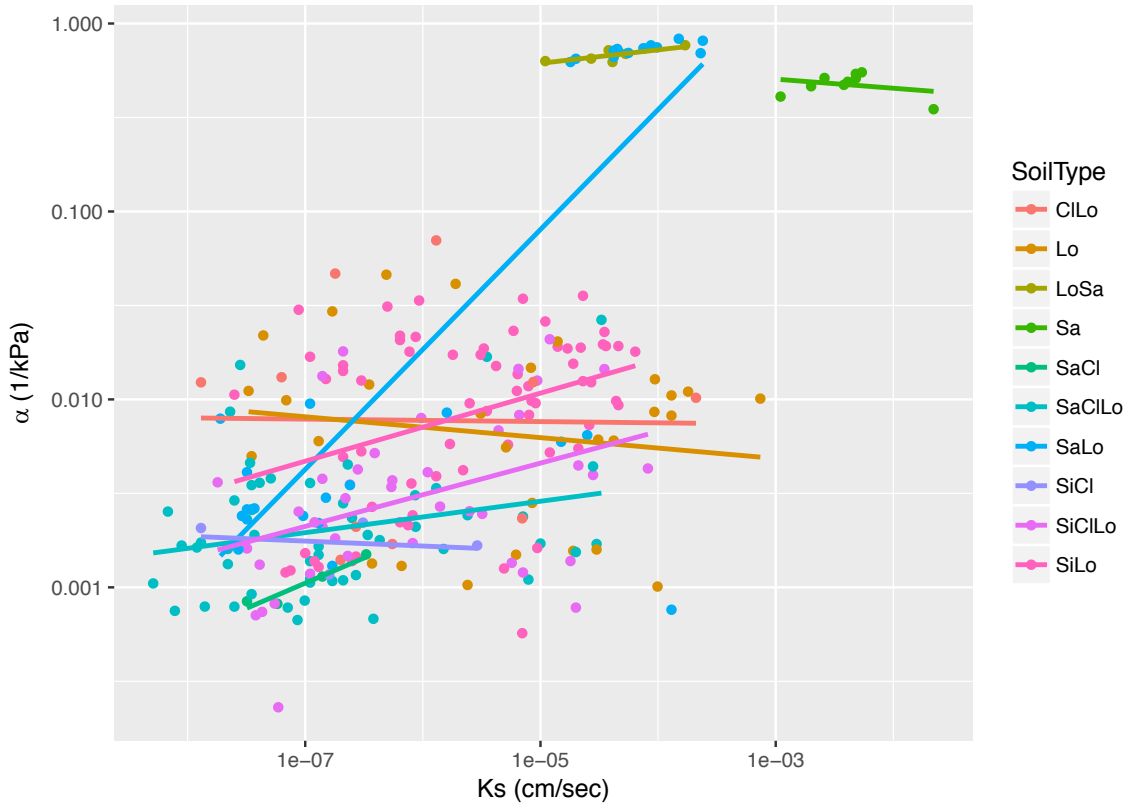

Figure 7. Estimated linear relationships within each soil type for the data provided by Benson (2017). Pearson's correlation coefficients, and 95% confidence intervals, are shown in Table 2 for the soil textural classes, and the individual soil classes are shown in panels in Figure 8.

A few important observations from Figure 6 are:

1. The clusters of observations in the upper right with large value for K_s and α belong to three distinct soil textural classes (sand, sandy-loam, and loamy-sand); they do not represent pairs of K_s and α across a range of soil types. The estimated linear relationship and correlation are heavily influenced by the location of the clusters relative to the cloud of other points because they have high leverage on the estimated relationship (see the difference in slope between the solid and dotted lines in Figure 6).
2. The relationship displayed in Figure 5 and the reported correlation coefficient based on the aggregated soil textural classes are not indicative of the relationships observed within individual soil textural classes. In fact, the observed relationships between K_s and α vary widely across soil textural classes, as seen in Figure 7. The estimated correlation for the aggregated data does not appear to be useful for individual soil textural classes and, therefore, should not be generally applied to distribution development for PA models meant to apply to specific soil textural classes.
3. The Pearson's correlation coefficient and the estimated relationship shown in the plot in Figure 5 do not match those for the data provided to Energy*Solutions* by Benson in 2017

(compare Figure 5 to Figure 6). The data presented in Figure 6 are based on 253 pairs of K_s and α, which matches the number of pairs expected based on Table 2 in Benson & Gurdal (2013). However, it is clear the data do differ slightly (e.g., there are two points near α of 0.1 kPa^{-1} in Figure 5 that do not appear in Figure 6). This discrepancy could not be reconciled in this investigation. Regardless, the general conclusions and arguments do not depend on the value of the correlation coefficient reported or small differences between the two data sets.

Patterns in aggregated data do not apply to individual soil textural classes

For the correlation based on data aggregated over all soil textural classes to be an appropriate description for individual soil textural classes, the relationships within soil textural classes should look similar to the pattern observed in the aggregated data. The existence of a different relationship for aggregated data (or a population) as compared to data separated by subgroups (or subpopulations) is a common and well-studied statistical phenomenon known by names such as Simpson's Paradox and ecological fallacy (e.g., Wagner (1982) and Ch. 9 of Ramsey and Schafer (2013)). This observation is often expected when, as shown in Figure 6 and Figure 7, the ranges of values for each variable vary by group, sometimes greatly. This creates a situation where subgroups with little correlation, or even negative correlation, can stack together to induce positive correlation over the population. Potentially misleading conclusions and predictions can result through the assumption that subgroups behave similarly to the aggregated population with respect to the association between the two variables. The assumed correlation within a population need not be the same as the correlations within its subpopulations.

The observed relationships between K_s and α within the data provided by Benson in 2017 clearly vary in magnitude and sign for different soil textural classes. The data for each soil textural class are plotted in their own panels (with different x and y axis scales) in Figure 8 to supplement information in Figure 7. Table 2 provides the estimated correlation coefficients and their associated 95% confidence intervals for each soil textural class. There is no evidence in these data that the pattern in the aggregated data across soil types should apply at the scale of a particular waste cover primarily made up of one soil textural class. Benson and Gurdal (2013) suggest a large positive correlation exist for data aggregated across soil textural classes, but, as shown above and below, it is important to consider the soil textural class when introducing the assumption of correlation into distribution development for the PA model.

Correlation coefficients can be useful statistics to provide the direction and strength of a linear relationship between two random variables (Ramsey and Schafer 2013). Few of the soil textural classes in the data from Benson (2017) seem to exhibit clear linear associations, thus limiting the usefulness of the correlation coefficient as a summary measure of the relationship. Statistical hypothesis tests can be helpful if evidence against a particular null hypothesis is of interest, but confidence intervals provide more information about uncertainty and are not tied to a particular null hypothesis. The 95% confidence interval can be interpreted as a range of plausible correlations that could be obtained from different random datasets of the same size from the same population.

Table 2. Estimated Pearson's correlation coefficients between K_s and α on the log scale by soil textural class, and associated 95% confidence intervals, calculated using the data provided by Benson in 2017 data.

Soil Textural Class	Estimated correlation	95% lower limit	95% upper limit
Clay Loam	-0.01	-0.64	0.62
Loam	-0.15	-0.49	0.23
Loamy Sand	0.79	-0.06	0.98
Sand	-0.28	-0.79	0.48
Sandy Clay	0.96	-0.02	1.00
Sandy Clay Loam	0.25	-0.03	0.49
Sandy Loam	0.80	0.63	0.90
Silty Clay	-0.20	-0.97	0.94
Silty Clay Loam	0.39	0.10	0.62
Silty Loam	0.36	0.12	0.55

On the log scale, seven of the ten soil textural classes represented in the data from Benson and Gurdal (2013) have negative estimated correlations or have 95% confidence intervals that overlap zero. The widths of the confidence intervals demonstrate the substantial uncertainty in the correlations of the underlying populations, given the available data.

It is also important to combine the information in Table 2 with that in Figure 7 and Figure 8. For example, the sandy loam soil class (SaLo) has a point estimate with a large magnitude (0.80) and a confidence interval suggesting a positive correlation between K_s and α (0.63, 0.90), but a closer look at the plot of the data for that soil textural class in Figure 8 calls into question the validity of that conclusion based on the cluster of points with high leverage driving the correlation.

For the Clive DU PA Model v1.4, the objective is to develop distributions for the Unit 4 soil described as *Silty Clay*, which shows no evidence of a positive correlation in the four samples in the Benson and Gurdal (2013) data (see Figure 8, Figure 9, and Table 2).

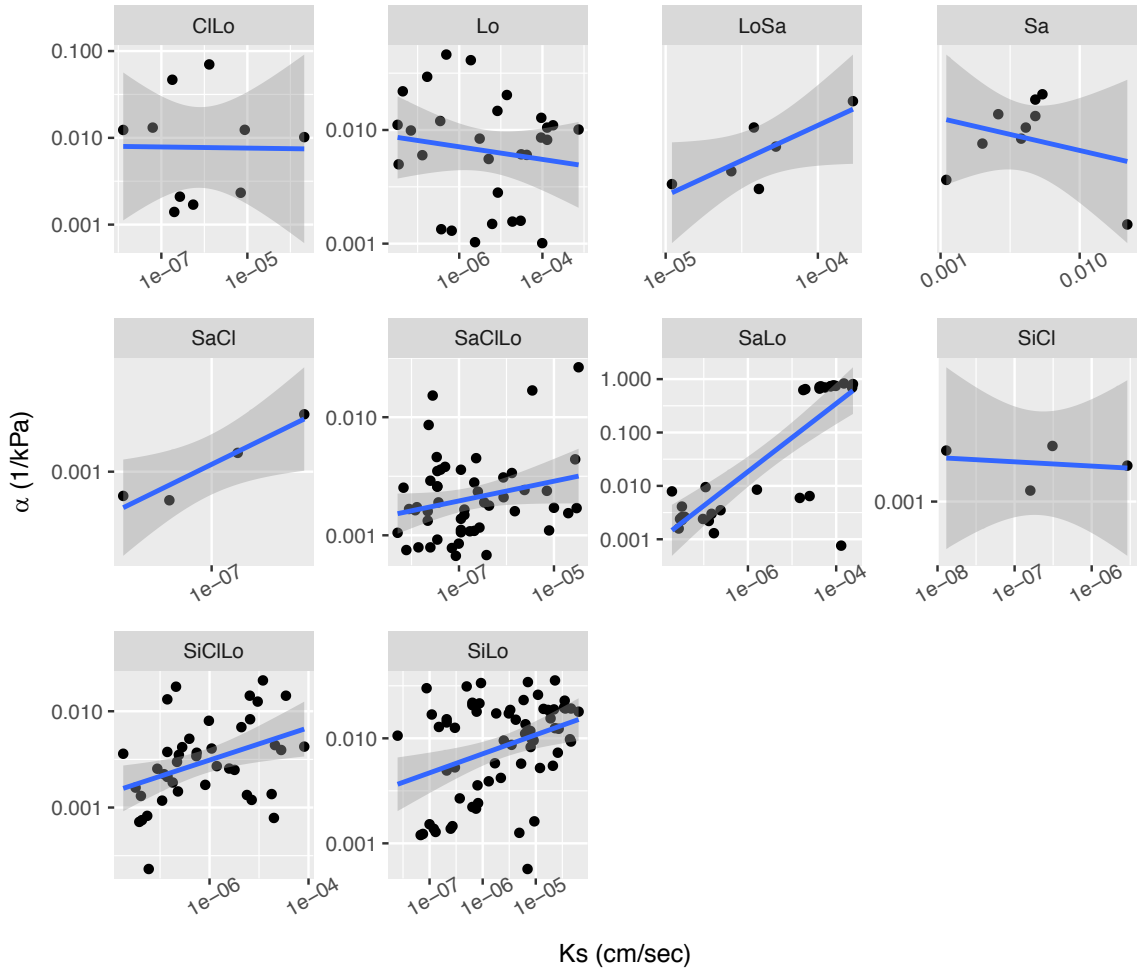

Figure 8. Estimated linear relationships by soil textural class for the data plotted in Figure 6 and Figure 7. Note the x and y axes are allowed to change among panels and are on the log10 scale.

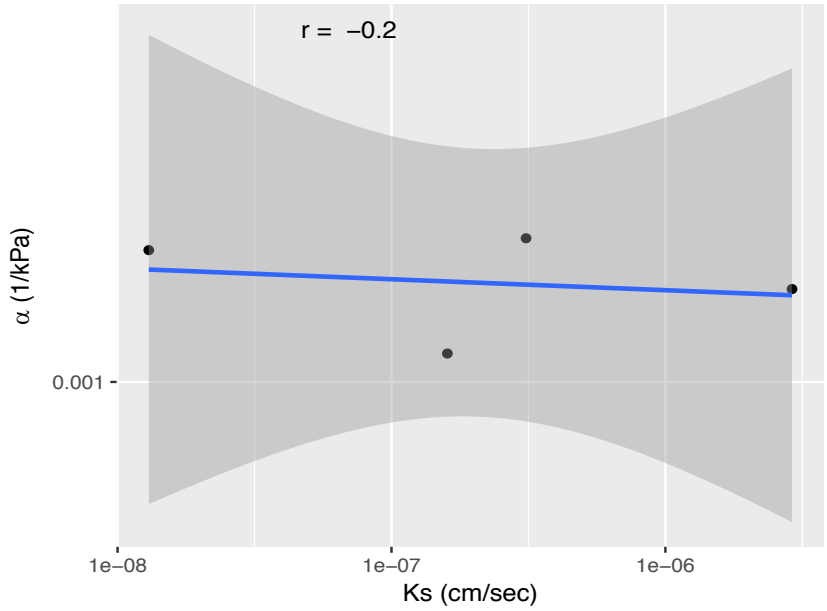

Figure 9. Estimated linear relationship on the log scale between α and K_s for Silty Clay. Pearson's correlation coefficient is -0.2, with a very wide 95% confidence interval of (-0.97, 0.94).

Observed sample correlations from independent random variables

Assessing evidence of a theoretical correlation between two variables based on relatively few samples, as is the case for the separate soil textural classes, is very difficult. Figure 10 illustrates estimated linear relationships that could be observed even when the two variables are truly independent. The panels are created by taking random draws from independent standard normal distributions with sample sizes of 6. Note the different conclusions one might draw about correlation between the two random variables just from looking at one of the sixteen panels. The difficulty of assessing evidence for a theoretical correlation due to small sample sizes can lead to the desire to increase the number of samples used by aggregating the data of immediate interest with that from related groups. As discussed above, this should be done with caution.

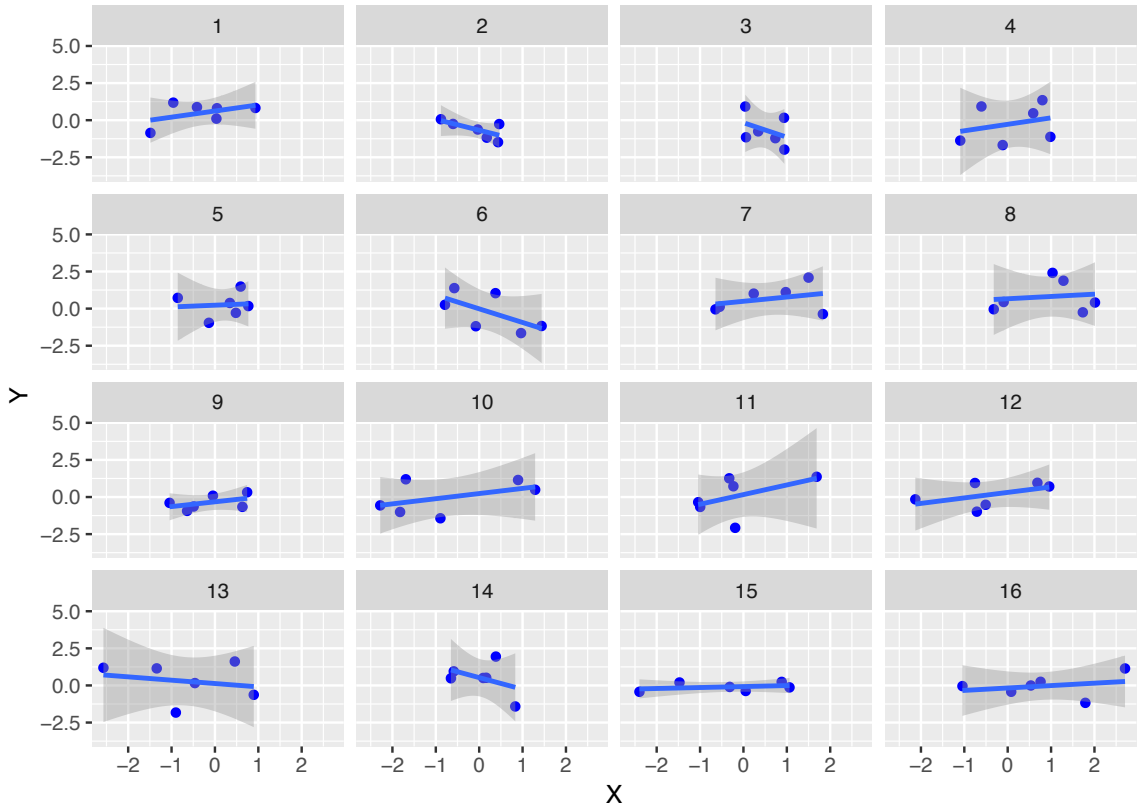

Figure 10. Estimated linear relationships based on 16 realizations of six random pairs of observations that come from statistically independent variables (x and y were drawn independently from two standard normal distributions).

Summary

In summary, there is not evidence of a strong linear relationship between α and K_s that should be incorporated into PA distributions, particularly for the Unit 4 soil within the Silty Clay soil textural class found at the Clive Site. Additionally, incorporating correlation into distribution development without adequate empirical and theoretical evidence should be done with care to avoid excluding combinations of values of the two variables that are actually plausible (i.e., to avoid inadvertently excluding realistic scenarios). The argument for correlation between K_s and α suffers from some common statistical misconceptions and misuses of correlation, as described in detail in the response. It is clear from the exploratory analysis conducted here that soil textural classes should be taken into account when assessing possible correlation between K_s and α for a particular site. The two variables exhibit very different relationships within different soil textural classes—a clear indication that the aggregated correlation should not be applied to the individual soil textural classes. In the particular soil textural class used in the Clive DU PA Model v1.4, Silty Clay, there are very few samples available in Benson and Gurdal (2013) and no evidence of a positive linear relationship between the K_s and α parameters.

Clay Liner

The Federal Cell is constructed on top of a compacted clay liner. Disposal involves placing waste on a prepared clay liner that is approximately 2.5 m (8 ft) below the ground surface. The liner is constructed of compacted local clay, i.e., Unit 4 material. Porosity and bulk density values for the clay liner are assumed to be the same as for the Radon Barrier Clays, as these clays are all compacted, unlike the surface and ET layer Unit 4 material. Properties of nine Unit 4 cores acquired at the Clive Site were determined by Bingham Environmental (1991, 1994). Grain size distributions were determined for nine cores and saturated hydraulic conductivities and water retention relations determined for two of the cores.

The GoldSim software platform cannot calculate flow of water from the cover surface to the water table using the unsaturated flow equation the way that variably saturated numerical flow models (e.g. HYDRUS) can. GoldSim includes flow by assigning a flow rate or flux for a realization from a statistical distribution of fluxes. In this context a GoldSim realization is "a single model run within a Monte Carlo simulation. It represents one possible path the system could follow through time" (GTG 2014). This water flux distribution is developed from a collection of results obtained from simulations using more complex models that incorporate daily changing weather conditions at the surface and that allow for many flow models to be run encompassing a range of hydraulic input parameter values. The resulting statistical distribution represents the net infiltration or water flux at the top of the waste. For any given realization, the same value of the flux drawn from the distribution is assigned to each cell representing the pathway through the waste as inflow to the cell and outflow from the cell. The clay liner is represented in the model by four cells below the waste. The outflow from the bottom cell representing the waste is connected to the inflow of the top cell of the clay liner. Each of the clay liner cells are assigned the same flux as the waste.

The layer above the clay liner with the lowest hydraulic conductivity is the Upper Radon Barrier. As described in Section 2.4.1, the distribution for the hydraulic conductivity of this layer has a minimum value of 4.32×10^{-3} cm/day, which is the engineering design specification. The distribution has 1st, 50th, and 99th percentile values of 0.65 cm/day, 3.8 cm/day, and 52 cm/day, respectively, which are from a range of in-service ("naturalized") clay barrier K_s values described in Section 6.4, p. 6-12 of Benson et al. (2011). Given this distribution, any K_s value chosen from the distribution other than the minimum is a value greater than the initial construction specification. As described above, each cell from the bottom of the waste to the top of the upper aquifer is assigned the same water flux drawn from the distribution for that realization, including the clay liner cells. As larger fluxes are drawn representing the variability due to naturalization of the cover materials, those same fluxes are applied to the clay liner representing naturalization of that layer.

UDEQ has argued that the modeling approach described above does not account for liner degradation over time and that there are problems with the assumed liner hydraulic conductivity values (see the responses to UDEQ Interrogatories 05/2 and 90/2). With respect to the first issue, liner degradation is accounted for by using a statistical distribution of water fluxes for the modeling as described above. This distribution takes into account a range of possible values for saturated hydraulic conductivities greater than the engineering specification. The next issue is

immaterial because the water flux through the clay liner cells depends only on the value of the water flux at the top of the waste drawn from the water flux distribution. This means that liner hydraulic properties are assumed to be the same as the radon barriers.

UDEQ states that modeling of the clay liner "should employ hydraulic parameters representative of a clay liner." They go further to recommend a reference for clay hydraulic properties not based on samples from the Clive Site. As described above, hydraulic properties for the clay liner were obtained from testing of two cores acquired from the Clive Site of Unit 4 silty clay (Bingham Environmental (1991, 1994)).

The last issue raised by UDEQ with respect to the clay liner is that van Genuchten hydraulic function α parameter and the saturated hydraulic conductivity values must be correlated (also Interrogatories 05/2, 21/2, 60/2, 90/2, 153/2, and Comment B.4). See the response to Interrogatory 05/2.

Infiltration

See the response to Interrogatory 05/2 Evapotranspiration Cover (ET Cover).

Erosion of Cover

UDEQ points to issues on erosion raised in Section 4.4.2 of the SER (SC&A 2015b). These issues are addressed in the response to Interrogatory 71/1.

Calculations to evaluate the stability of the design with respect to gully erosion for the ET cover of the Class A West cell were provided in Appendix D of Energy*Solutions* (2015). Similar calculations for the Federal Cell are presented in the response to Interrogatory 71/1.

Effect of Biologicals on Radionuclide Transport

SWCA Environmental Consultants (SWCA) was contracted by Energy*Solutions* to acquire field data at the Clive Site to identify representative study areas and to collect data to "document the diversity and composition of plant and animal species and to quantify soil mixing by burrowing mammals and ants associated with each vegetation community" (SWCA 2013). In addition, six excavations were completed and surveyed to quantify the aboveground and belowground size of the dominant plant species, and the maximum rooting depth and width of root of the dominant species. This work was focused on characterizing the biotic aspects of the ET cover system at the Clive Site for the DU PA Model (SWCA 2011). SWCA is a nationwide firm of environmental professionals operating since 1981 and is well known for their work in multiple environmental sectors, including ecology.

Field studies and analyses were conducted by SWCA at the Clive Site including quantifying vegetation, small mammal distributions, and mammal burrow and ant mound size and densities at the Clive Site and nearby ecologically analogous sites. Additionally, several excavations in the Unit 4 soils were completed to estimate ant mound depth and soil volume transported to the surface by ants for the DU PA Model (SWCA 2011).

SWCA describes the ecological context for the ET cover design at the Clive Site in their responses to Round 1 Interrogatories from UDEQ. They note that the design for Clive is consistent with both published ET cover-system recommendations (ITRC 2003; Peace et al. 2004; Scanlon et al. 2005) and with the site-specific climate and ecology documented through the studies conducted by SWCA (2011, 2012). As summarized from SWCA (2013), the ecology at the Clive Site can be characterized by the following:

- The dominant shrub species are small in stature compared to those of the same species in deeper more fertile soils and/or in areas of greater annual precipitation.
- The distributions, densities, and stature of plant species at the Site are determined by high soil salinity, soil pH, low fertility, and aridity.

Based on data collection and analysis and the proposed cover design, SWCA evaluated the potential for disturbance by plant roots, mammals, and ants to result in increased infiltration (SWCA 2013). The Surface and Evaporative Zone layers are composed of native Unit 4 material and revegetated with native, locally adapted plant species. The target vegetation community is designed to represent the diversity and density of the native vegetation (SWCA 2013). With this combination of local materials and plants, the hydrology and ecology of the upper layers of the cover will be similar to native undisturbed areas at the Site.

Based on evidence from analogous sites detailed in SWCA (2013), the densities of plant roots and burrows will be sparse in these layers and infiltration would be minimally affected. Total soil disturbance due to mammal burrowing was estimated by SWCA (2013) for two cases of vegetation conditions. These cases are considered because these authors noted an association between vegetation conditions and mammal activity. Under expected vegetation conditions, soil volume disturbed by mammal activity was less than $1/100^{th}$ of a percent of the total soil volume. Under a worst-case scenario of vegetation dominated by greasewood, the soil volume disturbed was $1/10^{th}$ of a percent of the total soil volume of the ET cover. Their conclusions, supported by detailed evidence presented in SWCA (2013), were that the Surface and Evaporative Zone layers would be deep enough to allow for ant activity and some mammal burrowing and soil movement without compromising the functions of the lower layers.

SWCA concludes that, despite the low density and small size of plants and mammals at the Site, local plants and animals could penetrate the Frost Protection layer but “the amount of soil disturbance that could potentially occur on the ET cover is minute, compared to the total soil volume on the ET cover. Similarly, the amount of water infiltration that could occur in association with biointrusion of the ET cover is also minute.”

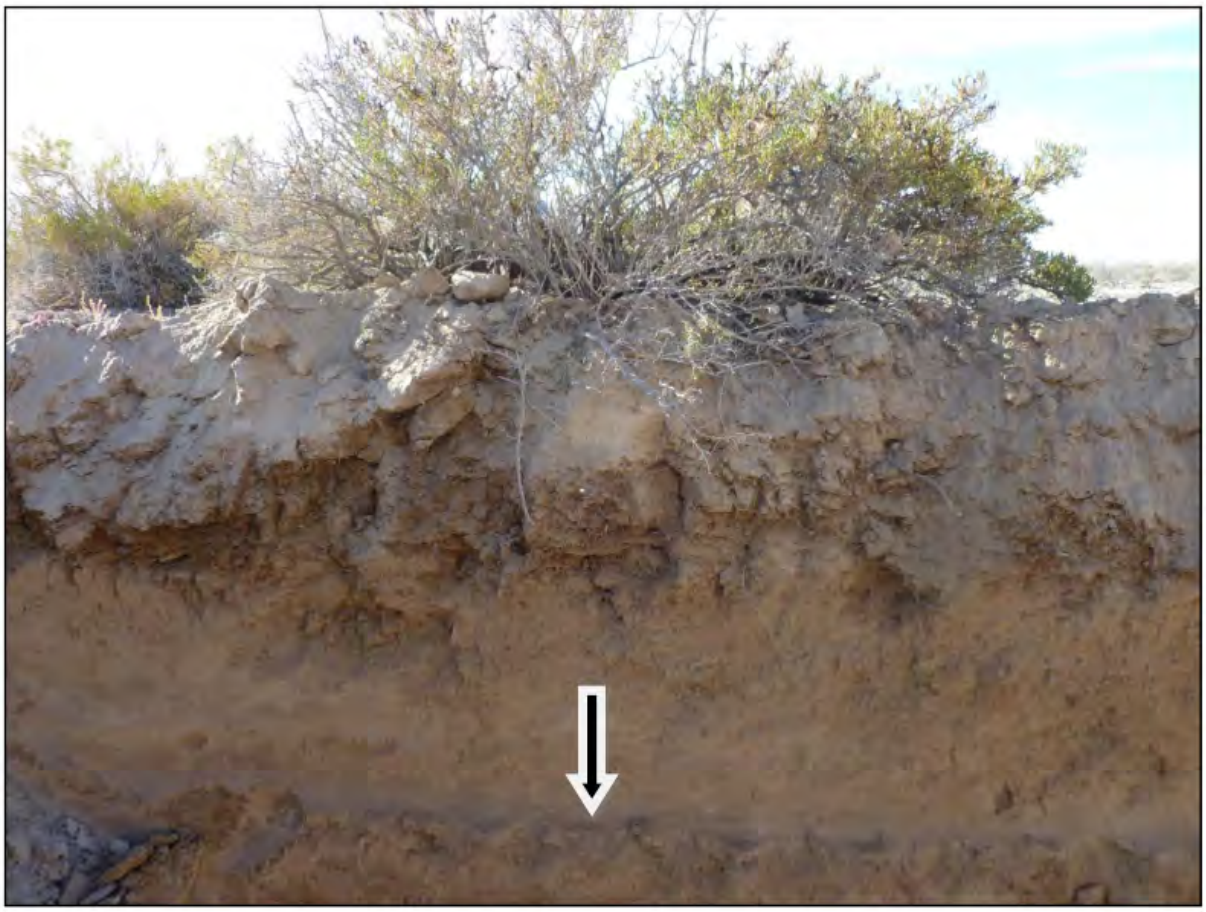

Figure 11. Borrow soil cross-section below a greasewood plant shows the compacted clay layer at approximately 60-cm depth. Roots extend laterally and do not penetrate the compacted layer (SWCA 2011).

The potential for greasewood roots to extend to depths greater than the cover layers is recognized by SWCA. SWCA (2013) notes, however, that "the aboveground mass of greasewood plants on and near Clive is consistent with low water availability." Roots are expected to follow water availability and not penetrate clay layers. This behavior was documented by SWCA (2013) in an excavation at the Clive Site showing lateral root growth of a greasewood plant at the Site. Roots were seen to extend vertically downward to the top of a clay layer at approximately 60 cm depth (Figure 11). At the clay layer roots extended only laterally and did not penetrate the layer. The explanation for this rooting behavior from the observation of SWCA, consistent with other research, is that infiltrating water would tend to perch on lower permeability clay layers causing plant roots to grow laterally following water availability (Groeneveld 1989).

SWCA (2013) conclude from their observations at the Clive Site and ecological analog sites that the low fertility and alkalinity of the soils and the aridity of the climate limit the growth of plants at the Site and would inhibit the development of large deep-rooted plants in the cover. Their opinion is that, while greasewood will eventually become established at the Site, roots will follow available water and remain within the Surface, Evaporative Zone, and Frost Protection

Layers. Additional evidence supporting the projection of limited greasewood root penetration at the Site presented by SWCA (2013) includes:

- The water table depth exceeds maximum levels accessible by greasewood.
- There is little or no capillary rise above the water table.
- The root to shoot stature of greasewood at Clive is not sufficient to root deeply.
- Regardless of plant stature, the majority of root biomass is concentrated in the upper soil.
- Nutrients are concentrated near the surface in desert soils.

Local Unit 4 material is used for the upper layers of the cover, and these layers will be vegetated with native, locally adapted plant species. The hydraulic properties of these layers are expected to be similar to those of undisturbed areas of the Site, which will experience the same biotic activity as the upper layers of the cover. Using hydraulic conductivity measurements of native Unit 4 samples from the Site as inputs to the model accounts for the influence of biotic activity on infiltration.

Frost Damage

Calculations of frost depth at the Clive Site were made by Hansen, Allen, and Luce (HAL), a professional engineering firm. These calculations were provided to UDEQ in Appendix E of the Updated Site-Specific Performance Assessment (Revision 2) (Energy*Solutions* 2015).

HAL chose to use the modified Berggren equation to calculate frost depth because of its long-established use and acceptability by the engineering community. This method, first presented by Berggren in 1943 and further refined by Aldrich and Paynter in 1953, was later adopted by the US Army Corps of Engineers and other agencies as their preferred method for frost depth determination (Departments of the Army and the Air Force 1988).

The frost depths calculated as part of this analysis give results that are in line with the depths of cover and frost protection proposed in the Energy*Solutions* ET Cover system design. The proposed radon barrier begins at depths ranging from 30 inches to 42 inches, which provides frost protection for the calculated 100-year frost penetration depth of 22.4 inches to 27.8 inches for the top slope and side slope, respectively.

A statistical distribution for saturated hydraulic conductivity of the radon barriers used for modeling flow in the cover was developed from in-service properties based on the results of Benson et al. (2011). Use of these properties as inputs to the flow models takes into account changes in hydraulic properties due to freeze/thaw cycles assumed by Benson et al. (2011). See the response to Interrogatory 21/2 for a discussion of the development of the saturated hydraulic conductivity distribution for the radon barriers (Section 2.4.1).

Early degradation of cover layer properties described by Benson et al. (2011) is not consistent with soil formation observations at the Clive Site. Recent field studies (Neptune 2015b) provide evidence for a site-specific conceptual model of weak development of soil profiles (limited soil formation) in a setting influenced by low rates of deposition of eolian silt in the Holocene history. See the response to Interrogatory 05/2 Evapotranspiration Cover (ET Cover) (Section 2.1.1) for a detailed discussion of soil formation at the Clive Site.

2.2 Interrogatory CR R313-22-32(2)-10/3: Effect of Biologicals on Radionuclide Transport

DEQ Conclusion from April 2015 SER, Appendix C:

As discussed in the DU PA SER (Section 4.4.3), Energy*Solutions* has not shown that the cover system is sufficiently thick or designed with adequate materials to protect the cover system or the underlying bulk waste in the embankments against deep rooting by indigenous greasewood (a species known to penetrate soils at other sites down to 60 feet) or other plants, or against biointrusion by indigenous ants or mammals (e.g., with maximum documented burrowing depths greater than the proposed cover thickness). Higher rates of infiltration are typically associated with higher contaminant transport rates. Under Utah rules, infiltration should be minimized [see UAC Rule R313-25-25(3) and (4)]. DEQ cannot determine the adequacy of the DU PA until Energy*Solutions* accounts for greater infiltration through the cover system at the Federal Cell embankment due to biointrusion by plant roots and by animals. Therefore, this interrogatory remains open.

DEQ Critique of DU PA v1.4, Appendix 5: Energy*Solutions*/Neptune retain the same assumptions with respect to biointrusion depths and potential impact on infiltration in v1.4 as were provided in v1.2.

In v1.4 Appendix 5 (p. 33), Energy*Solutions* indicates that root water uptake was modeled assuming the roots extended to the bottom of the evaporative zone layer and that rooting density decreased with depth. This text seems to contradict the statement in v1.4 Appendix 5 (p. 33) that root distribution was modeled as extending into the frost protection layer with a maximum depth of 31 inches (80 cm). The base of the evaporative zone would be at 18 inches. Figure 1 indicates that the roots cease within the frost protection layer. The impact of the rooting depth in v1.4 is to remove water from the system and thereby reduce the infiltration rates. The concern raised by the interrogatory is related to the roots creating preferential pathways and thereby increasing the infiltration.

DEQ Critique of DU PA Appendix 21: Energy*Solutions*/Neptune state (p. 15):

> *It is important to recognize how the range of rooting depths discussed in the comment actually relates to what was used as a maximum rooting depth in GoldSim Models v1.2 and v1.4. A maximum root depth of 5.7 meters (18.7 ft) (Robertson 1983) is used in the Model, so the Model already assumes that roots extend beyond the radon barrier. In addition, v1.4 of the GoldSim Model assumes increased permeability, correlation between saturated hydraulic conductivity and the hydraulic function alpha parameter, and homogenization of the cover materials, with no physical barriers to either plant roots or infiltration.*

It is unclear how the specification of the rooting depth in GoldSim is particularly relevant to the concern expressed in the comment pertaining to potential increased infiltration rates due to biointrusion of plants and animals. The rooting depth in GoldSim is related to the depth of contaminant uptake, redistribution of contamination, and assimilation of contaminants once the plant dies rather than changes to the hydraulic properties that would allow greater infiltration.

Plant roots will almost certainly extend downward and into the radon barrier. These roots will then penetrate into the underlying waste if water is available in the waste. As described Benson et al. (2008), roots were observed in the radon barrier in the caisson lysimeters exhumed at

Monticello in 2008. These were at depths of 1.6–1.9 m bgs (see Figure 10-1 below). The roots desiccated the radon barrier, causing large cracks and an increase in Ks.

Furthermore, Energy*Solutions* has used a homogeneous cover profile in the most recent simulations. This was not the intent of the previous comments and approach outlined in Appendix E to the April 2015 SER and was misconstrued from the parameter recommendations provided in Appendix E. The cover profile should retain a layered structure representative of the materials planned for each layer, but with the hydraulic properties of each layer adjusted to reflect pedogenesis. The parameters in the 2015 recommendations were presented as a guide for reasonable ranges consistent with the recommendations in NUREG/CR-7028 (Benson et al. 2011).

2.2.1 Interrogatory Response

As described in the response to Interrogatory 05/2, SWCA acquired field data at the Site and conducted extensive literature reviews to "document the diversity and composition of plant and animal species and to quantify soil mixing by burrowing mammals and ants associated with each vegetation community" (SWCA 2013). Based on data collection and analysis and the proposed cover design, SWCA evaluated the potential for disturbance by plant roots, mammals, and ants to result in increased infiltration (SWCA 2013) and determined that soil disturbance and increased infiltration due to biotic activity would be minute. Their evaluation does not support UDEQ's assertion that biointrusion of plants and animals will substantially increase infiltration. See the response to Interrogatory 05/2: Radon Barriers.

UDEQ correctly points out an error in the description of the maximum modeled rooting depth in Section 12.1, p. 33 of Appendix 5 of the Clive DU PA Model v1.4 (Neptune 2015c). The correct description is on p. 36 of Section 12.3 of the same document: "Root distribution was modeled as extending into the frost protection layer with a maximum depth of 31 inches (80 cm). Root density was modeled as decreasing linearly with depth." This description is consistent with the maximum rooting depths and rooting density shown for the model (Figure 1 of Neptune (2015c)) and observed in excavations at the Site (Figure 9 of Neptune (2015c)).

UDEQ makes the inference that observed root penetration and cracking of clay layers at the Monticello Site means that similar root penetration and degradation of the radon barriers will be likely at Clive. Monticello and Clive are not comparable sites with respect to rooting depths. SWCA (2013) describes the important ecological differences between Monticello and Clive:

- Monticello receives approximately 50% greater average annual precipitation than Clive (15.4 in).
- The Monticello ET cover consists of clay-loam to sandy-loam soils that are less alkaline and more fertile than the saline, alkaline silty-clay soils at Clive (Waugh et al. 2008).
- The native vegetation at Monticello is dominated by big sagebrush shrublands and grasslands that are more diverse and of larger stature—with greater target plant densities and cover for the ET cover—than those proposed at Clive.

The last issue of this interrogatory raised by UDEQ is that the hydraulic parameter distributions and correlations used for modeling of flow in the cover system based on the recommendations of

Benson et al. (2011) were not how the recommendations were intended by UDEQ to be implemented.

> Furthermore, Energy*Solutions* has used a homogeneous cover profile in the most recent simulations. This was not the intent of the previous comments and approach outlined in Appendix E to the April 2015 SER and was misconstrued from the parameter recommendations provided in Appendix E. The cover profile should retain a layered structure representative of the materials planned for each layer, but with the hydraulic properties of each layer adjusted to reflect pedogenesis.

The proposed cover system shown in Figure 1 is composed of layers that either store and release water or act as a barrier. The proposed system does not include geomembranes. UDEQ argues that input parameter distributions for the α, n, and K_s hydraulic parameters be developed using recommended ranges for hydraulic properties from NUREG/CR-7028 (Benson et al. 2011). Benson et al. (2011) provide these recommendations in Section 10.2:

- The saturated hydraulic conductivity of fine-textured earthen storage and barrier layers can be assumed to range between 1×10^{-7} m/s and 5×10^{-6} m/s.
- The porosity of earthen storage and barrier layers will likely range between 0.35 and 0.45.
- The α-parameter in the van Genuchten equation, which is used to describe the SWCC (soil water characteristic curve) for hydrologic simulations, varies between 0.01 and 0.33 kPa^{-1} for field-scale barrier and storage layers.
- The n-parameter in van Genuchten's equation, which is used to describe the SWCC for hydrologic simulations, varies over a very small range (typically between 1.2 to 1.4).

Note that in assigning hydraulic properties no distinction is made by Benson et al. (2011) between storage and barrier layers. Based on their conceptual model of formation of soil structure in cover systems, there is no difference in the in-service properties of what were constructed as storage layers or barrier layers. The only distinctions in properties between depth intervals in the flow model used for the cover simulations are the initial conditions, which are minimized by long simulation times, root density (which is maintained as a constant throughout the cover depth), and the hydraulic properties of the intervals. Given their conceptual model that makes no distinction between the properties of storage and barrier layers, the cover can no longer be represented by a layered system. UDEQ objects to this homogeneity in hydraulic properties in this interrogatory, but that is the only logical outcome of applying the Benson et al. (2011) method to the ET cover.

2.3 Interrogatory CR R317-6-2.1-20/2: Groundwater Concentrations

DEQ Critique of DU PA v1.4, Appendix 10: See Interrogatory 201 for further discussion.

DEQ Critique of DU PA Appendix 21: Energy*Solutions/Neptune* state (p. 16):

> *The conceptual model of cover "naturalization" described in Appendix E of the SER (SC&A 2015) is that plant and animal activity and freeze-thaw cycles result in disturbance and mixing of soil layers in the upper portion of the cover system subject to their influences. The extent of the influence of these processes decreases with depth of*

> *roots, animal burrowing, and frost penetration. This conceptual model does not maintain the designed functions of store and release layers and barrier layers to reduce net infiltration. Using this conceptual model, the upper portion of the soil profile subject to naturalization processes is considered to be homogeneous with respect to the hydraulic properties affecting net infiltration. For the Clive Site, the hydraulic properties of the waste below the cover are modeled as Unit 3 material and would be subject to the same naturalization processes as the materials used to construct the cover.*
>
> *With this conceptual model, the depth to the waste would be reduced by erosion but the net infiltration will not vary. The net infiltration is determined by climate and hydraulic properties. If the hydraulic properties are assumed to be homogeneous and determined by climate and biotic activity, loss of material from the surface of the cover will not change the net infiltration.*

Energy*Solutions* has used a homogeneous cover profile in the most recent simulations. This was not the intent of our previous comments and approach outlined in Appendix E to the April 2015 SER and was misconstrued from the parameter recommendations provided in Appendix E. The cover profile should retain a layered structure representative of the materials planned for each layer, but with the hydraulic properties of each layer adjusted to reflect pedogenesis. The parameters in the 2015 recommendations were presented as a guide for reasonable ranges consistent with the recommendations in NUREG/CR-7028.

Energy*Solutions* has conducted a series of analyses to evaluate the impact of erosion on percolation rates from the cover. In one case, the simulation included loss of 1.2 m of cover soil. Energy*Solutions* reports that percolation rates obtained for the full thickness cover and a cover eroded by 1.2 m are essentially the same.

This is not logical given that the soil in the cover is required to store the water during cooler and wetter periods, and then release the water during drier periods. The proposed cover is 1.52 m thick. If the cover thickness is reduced by 1.2 m via erosion, then the soil water storage capacity of the cover will be reduced by approximately 80%, and the percolation should change accordingly. This result without supporting analysis makes all of the HYDRUS modeling suspect.

Additional quantitative and mechanistic evidence is needed to support the outcomes in this part of the report. Water balance graphs, which depict the temporal variation in water balance quantities (rather than a water balance quantity chart) could be used to illustrate whether the outcomes are reasonable. Water balance graphs typically are created using daily output predicted from a water balance model and show the seasonal variation in each water balance quantity. Examples of water balance graphs are shown in Figure 20-1. These graphs depict actual water balance data; water balance graphs from a model prediction would be similar. The soil water storage record in the water balance graph would be compared to the soil water storage capacity of the eroded profile.

Significantly higher technetium-99 (^{99}Tc) concentrations were obtained for percolation rates predicted using the hydraulic properties Energy*Solutions* developed with the recommended approach (Appendix E, April 2015 SER) relative to the percolation rates predicted in their previous analyses (Figure 20-2). The differences are very large, which is difficult to understand given that the percolation rates predicted for the cover are on the order of 1 mm/yr and are consistent with percolation rates measured for covers placed at other sites in the region.

If the impact on groundwater concentrations is this sensitive to percolation rates on the order of 1 mm/yr, then detailed assessment and proof of the cover design should be particularly important. Energy*Solutions* should consider installing a lysimeter to confirm that the cover modeling is reliable.

2.3.1 Interrogatory Response

In this interrogatory UDEQ proposes contaminant transport from the Federal Cell beginning with the formation of gullies on the cover leading to increased infiltration rate and leaching of contaminants into the upper aquifer.

The first part of this interrogatory points to soil erosion issues raised in Section 4.4.2 of the Safety Evaluation Report (SC&A 2015a). UDEQ expresses concerns that gullies will form and enhance radon diffusion, deep infiltration, and contaminant transport. Energy*Solutions,* however*,* has provided plans for both ecological and engineering measures to address these concerns by minimizing gully formation. Demonstration of the stability of the cover is addressed in the response to interrogatory 71/1.

At the request of UDEQ, Energy*Solutions* has simulated the impact of erosion on net infiltration using the conceptual model of in-service (naturalized) covers described in Appendix E of the SER (SC&A 2015b). These simulations showed that a loss of 1.2 m would have little effect on the net infiltration rate. UDEQ argues that "This is not logical given that the soil in the cover is required to store the water during cooler and wetter periods, and then release the water during drier periods."

The conceptual model of the in-service cover (naturalization) described in Appendix E of the SER (SC&A 2015b) and Benson et al. (2011) is that plant and animal activity and freeze-thaw cycles result in disturbance and mixing of soil layers in the upper portion of the cover system subject to their influences. In this conceptual model, these processes lead to the development of soil structure but not soil horizons. The extent of the influence of these processes decreases with depth of roots, animal burrowing, and frost penetration. This alternative conceptual model of soil formation is discussed in the response to interrogatory 20/2.

UDEQ maintains that input parameter distributions for the α, n, and K_s hydraulic parameters for water flow modeling be developed using recommended ranges for hydraulic properties from NUREG/CR-7028 (Benson et al. 2011). However, these ranges are considered unrealistic. Based on UDEQ's conceptual model of formation of soil structure in cover systems, there is no difference in the in-service properties of what were constructed as storage layers or barrier layers (Benson et al. 2011). Normally, the distinction in properties between depth intervals in the flow model that constitute layers used for the cover simulations are the hydraulic properties of the intervals. The UDEQ conceptual model does not maintain the differences in hydraulic properties that provide the designed functions of store and release layers and barrier layers. Thus, the cover can no longer be represented by a layered system. UDEQ objects to this homogeneity in hydraulic properties in this interrogatory, but that is the only logical outcome of applying the Benson et al. (2011) method to the ET cover.

Using this conceptual model, the upper portion of the soil profile subject to naturalization processes is considered to be homogeneous with respect to the hydraulic properties affecting net infiltration. For the Clive Site, the hydraulic properties of the waste below the cover are modeled as Unit 3 material and would be subject to the same naturalization processes as the materials used to construct the cover. As soil is lost due to erosion, disturbance due to biotic activity and

freeze-thaw extends deeper to maintain the same thickness of "naturalized" soil characterized by the same ranges of hydraulic properties. The net infiltration is determined by climate and hydraulic properties. If the hydraulic properties are assumed to be homogeneous and determined by climate and biotic activity, the loss of material from the surface of the cover due to erosion is compensated by a deepening of the naturalized soil profile. The thickness of the naturalized soil remains the same and net infiltration will not change. Given the approximately 10-meter depth of burial of the DU, the logical projection of this conceptual model is that this process of soil loss from the surface and deeper extension of soil formation would continue for a very long time before the soil above the waste was thin enough to influence the net infiltration. The hydraulic property recommendations and cover material naturalization presented in Benson et al. (2011) and in Appendix E of SC&A (2015a) are not reasonably applicable for the Clive Site (see the response to Interrogatory 05/2). Further, the cover design is demonstrated to be stable with respect to sheet erosion and gully formation. See the response to Interrogatories 71/1 and 191/3 for further discussion on erosion analyses.

UDEQ requests that daily water balance plots of the flow simulation results be provided. UDEQ has been provided with annual averages for water balance components of precipitation, runoff, evapotranspiration, storage, and deep drainage. Daily water balance is not the appropriate scale to evaluate a performance assessment model. See the response to Interrogatory 21/2 for a discussion of evaluation of flow model water balance.

UDEQ notes that higher technetium-99 concentrations resulted from the simulations using the unrealistic ranges for hydraulic properties from NUREG/CR-7028 (Benson et al. 2011) requested by UDEQ. It is not unexpected that unrealistic results will come from a model using unrealistic input parameters.

2.4 Interrogatory CR R313-25-8(4)(d)-21/2: Infiltration Rates

DEQ Critique of DU PA v1.4, Appendix 5: Energy*Solutions*/Neptune describe their approach to parameterizing the radon barriers for v1.4 as follows (pp. 39–40):

> *An expanded assessment of the performance of the radon barriers was made possible by developing a distribution for the saturated hydraulic conductivity (Ks) of the radon barriers to use for the modeling. The Ks values for the radon barriers were sampled from a distribution developed from a minimum value of 4.32×10^{-3} cm/day corresponding to the design specification for the upper radon barrier (Whetstone 2007, Table 8), and 1st, 50th, and 99th percentile values of 0.65 cm/day, 3.8 cm/day, and 52 cm/day, respectively, which are from a range of in-service ("naturalized") clay barrier Ks values described by Benson et al. (2011, Section 6.4, p. 6-12). A shifted lognormal distribution was fit to the 1st, 50th, and 99th percentiles, and the minimum value of 4.32E-3 cm/day was used as a shift. The resulting distribution is:*
>
> $Ks \sim Lognormal\ geom.\ mean: 3.37\ cm/day,\ geom.\ sd: 3.23\ cm/day,$ *with a right shift of 0.00432 cm/day*
>
> *For all HYDRUS simulations, the same Ks value was applied to both the upper and lower radon barriers.*

> *Correlations between α and n were investigated by analyzing the combinations of α and n for the 12 textural classes in Rosetta (Schaap, 2002), and no correlations were evident. There were also no statistically significant correlations between Ks and α or n.*
>
> *The developed 50 sets of uncertain parameters for α, n, and Ks were then used as hydraulic property inputs to 50, 1000-year simulations using HYDRUS-1D.*

This approach varies from that taken in DU PA v1.2 as described below (Neptune 2014, Appendix 5, pp. 41–41):

> *An expanded assessment of the performance of the radon barriers was made possible by developing a distribution for the saturated hydraulic conductivity (Ks) of the radon barriers to use for the modeling. The Ks values for the radon barriers were sampled from a distribution developed from a minimum value of 4×10^{-3} cm/day corresponding to the design specification for the upper radon barrier (Whetstone 2007, Table 8), and 50th and 99th percentile values of 0.7 cm/day and 52 cm/day, respectively, which are from a range of in-service ("naturalized") clay barrier Ks values described by Benson et al. (2011, Section 6.4, p. 6-12). A normal distribution was fit to the 50th and 99th percentiles, and the minimum value of 4E-3 cm/day was used as a shift. For all HYDRUS simulations, the same Ks value was applied to both the upper and lower radon barriers.*
>
> *Correlations between α and n were investigated by analyzing the combinations of α and n for the 12 textural classes in Rosetta (Schaap, 2002), and no correlations were evident. There were also no correlations between Ks and α or n.*
>
> *The developed 20 sets of uncertain parameters for α, n, and Ks were then used as hydraulic property inputs to 20 1000 year simulations using HYDRUS-1D.*

The infiltration results for v1.4 are presented on p. 45 of Appendix 5:

> *The 50 HYDRUS-1D simulations resulted in a distribution of average annual infiltration into the waste zone, and average volumetric water contents for each ET cover layer. Infiltration flux into the waste zone ranged from 0.0067 to 0.1 mm/yr, with an average of 0.024 mm/yr, and a log mean of 0.01 mm/yr for the 50 replicates." These fluxes are significantly lower than those calculated in v1.2 and provided on p.45 (Appendix 5) "Infiltration flux into the waste zone ranged from 0.007 to 2.9 mm/yr, with an average of 0.42 mm/yr, and a log mean of 0.076 mm/yr for the 20 replicates.*

Since it appears that the greatest change between v1.2 and v1.4 is that the K_{sat} values were increased in v1.4, it is not clear why the infiltration rates would decrease since increasing K_{sat} values are typically accompanied by increasing infiltration rates. However, deciphering why the predictions differ is nearly impossible with the output provided. Understanding the outcome requires water balance graphs showing the seasonal hydrologic cycle and the dynamics of water throughout the year. The difference in the predictions may have to do with the shape of the normal distributions that were used. They are similar, but as described below using the lower bound constraint may have affected the distribution of K values that are predicted.

Probability density functions (PDFs) are shown in Figure 21-1 that were used to describe uncertainty and spatial variability in the saturated hydraulic conductivity of the radon barrier in the Unsaturated Zone Modeling reports submitted in June 2014 and October 2015. A PDF is analogous to a histogram, describing the probability density associated with a particular value of the random variable for a defined probability distribution (in this case, the three-parameter log-

normal distribution). The distributions for 2014 and 2015 were parameterized to the extent practical using the methodology described in the 2014 and 2015 Unsaturated Zone Modeling reports. A three-parameter log-normal distribution was used given that the 2014 and 2015 reports indicate that a lower bound > 0 was stipulated in the 2014 and 2015 reports. A description of the three-parameter log-normal distribution can be found in Zhai and Benson (2006).

For 2014, the distribution was parameterized using a lower bound (ξ) = 0.004 cm/d, a log-mean (μ) of -0.357 corresponding to a 50thpercentile of 0.7 cm/d, and a log-standard deviation (σ) of 1.85. The lower bound and log-mean are equal to the values stipulated in the 2014 report. The log-standard deviation was obtained iteratively by ensuring that the 99th percentile equaled 52 cm/d, as described in the 2014 report.

Two PDFs are shown for 2015 in Figure 21-1 below because the fitting methodology and parameters cited in the 2015 report lead to ambiguity. The PDF marked “2015 reported” corresponds to ξ = 0.00432 cm/d (lower bound indicated in 2015 report), μ = 1.215 (corresponding to geometric mean of 3.37 cm/d indicated in 2015 report), and σ = 1.17 (corresponding to 3.23 cm/d referred to in 2015 report as the “geom. sd”). These parameters (“2015 reported”), however, do not yield a 1st percentile of 0.65 cm/d and a 99th percentile of 52 cm/d as indicated in the report (mathematically impossible). Thus, a second parameter set was selected (referred to as “2015 reported and fit”). This parameter set has ξ = 0.00432 cm/d (lower bound indicated in 2015 report), μ = 1.215 (corresponding to geometric mean of 3.37 cm/d indicated in 2015 report), and σ = 1.17. The log-standard deviation (σ) was selected by iteration so that the 99th percentile equaled 52 cm/d, as indicated in the report. However, the 1st percentile could not be matched along with the 99th percentile (mathematically impossible). The 1st percentile hydraulic conductivity for the distribution “2015 reported and fit” is 0.1 cm/d.

The PDFs in Figure 21-1 provide insight into the unexpected outcomes for the percolation rates predicted in 2014 and 2015, the latter percolation rates being lower despite substantially higher geometric mean saturated hydraulic conductivity. For the PDF marked “2015 reported and fit,” which seems to be the PDF most likely used as input to the model, the upper tail of the distribution is much lighter than for the 2014 PDF (e.g., the probability of high hydraulic conductivities is lower in the 2015 modeling). Consequently, the percolation rates tend to be lower in the 2015 report relative to those in the 2014 report. This would not be the case if the parameters corresponding to “2015 reported” were used as input to the model, as the PDF for this case generally has a heavier upper tail relative to the PDF used as input to the 2014 model.

This ambiguity highlights an important issue: reports issued by Energy*Solutions* should include sufficient information for an independent party to reproduce the outcomes without ambiguity. At a minimum, probabilistic descriptions should show a mathematical description of the distribution employed (e.g., probably distribution and definition of parameters) and a list of the values assigned to each parameter for each case being analyzed.

DEQ Critique of DU PA v1.4, Appendix 21:

Naturalized Cover

Significant disagreement remains regarding appropriate hydraulic properties to represent “naturalized” conditions (Energy*Solutions* nomenclature) for the cover. Energy*Solutions* states correctly that hydraulic properties they developed with the approach recommended in Appendix E to the 2015 SER are significantly different from those used in their previous analyses for the DU PA. This is not surprising, as the hydraulic properties Energy*Solutions* had used in previous

analyses (Bingham Environmental 1991) were obtained nearly three decades ago using poorly documented sampling and testing methods. Techniques for undisturbed sampling and measurement of unsaturated hydraulic properties have improved dramatically since the Bingham Environmental data set was created. The quality and relevancy of the Bingham Environmental data used by Energy*Solutions* is suspect, and there is good reason for hydraulic properties obtained using the approach recommended in Appendix E (April 2015 SER) to differ significantly from those Energy*Solutions* has used in past analyses.

Energy*Solutions* also states that the parameters sets obtained with the approach recommended in Appendix E (2015 SER) "*are conservative*" and "*do not represent the likely evolution of the cover system*." Energy*Solutions* also states that the model predictions "*do not make sense*." Energy*Solutions* will need to provide quantitative evidence to support these assertions. The photographs in Figures 4 and 5 of Appendix 21 are inconclusive and provide no quantitative basis to support inferences that structural development and alterations in hydraulic properties do not occur at Clive. Structural development that occurs in covers due to pedogenesis generally is not visible at the scale represented in these photographs. Moreover, the smearing that occurs in test pits can obscure structure that is present. If Energy*Solutions* wishes to use these analogs as evidence to support hydraulic properties representing long-term conditions significantly different from NUREG/CR-7028 (Benson et al. 2011), Energy*Solutions* should conduct appropriate measurements on these in-place materials to demonstrate that the hydraulic properties are indeed different from the abundance of data in NUREG/CR-7028.

Energy*Solutions* goes on to argue that the Clive location is not represented properly using the data set in NUREG/CR-7028, and indicates that less extensive pedogenic change should be expected at Clive relative to the sites in NUREG/CR-7028. They attribute more extensive pedogenic change to a greater abundance of biota as well as surface and subsurface biomass at sites in humid climates, which is incorrect. Changes in hydraulic properties due to pedogenesis are predominantly caused by cycling in state of stress due to seasonal changes in pore water suction. Those cycles tend to be *larger* in arid regions than in humid regions, which promotes greater volume change and more rapid pedogenesis. In fact, conceptually, pedogenesis should occur more rapidly, and be more extensive, in a more arid climate such as Clive relative to a more humid climate. However, as shown in NUREG/CR-7028, climate effects are not significant over time, as structure develops and hydraulic properties are altered in essentially all climates.

Energy*Solutions* also suggests that the Clive site is outside the range of sites represented in the data included in NUREG/CR-7028. DEQ does not agree with the suggestion that the semi-arid climate at Clive is greatly different from the climate at sites in Apple Valley, California, Monticello, Utah, or Boardman, Oregon. Each of these sites is semi-arid to arid and not greatly different from Clive. To further address this issue, data from other sites in the region should be considered as discussed in Interrogatory 189. These sites include the Monticello Uranium Mill Tailings Repository, the Blue Water Uranium Mill Tailings Reclamation Site near Grants, New Mexico, and the Cheney Disposal Facility near Grand Junction, Colorado. While none of these sites has the same climate as Clive, they are sufficiently similar to be considered reasonable analogs. An argument against the relevancy of these analogs, especially without data, is not logical.

Homogeneous Cover

Energy*Solutions* has used a homogeneous cover profile in the most recent simulations. This was not the intent of our previous comments, and was misconstrued from the parameter recommendations provided in Appendix E of the 2015 SER. The cover profile should retain a layered structure representative of the materials planned for each layer, but with the hydraulic properties of each layer adjusted to reflect pedogenesis. The parameters in the 2015 SER

recommendations were presented as a guide for reasonable ranges consistent with the recommendations in NUREG/CR-7028.

Correlation and Range of Hydraulic Properties

The hydraulic properties Energy*Solutions* developed based on the multivariate normal random generator as recommended by DEQ/SC&A are consistent with those in NUREG/CR-7028 for "naturalized" conditions. The cross-correlation structure between K_S and α, based on ln Ks and ln alpha, is also consistent with the literature, as shown in Figure 21-2.

The scatter in this correlation is characteristic of real data, and the correlation is realistic. However, the range is constrained for both K_S and α because Energy*Solutions* used the lower-end standard deviation provided in the 2015 Appendix E SER recommendations. A broader range would have been obtained using the typical and high-end recommendations for the standard deviation.

Energy*Solutions* indicates that the lower end standard deviation was used "to keep the input parameters within the ranges" of the 2015 Appendix E SER recommendation, which was not the intent of the recommendation. Energy*Solutions* should conduct their simulation using a typical standard deviation for each parameter. This will likely affect only the tails in the percolation data (high and low percolation rates in Figure 2 of Appendix 21) but likely will affect the 95th percentile doses (reported in Table 5 of Appendix 21).

Furthermore, the NUREG/CR-7028 recommended range of α values utilizes averaged values for the entire cover system for each embankment studied in the NUREG, not individual sampling points, or small parts of an embankment. The information is already presented at the scale needed for application to a single cover system on a single embankment. Therefore, either upscaling, or sub-sampling of the data, by Neptune to get a narrower range of α values for an embankment cover system would be neither necessary nor appropriate.

For all sets of realizations, the mean and the standard deviation (or ln std deviation for Ks and alpha) should be cited.

Unsaturated Flow Model Output

Percolation rates predicted with the hydraulic properties developed by Energy*Solutions* using the procedure recommended in Appendix E to the 2015 SER are reasonable and consistent with percolation rates measured and predicted for other final covers in regions of similar aridity, as reported in NUREG/CR-7028. Energy*Solutions* predicts percolation rates ranging from 0.57 to 1.31 mm/yr using hydraulic properties developed with the procedure recommended by DEQ/SC&A. As a comparison, percolation ranging from 0.0 to 3.8 mm/yr have been measured using an ACAP lysimeter at the U.S. Department of Energy's (DOE's) Monticello U-Mill Tailings Disposal Facility in Monticello, Utah, over the period 2000–2016. Percolation rates at other arid or semi-arid sites described in NUREG/CR-7028 with comparable cover profiles include Apple Valley, California (0–1.8 mm/yr), Boardman, Oregon (0 mm/yr), and Underwood, North Dakota (1.9–9.4 mm/yr).

As in past reports from Energy*Solutions*, the model predictions are difficult to interpret and evaluate with the level of detail provided. We have requested water balance graphs (see CR R317-6-2.1-20/2, Figure 20-1), which depict the important interplay between the water balance quantities throughout the water year. Energy*Solutions* has included an annualized water balance chart (Figure 3, Appendix 21), but this chart does not provide the additional information or insight

that is necessary for a proper evaluation of the model predictions. Water balance graphs should be provided.

Regression Model

The regression model used in GOLDSIM was updated using predictions obtained with the hydraulic properties Energy*Solutions* developed based on the method recommended in Appendix E to the April 2015 SER. This model relates the average annual percolation rate into the waste to the hydraulic properties of the cover soils. The regression method is not described in Appendix 21, but is likely the same method used by Energy*Solutions* in the past. Appendix 21 does not include supporting statistics confirming the significance of the regression and each of the independent variables included in the regression model. Thus, the efficacy of the regression cannot be evaluated.

Percolation rates predicted with the regression model and obtained directly from HYDRUS show a good comparison (see Figure 6 of Appendix 21). This is expected, because the regression model is based on the HYDRUS output. A concern raised before, and yet unresolved, is whether good agreement would exist between percolation rates predicted with the regression model and an independent set of predictions from HYDRUS using the same underlying inputs (e.g., a blind forward comparison). That type of evaluation is needed to confirm the validity of the regression model. For example, if an analysis was conducted with the typical standard deviations to obtain a broader range in outcomes, would the comparison between the predictions from the regression model and predictions from HYDRUS be in comparable agreement?

At a minimum, Energy*Solutions* should conduct an independent set of simulations where percolation is predicted with HYDRUS and then compared with predictions obtained with the regression model. This is the only fair means to evaluate the efficacy of the regression model. These predictions should be conducted with the typical standard deviations to get a realistic representation of the tails of the distribution of percolation.

2.4.1 Interrogatory Response

Radon Barrier K_s Distribution

UDEQ raises a number of issues in this interrogatory. The first is a request for clarification of what probability distribution was used in v1.4 for the saturated hydraulic conductivity, K_{sat}, of the radon barriers. The distribution is clearly provided in Table 16 of the Clive PA Model Parameters v1.4 document (shown below in Figure 12), and is stated correctly in the interrogatory as a three-parameter log-normal distribution with "ξ = 0.00432 cm/d (lower bound indicated in 2015 report), μ = 1.215 (corresponding to geometric mean of 3.37 cm/d indicated in 2015 report), and σ = 1.17 (corresponding to 3.23 cm/d referred to in 2015 report as the "geom. sd")." It appears the confusion regarding the distribution stems from the difference between actual quantiles (percentiles) of the final distribution and the target quantiles that were used as a basis to inform the development of the distribution. Therefore, this response describes why this difference exists and provides more detail regarding how the final distribution was selected based on the available information.

Table 16. Upper radon barrier clay material properties

GoldSim element	value or distribution	units	reference / comment
UpperRnBarrierKsat_As Built	4e-3	cm/day	see Unsaturated Zone Modeling white paper
RnBarrierKsat_Natdist	LN(3.37, 3.23)	cm/day	*Ibid.*, right shift of 0.00432 is added after a value is pulled from the distribution

Figure 12. Table 16 from the Clive PA Model Parameters v1.4 document providing the distribution used. A description of the method used to select the geometric mean, geometric standard deviation, and minimum reported in this table, and the associated parameterization of the log normal were also provided in Appendix 14 of the Clive DU PA Model Final Report for v1.4.

For DU PA v1.4, the K_s distribution was based on 1st, 50th, and 99th target percentiles elicited from the relevant literature (Benson et al. 2011) to capture plausible values of K_s that could apply to the entire cover described by the distribution. A lognormal distribution was chosen as the distributional form to capture skew toward larger values. Parameters of the lognormal distribution were chosen such that the percentiles of the final distribution were close to the target percentiles.

In this case, the following information was used to obtain target quantiles for the distribution of K_s, where the values included in the distribution are meant to represent possible values for the entire cover (as opposed to small cores from different locations within the cover):

- Per Section 6.4, p. 6-12 (Benson et al. 2011), "For all but one site, K_s falls within the range of 7.5×10^{-8} and 6.0×10^{-6} m/s regardless of cover type…". The lower value of 7.5×10^{-8} m/s is 0.648 cm/day after conversion. This was rounded to 0.65 cm/day, and is used as the elicited target for the 1st percentile.
- The upper value quoted above, 6.0×10^{-6} m/s, is 51.84 cm/day after conversion. This is rounded to 52 cm/day, and was used as the elicited target for the 99th percentile.
- Per Section 6.4, p. 6-12 (Benson et al. 2011), "The geometric mean in-service hydraulic conductivity is 4.4×10^{-7} m/s." This geometric mean is 3.8016 cm/day after conversion from m/s to cm/day, and this was rounded to 3.8 cm/day. The geometric mean of a lognormal distribution is equal to the median, so this value was used as the elicited target for the 50th percentile of the distribution.
- A minimum value of 0.00432 cm/day was also specified to correspond to the design specification for the layers (Whetstone Associates 2011). This minimum value was used for the final distribution, but not to define a target percentile.

Neptune uses the open-source statistical software package R (R Core Team 2017), and functions to facilitate fitting of distributions to target quantiles, or percentiles. The function implements an optimization algorithm to find the log scale mean, log scale standard deviation, and, for a three-parameter distribution, a minimum value that together provide a lognormal distribution with

quantiles close to the targets. Due to the restrictions on the shape of the lognormal distribution, it is not possible to exactly match percentiles using only two parameters and the usual lower bound of 0; the goal is finding a distribution with percentiles close to, but not exactly equal to, the targets.

As a starting point, a three-parameter lognormal distribution was fit to provide a close match to the target percentiles. With three parameters to vary, the target quantiles were achieved, but this corresponded to a minimum value (implemented as a shift) of 0.43 to go with log-scale mean and standard deviation of 1.215 and 1.17, respectively. That is, the minimum value chosen shifts the lognormal distribution defined by a lower bound of zero by 0.43, and after shifting the distribution quantiles are very close to the targets (see Table 3). However, the minimum value needed to match the target quantiles is greater than the 0.00432 minimum deemed reasonable from expert knowledge of the site design, and, therefore, the smaller minimum was used for the final distribution for the PPA Model to ensure that is it possible to obtain random draws between 0.00432 and 0.42. The mean and standard deviation for the pre-shifted distribution were not changed. The change in minimum from 0.43 to 0.00432 changes the percentiles of the final distribution, but these were judged to be close enough to the target quantiles to be reasonable (see Table 3); the 1st percentile of the final distribution is 0.22 instead of 0.65 and the 99th percentile is 51.5 instead of 52. Note that a shift of 0.00432 is so small relative to the spread of the entire distribution that it is not discernible from a lower bound of zero in a plot of the probability density function (Figure 14) and it only changes the percentiles in the third decimal place.

Table 3 provides the percentiles from the distributions discussed above, compared to the target percentiles used to inform the distribution, and Figure 14 shows the associated probability density function (PDF) for the distribution used for v1.4 and reported in Figure 12. As is clear from Table 3, percentiles of the selected lognormal distribution are close to the elicited percentiles, while also adhering to the minimum chosen based on design knowledge of the Site.

The interrogatory presents Figure 21-1, along with curves meant to represent PDFs associated with different possible distributions used. It is not clear from the description how the curves were created for the “2015 reported” and “2015 reported and fit.” By definition, the area under a PDF must integrate to 1, and this is not the case for the curves displayed in Figure 21-1. It appears from the text that the “2015 reported” curve should match the PDF displayed in Figure 14, but it does not (the y-axis values between the two plots do not match). Because they are not truly probability density functions, it is difficult to evaluate them and to attempt to match them to actual probability distributions. For additional clarification of the percentiles associated with the final distribution, the code to get the percentiles from the final lognormal distribution using R statistical software is provided in a screenshot in Figure 13; the code also explains how the percentiles reported in Table 3 were obtained.

```
>
> qlnorm(p = c(0.01, 0.5, 0.99), meanlog = log(3.37), sdlog = log(3.23)) + 0.00432
[1]  0.2246368  3.3743200 51.5523540
>
```

Figure 13. R Statistical Software (R Core Team 2017) code and output for getting quantiles from the distribution of K_s used in v1.4.

Table 3. Percentiles associated with elicited information for the K_s distribution (cm/day), and the distribution actually used. These are based on a lognormal distribution with geometric mean of 3.37 cm/day and a geometric sd of 3.23 cm/day, with shifts for the minimum associated with each row. See Figure 13 for example R code to get the percentiles.

	1st Percentile	50th Percentile	99th Percentile
Elicited Percentiles (Target)	0.65	3.8	52
Percentiles from distribution (minimum=0, i.e., no shift)	0.220	3.370	51.548
****Percentiles from v1.4 distribution (minimum = 0.00432)**	**0.225**	**3.374**	**51.552**
Percentiles from distribution with minimum allowed to vary to match quantiles (minimum = 0.43)	0.650	3.800	51.978

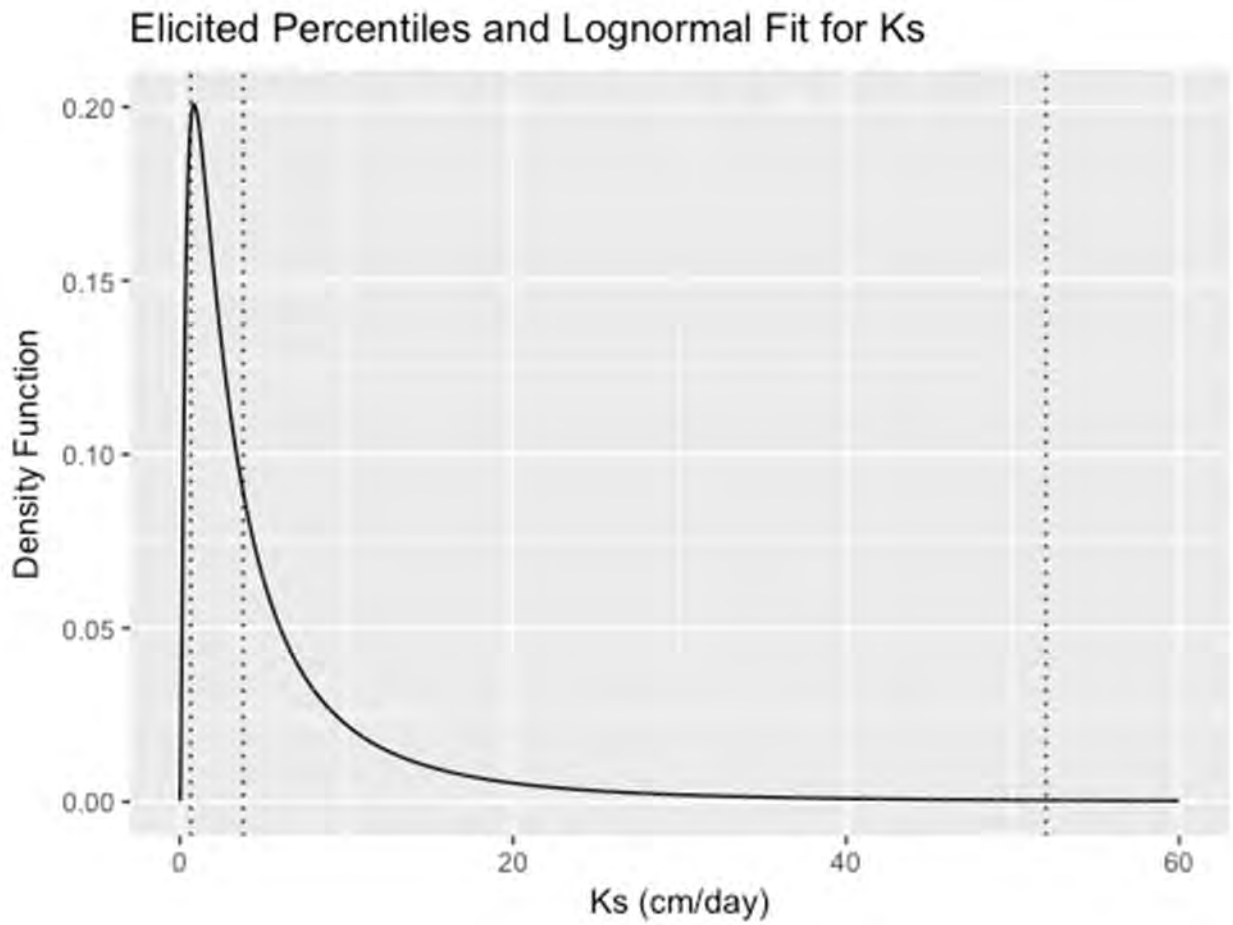

Figure 14. The lognormal distribution used for the K_s in v1.4. It is parameterized by a geometric mean of 3.37 (log-scale mean 1.215), a geometric standard deviation of 3.23 (log-scale standard deviation of 1.17), and a minimum of 0.00432 implemented through a shift of the distribution. The target 1st, 50th, and 99th percentiles are shown by the vertical dotted lines.

A log-triangular distribution was not used for this fit. Please see the response to Comment B.3 for a description of problems with using a log-triangular distribution.

UDEQ requests that "At a minimum, probabilistic descriptions should show a mathematical description of the distribution employed (e.g., probably [sic] distribution and definition of parameters) and a list of the values assigned to each parameter for each case being analyzed."

The description of hydraulic parameter distributions and the values of each of the parameters used for each flow simulation case were provided in Appendix 5 of the Clive DU PA v1.4 (Neptune 2015c). Values for parameters that were held constant were provided in Table 8 of Neptune (2015c). Development of a probability distribution for K_s of the radon barriers is provided here again in the response to Interrogatory 21/2. Values of each parameter varied for the 50 simulations are provided again in the response to Comment B.2.

Naturalized Cover

The next issue raised by UDEQ in this interrogatory is objection to the use of site-specific hydraulic property data provided in a report by Bingham Environmental (1991). UDEQ has criticized the use of hydraulic property results from testing of samples of Unit 3 and Unit 4 materials at the Clive Site by Colorado State University that were published in a report prepared by Bingham Environmental (see also UDEQ Comment B.4). UDEQ states that "Techniques for undisturbed sampling and measurement of unsaturated hydraulic properties have improved dramatically since the Bingham Environmental data set was created."

This statement is simply not true as there has been little change to the standard methods used to determine saturated hydraulic conductivity, volumetric water content, and water retention relations. The method commonly used to estimate the van Genuchten hydraulic function parameters from water retention data is the RETC software published in 1991 by van Genuchten et al. (1991). UDEQ states further "The quality and relevancy of the Bingham Environmental data used by Energy*Solutions* is suspect." And, with respect to van Genuchten parameters derived from the testing, "This α is based in part on historic measurements made at Colorado State University on core samples obtained at the Clive site by Bingham Environmental (1991), which are known to be too small and too disturbed to adequately represent in-service conditions. The relevancy of this historic data from Bingham Environmental is dubious, at best."

There is no indication in the text of Bingham Environmental (1991) or in the test result sheets from Colorado State University that the data were considered irrelevant, suspect, or dubious. Colorado State University hosts an internationally recognized Civil and Environmental Engineering Department. Their facilities include the Groundwater and Porous Media Laboratory, where testing of the samples from the Clive Site was conducted. UDEQ has provided no basis for disparaging the technical capabilities of this laboratory.

Following these statements, UDEQ reiterates their position that hydrogeologic models are not site specific. They argue that statistical distributions for hydraulic property parameters used for flow modeling of cover material described in Benson et al. (2011); SC&A (2015a, 2015b) should be universally applied irrespective of climate, ecology, or geologic setting of the site. See the responses to Interrogatory 05/2 and Interrogatory 153/2. UDEQ lists a number of waste disposal sites that they consider to be analogs to the Clive Site: Monticello Uranium Mill Tailings Repository, the Blue Water Uranium Mill Tailings Reclamation Site near Grants, New Mexico, and the Cheney Disposal Facility near Grand Junction, Colorado. The response to Interrogatory 192/3 discusses why these sites are not suitable analogs for the Clive Site.

Homogeneous Cover

UDEQ raises objections in this interrogatory regarding how simulations were conducted using in-service cover properties as requested by UDEQ. An alternative set of 50 HYDRUS simulations was conducted using input parameters derived from the distributions and methods described by Dr. Craig Benson in Volume 2, Appendix E, of the Safety Evaluation Report (SER) prepared by SC&A (SC&A 2015a), consistent with the request of UDEQ to use this approach.

These models represent modifications to previous models required in response to the SER issues. These models are conservative and do not represent the likely evolution of the cover system.

UDEQ objects to use of an essentially hydrologically homogeneous cover for these alternative simulations, stating that:

> This was not the intent of our previous comments, and was misconstrued from the parameter recommendations provided in Appendix E of the 2015 SER. The cover profile should retain a layered structure representative of the materials planned for each layer, but with the hydraulic properties of each layer adjusted to reflect pedogenesis. The parameters in the 2015 SER recommendations were presented as a guide for reasonable ranges consistent with the recommendations in NUREG/CR-7028.

Given the UDEQ conceptual model of making no distinction between the properties of storage and barrier layers, the cover can no longer be represented by a layered system. Please see the response to Interrogatory 10/3 for a discussion of the consequence of using the Benson et al. (2011) method for developing hydraulic input parameters.

The hydraulic property recommendations and cover material naturalization presented in Benson et al. (2011) and in Appendix E (SC&A 2015a) are inappropriate for the Clive Site. See the response to Interrogatory 05/2.

Correlation and Range of Hydraulic Properties

See the response to Interrogatory 05/2 regarding the lack of correlation of hydraulic properties of Unit 4 soil.

In the application of the Benson et al. (2011) and Benson and Gurdal (2013) method in Appendix E (SC&A 2015a), the low variance option was selected for the spreadsheet calculations specified in Appendix E for creating sets of parameters for flow modeling. This choice was made because the “typical” and “high” variance options produced parameter values outside the range of recommended values. Though not clear in Appendix E (SC&A 2015a), from the references cited the variances used in the spreadsheet appeared to be estimated from point data, not from mean values. A distribution of means, associated with a lower variance than a distribution of point values, is better aligned with the scale of the PA Model. Neither upscaling nor sub-sampling of the data was used in developing the hydraulic parameter distributions for the alternative set of 50 HYDRUS simulations described in Appendix 21 (Neptune 2015f).

For Clive DU PA Model v1.4 (Neptune 2015c), estimates of the uncertainty in the hydraulic properties of Unit 4 materials that compose the surface and evaporative zone layers of the ET cover were needed. These were obtained by using the α and n values from the distributions (mean and standard deviation) for each parameter from the Rosetta database of hydraulic parameters for the textural class of silty clay (Schaap 2002). Details of the development of distributions for α and n parameters for the surface and evaporative zone layers are given in the response to Comment B.2.

The α and n distributions in Appendix 5 of Clive DU PA Model v1.4 (Neptune 2015c) are based on the standard error of the average from the Rosetta database, rather than the sample standard deviation of the data. The reason for the use of the standard error of the average is to develop the distribution at the spatial scale consistent with how the values will be used in the PA Model (see Section 1.1 and Appendix 14 of the Clive DU PA Model v1.4 (Neptune 2015e) for more discussion of scaling). The Rosetta database is comprised of measurements from point locations or single cores, thus representing a smaller scale than the site-scale values needed for the PA Model. Averages of the small-scale values are used to represent larger site-scales consistent with the scale represented by GoldSim cells in the model. The standard error of the average represents the expected variability among averages from different random datasets of 28 measurements (i.e., the approximate sampling distribution of the average), or can be thought of as representing uncertainty in the value of the true population mean, so that values from the distribution represent possible site-scale averages (or means).

Unsaturated Flow Model Output

UDEQ compares the net infiltration rates simulated using the alternative distributions based on the hydraulic property recommendations and cover material naturalization presented in Benson et al. (2011) and in Appendix E (SC&A, 2015) with rates from a number of sites they regard as analogs to the Clive Site. These hydraulic property recommendations are inappropriate for the Clive Site. See the response to Interrogatory 189/3 for a discussion on the applicability of these sites as analogs.

UDEQ requests plots of flow model water balance components on a daily basis. These components are precipitation, runoff, infiltration, evaporation, transpiration, storage, and net infiltration (deep drainage).

Steady-state annual averages of net infiltration and water content from the HYDRUS simulations are the model results used to develop statistical distributions of these parameters for inputs to the GoldSim model for the Clive DU PA. The GoldSim model samples inputs randomly at the beginning of time for a single realization of the simulation, and those values that represent the input distributions are used throughout the realization time. The model was deliberately run for a long period of time (1,000 years) in order to reach a near-steady state net infiltration rate that is not influenced by the initial conditions. Flow model results for use in the GoldSim DU PA model consisted of the daily fluxes from the bottom of the Lower Radon Barrier and the water contents for the Surface Layer, Evaporative Zone Layer, Frost Protection Layer, and Upper and Lower Radon Barriers averaged over the years 900 to 1000 (36,525 days) of the simulation. Changes in storage were zero when averaged over the last 100 years of the simulations. Runoff was also negligible. The water balance plots showed the remaining components of water balance: precipitation, evaporation, transpiration, and net infiltration as annual averages.

Water balance plots were provided to UDEQ for a range of net infiltration rates in Appendix 21 of the Clive DU PA v1.4 (Neptune 2015f). The results of five simulations were shown representing the 10th, 30th, 50th, 70th, and 90th percentile net infiltration values from 50 HYDRUS flow model simulations. Average annual values for each nonzero water balance component (precipitation, evaporation, transpiration, and net infiltration) were presented. Using annual

average parameter values and their associated uncertainty reflects the spatial and temporal scale of the net infiltration and water content in the DU PA Model. The variability of data at points in time and space is not the appropriate representation of variance in a PA model.

Regression Model

In this section of the interrogatory UDEQ raises four different issues regarding the model abstraction that are intermingled in the interrogatory comments. This section of the response begins by reiterating the goal of the model abstraction, and then addresses the issues separately to avoid further conflating them.

Goal of model abstraction

As described in Section 1.1 and Appendix 14 (Neptune 2015e), the goal of "model abstraction" in the context of PA modeling is to build a relatively simple statistical model to approximate the relationship between the input parameters and an output of interest obtained from a sophisticated, and usually computationally intensive, process-based model. For example, net infiltration may be calculated using a process-based model like HYDRUS for a given set of input parameters.

The process model, HYDRUS in this case, is run at many combinations of input parameters, chosen to explore the relevant region of the multi-dimensional parameter space of the inputs. The goal is to explore the parameter space of the input parameters as much as is possible for a given number of HYDRUS runs in order to gain as much information as possible to predict the response for new combinations of input parameter values that may be used for a PA model run. It is often the case that a relatively simple statistical model can be used to predict the output of a very complicated process model, not by re-approximating the physical processes represented in the process model, but just by capturing the overall relationship, perhaps as a function of few input parameters and simple functional forms. The statistical model will predict a reasonable value that would have been obtained from HYDRUS and is not expected to match the HYDRUS result exactly. HYDRUS is an approximation of reality, and the model abstraction is a simple approximation to HYDRUS. Uncertainty in predictions from the statistical model can also easily be incorporated into distribution development if desired.

The success of the statistical model in predicting the output depends on the information contained in the original runs of the HYDRUS model used to fit the model. There are three settings to consider when evaluating the predictive ability of the statistical model for use in a PA model: (1) predictive success at the same input parameter values used in the original HYDRUS runs (in-sample prediction), (2) predictive success at new input parameter values within the region explored in the original HYDRUS runs (out-of-sample prediction based on interpolation), and (3) prediction success at input parameter values beyond the region explored in the original HYDRUS runs (extrapolation).

Need for "significance of the regression" for assessing its efficacy

The goal of building a statistical model for prediction differs from the goal of developing a model to understand and explain relationships (e.g., Shmueli (2010); Ramsey and Schafer (2013); Rawlings et al. (1998)). The different goals lead to different strategies and statistical

methods. Statistical models developed for the goal of prediction are often different from those developed for the goal of explanation, and some of the tools developed for use when the goal is explanation should not be used in the same way.

The linear regression models developed for predicting water content and net infiltration are based on the results of modeling performed using the HYDRUS software. The model for net infiltration is the focus of the interrogatory comments. Even when the goal is prediction, statistical software typically provides p-values for individual regression coefficients; this does not imply they should be used to assess the "efficacy of a regression" for prediction as suggested in the interrogatory comments. In this case, the model for net infiltration contains α and n as predictors, with p-values of 6.36×10^{-12} and 0.000108, respectively. The hypothesis tests associated with these p-values for individual coefficients should not be used simultaneously to assess predictive ability of the model (despite common misuses in practice). Instead, they simply provide a summary of the degree of statistical evidence that the slope of the linear relationship between the predictor (α or n) and the mean net infiltration differs from zero, while holding the other predictor constant. For the goal of prediction, any variable thought to be useful for prediction can be included in the model (Kutner et al. 2005; Ramsey and Schafer 2013). Use of a large number of predictors, including some that contribute little to predictive performance, can lead to larger standard errors of prediction, but in this case the standard errors of prediction are not ultimately used and the number of predictors is so small (two or three) that there is no danger in including too many predictors. Instead of relying on p-values, the usefulness of the regression model should be primarily judged by the plot of the predicted values from the regression vs. the original values obtained from HYDRUS, as well as by measures of out-of-sample predictive performance, such as those obtained from hold-out datasets and/or cross-validation, both of which are provided in this response.

A comparison of the predictions from the regression model for net infiltration rate (mm/yr) to the original results from HYDRUS are shown in Figure 15. For simplicity, the linear regression model was developed using the inputs and net infiltration results on the scales ultimately used as inputs to the PA Model, rather than on a logarithmic scale. It is expected that the linear regression will miss some curvature found in the Clive DU PA Model v1.4 HYDRUS results (Neptune 2015c), but it is developed as a simple and easy-to-implement approximation that can be easily incorporated in the PA Model using GoldSim. The R-squared value indicates the proportion of variance in HYDRUS results explained by the linear regression predictions; 0.67 is deemed reasonable given the observed relationship in Figure 15. The bulk of the net infiltration predictions from the regression (between approximately .01 and 0.05 mm/yr) are slightly larger than the values from HYDRUS, providing a conservative approximation within that range.

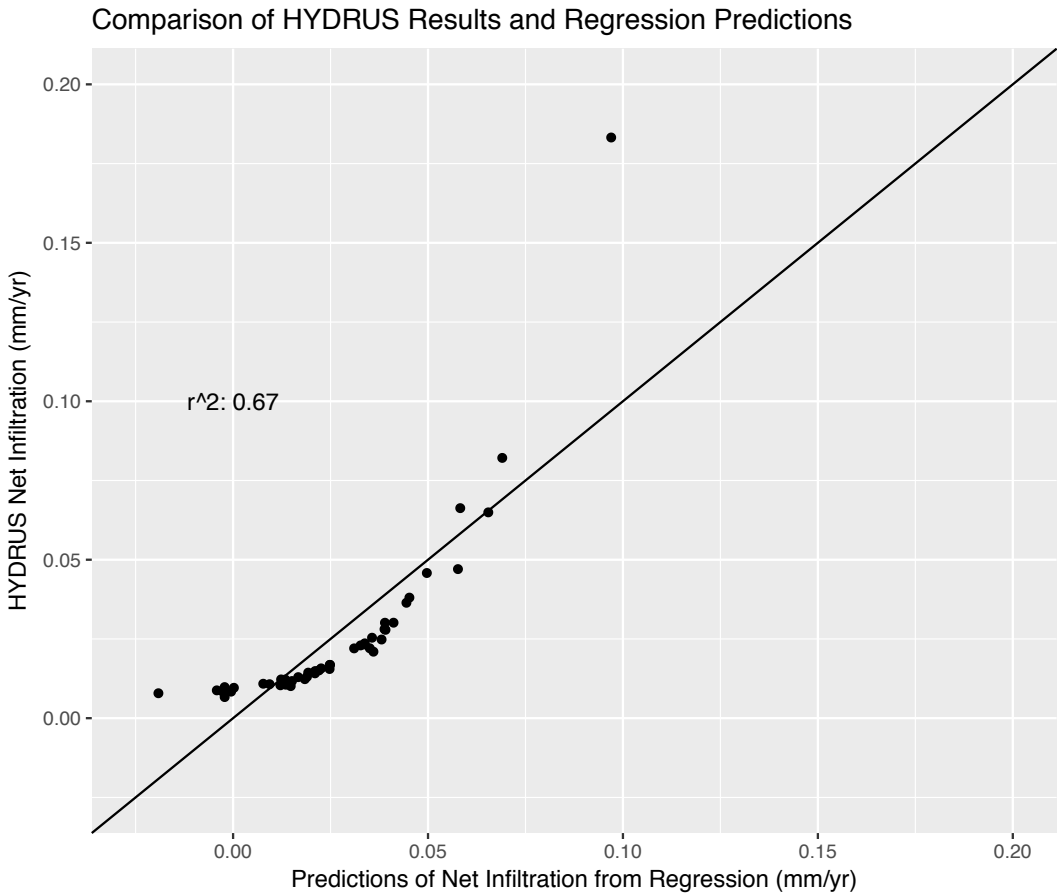

Figure 15. The average annual net infiltration values obtained from HYDRUS compared to the predictions from the linear regression model abstraction. The results from the 50 HYDRUS realizations were used to develop the regression model abstraction, and therefore this plot depicts in-sample predictive performance. The one-to-one line is shown for reference.

The existence of "typical standard deviations"

The standard deviation used for a distribution representing the current state of knowledge in an input parameter for a PA model should be evaluated relative to the temporal and spatial scale it is meant to represent in the PA model (see Section 1.1 and Appendix 14 (Neptune 2015e)) for more discussion on scaling). Therefore, it is not productive to define a "typical standard deviation" without reference to the scale it is meant to apply to. A "typical" standard deviation representing large scales will not be the same as a "typical" standard deviation representing small scales. That is, the variability among individual measurements taken at particular points in space and time is not expected to be the same as that among quantities meant to describe large volumes of materials over long periods of time. Hence, the adequacy of one distribution should not be judged relative to a "typical" distribution developed for a different goal.

Evaluation of out-of-sample prediction outside the range needed for the PA Model (extrapolation)

For the most efficient use of information and the best predictions within the context that the model abstraction will be used, the abstraction should be developed based on the distributions used in the PA model and *not* on different distributions that might be wider to reflect possible smaller-scale values or different assumptions. Developing the model abstraction for wider distributions is a waste of the limited resources available (mainly computational time running HYDRUS in this case) to effectively explore the region of the parameter space needed for the PA model. That is, it is more efficient to do a better job exploring the specific region of the input parameter space that will actually be needed for the PA model than to spread the effort out over values that will not be sampled in the PA model (thereby decreasing the predictive ability within the region needed for the PA model). Statistical modeling for prediction should always be tied as closely as possible to the region within which it will ultimately be used to obtain predictions.

Models cannot be assumed to perform well outside of the parameter space they were developed for unless assumptions that the relationships should continue into other regions of the parameter space can be justified (e.g., a linear relationship estimated for one region is expected to continue into neighboring space). In the context of model abstraction for PA models, the original HYDRUS runs should explore the parameter space covered by the distributions for inputs that will ultimately be used for the PA model; this avoids the second issue as long as the number of original runs of the HYDRUS model is large enough to adequately explore the multi-dimensional space. The model abstraction is not designed to be used with different distributions for input parameters, particularly if new distributions are wider than those used to inform the original HYDRUS runs. As described above, it is actually a waste of resources to spread effort out over a wider range than needed, at the expense of less information in the range of interest. With this in mind, evaluation of out-of-sample prediction outside the range of inputs needed for the PA model (i.e., extrapolation) is not considered a meaningful goal. The interrogatory comments suggest this should be considered, but because the regression model is not designed to be used with different input distributions, this is not undertaken. The values of the inputs for the 50 HYDRUS runs associated with v1.4 are based on the same distributions used in the PA model.

Evaluation of out-of-sample prediction within range modeled (interpolation)

The model abstraction should be evaluated with respect to out-of-sample prediction *within* the range covered by the original inputs to HYDRUS. The best-case performance of the regression model will be its ability to predict the output for the values of the input parameters used to obtain the original HYDRUS results and used to fit the regression model (termed “in-sample” prediction) (see Figure 15). Therefore, it is important to check the ability to predict at new sets of input values that fall within the region explored by the original HYDRUS runs; this is how the model will be used to obtain predictions for the PA Model (out-of-sample prediction via interpolation). The best method for evaluating “out-of-sample prediction” is to run the HYDRUS model for an additional number of runs, use the model abstraction to predict the output, then compare the predictions to the actual HYDRUS outputs (evaluation based on an independent sample). This is often described as using a “hold-out” data set—the model is fit using a subset of

the data available and then tested independently on the "hold-out" data set. Predictive performance is not expected to be as good as for in-sample prediction, but if the model is effective at predicting within the space explored in the original HYDRUS runs, it should be similar. The downside of the "hold-out" method is that information potentially available to inform the building of the regression model is not used because it is withheld only to be used for model evaluation. Another method, k-fold cross-validation, allows use of information from all the HYDRUS runs while still approximating out-of-sample prediction performance (described in many statistics textbooks such as Hastie et al. (2009)). Cross-validation proceeds by repeatedly splitting the available data into a "training set" and a "test set," where the model is repeatedly fit for each training set and predictive ability is tested for each test set. Then, the results from all the predictions are combined to estimate out-of-sample predictive ability. The "k-fold" refers to the size of the test sets relative to the training sets and also relates to the number of different splits, and subsequent model fits, needed to carry out the procedure. For each split into a training and test set, predictive accuracy can be summarized, and then combined across the splits. Each observation will have a prediction, but the prediction will come from a model fit to a random subset of 2/3 of the data instead of all the data. Then, typical summaries can be calculated, such as root mean squared error (RMSE), and R-squared between the original values from HYDRUS and the predictions.

For the net infiltration linear regression model, 3-fold cross-validation performed with the 50 v1.4 HYDRUS runs (Neptune 2015c) yields an RMSE for out-of-sample prediction of 0.018 and an R-squared value of 0.57 (Figure 16). The regression model using all of the data for in-sample prediction has an RMSE of 0.016 and an R-squared value of 0.67 (Figure 15). The in-sample RMSE is expected to be less than that obtained via cross-validation to approximate out-of-sample. In this case, the values are judged close enough to trust the out-of-sample prediction implemented for new sets of input parameters used for the PA Model. A further check compares the 1000 predictions of net infiltration actually used in the v1.4 PA Model with the 50 net infiltration rates obtained from the original HYDRUS runs. Figure 17 displays these two sets of values ordered from smallest to largest and spaced so that the 50 HYDRUS results cover the same x-axis as the 1000 regression predictions from different inputs. The two lines are expected to diverge near the minimum and maximum of the x-axis because the results based on 1000 different sets of inputs are expected to explore more extreme regions of the multivariate space than are observed in the 50, even with the same input distributions. The goal of the model abstraction is to produce a simple statistical model to provide reasonable predictions quickly and easily within the PA Model, and the comparison in Figure 17 shows that the predictions are consistent with those from the HYDRUS model, with a similar range and percentiles. This is consistent with the cross-validation results. It is easy to think of HYDRUS results as the "truth," but it is important for the general context of the modeling to remember that they too are approximations of reality and the goal of the model abstraction is reasonable predictions of net infiltration.

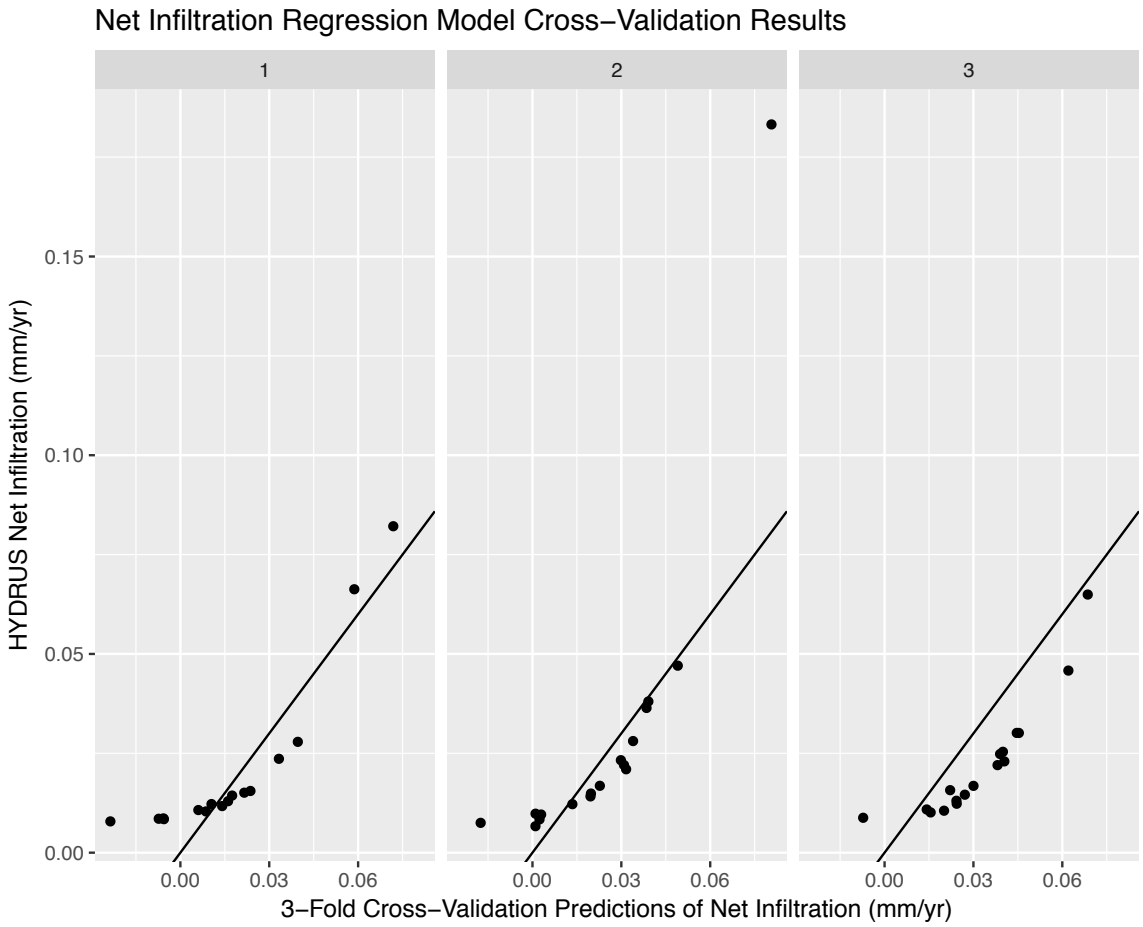

Figure 16. The average annual net infiltration values obtained from HYDRUS compared to the predictions obtained from test datasets via 3-fold cross validation. The original HYDRUS values predicted were not used to fit the regression equations used to obtain the predictions. This approximates out-of-sample predictive performance of the linear regression model abstraction. The one-to-one line is shown on each plot for reference.

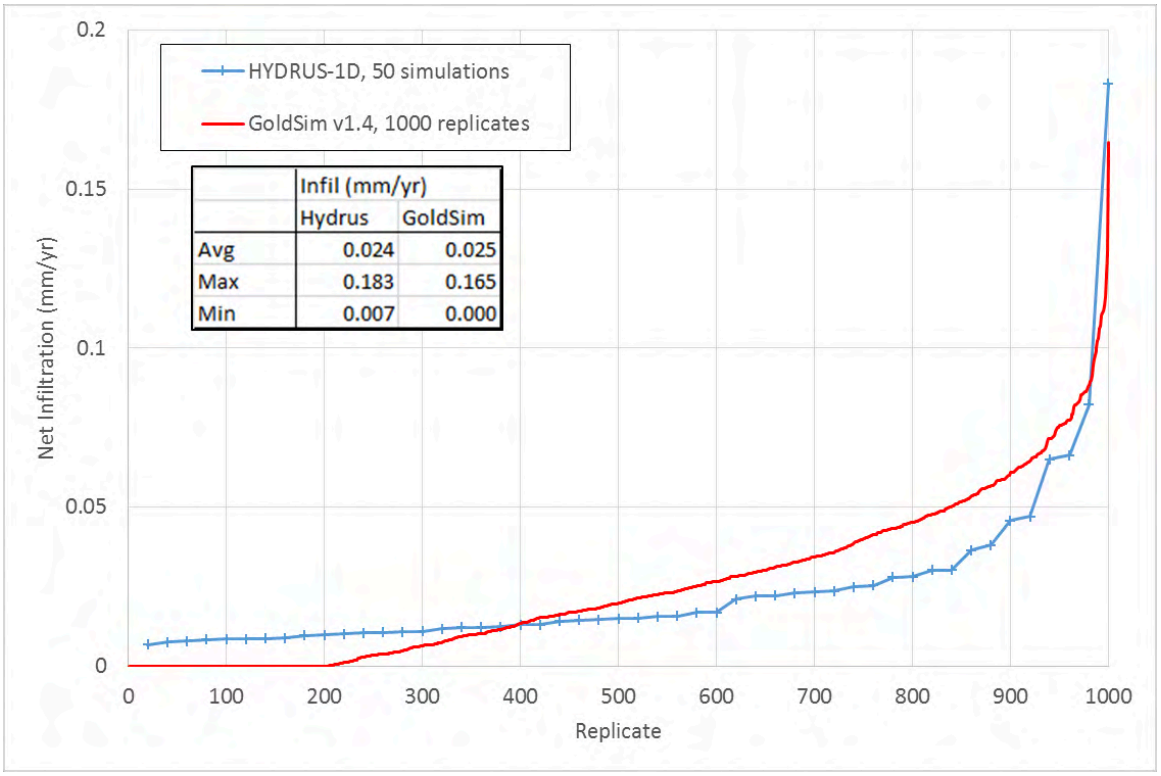

Figure 17. Comparison of 1,000 realizations of net infiltration using the linear model in GoldSim with the results of the 50 HYDRUS simulations of infiltration.

2.5 Interrogatory CR R313-25-8(4)(a)-28/3: Bioturbation Effects and Consequences

DEQ Critique of DU PA v1.4, Appendix 5: Energy*Solutions*/Neptune retain the same assumptions with respect to biointrusion depths and potential impact on infiltration in v1.4 as were provided in v1.2.

DEQ Critique of DU PA Appendix 21: Energy*Solutions* has conducted a series of analyses to evaluate the impact of erosion on percolation rates from the cover. In one case, the simulation included loss of 1.2 m of cover soil. Energy*Solutions* reports that percolation rates obtained for the full thickness cover and a cover eroded by 1.2 m are essentially the same.

This is not logical, given that the soil in the cover is required to store the water during cooler and wetter periods, and then to release the water during drier periods. The proposed cover is 1.52 m thick. If the cover thickness is reduced by 1.2 m via erosion, then the soil water storage capacity of the cover will be reduced by approximately 80%, and the percolation should change accordingly. This result without supporting analysis makes all of the HYDRUS modeling suspect.

Additional quantitative and mechanistic evidence is needed to support the outcomes in this part of Appendix 21. Water balance graphs, which depict the temporal variation in water balance quantities (rather than a water balance quantity chart) could be used to illustrate whether the outcomes are reasonable. Water balance graphs typically are created using daily output

predicted from a water balance model and show the seasonal variation in each water balance quantity.

Examples of water balance graphs are shown in Figure 20-1 (CR R317-6-2.1-20/2). These graphs depict actual water balance data; water balance graphs from a model prediction would be similar. The soil water storage record in the water balance graph would be compared to the soil water storage capacity of the eroded profile.

Clive lies in an area having a semi-arid climate. Only certain types of plants grow readily at Clive. Very little grass grows there. It's difficult to see how the limited variety and density of plants will provide adequate vegetative cover for erosion protection on an embankment. Energy*Solutions* should find and document natural analogs in the area that support their predictions, particularly since the predicted erosion rates appear too low to be realistic.

A related concern is the importance of the biological soil crust for sustaining plant growth and the high uncertainty regarding its characteristics at the Clive site. Energy*Solutions* should provide examples with quantitative data from sites in similar climate and with similar soils. These examples should show how biological soil crust is preserved or re-established, the timeline for re-establishment, and how presence (or not) of the biological soil crust affected erosion.

2.5.1 Interrogatory Response

This interrogatory begins by pointing to Section 4.4.3 of the SER (SC&A 2015b), stating that Energy*Solutions* has not demonstrated that the ET cover design is adequate to protect against intrusion by plants, animals, or ants. Field studies and analyses conducted by SWCA at the Clive Site and nearby ecologically analogous sites demonstrate that disturbance of the cover by plants, mammals, and ants will be negligible. See the response to Interrogatory 05/2.

UDEQ then raises concerns with the results of their requested simulations of the impact of erosion on net infiltration using the conceptual model of in-service (naturalized) covers described in Appendix E of the SER (SC&A 2015a). These simulations showed that a loss of 1.2 m would have little effect on the net infiltration rate. UDEQ argues that "This is not logical given that the soil in the cover is required to store the water during cooler and wetter periods, and then release the water during drier periods." This outcome is the result of applying UDEQ's conceptual model of soil formation processes in the cover materials. See the response to Interrogatory 20/2.

The next matter raised by UDEQ in this interrogatory is a request for daily water balance plots of the flow model results. UDEQ has been provided with annual averages for water balance components of precipitation, runoff, evapotranspiration, storage, and deep drainage. UDEQ claims that these water balance plots are not adequate and have produced numerous examples of daily water balance plots. Daily water balance is not the appropriate scale for evaluating a performance assessment model. See the response to Interrogatory 21/2 for a discussion of the evaluation of flow model water balance, and also see Section 1.1, Modeling for Probabilistic Performance Assessment.

Next UDEQ argues that "It's difficult to see how the limited variety and density of plants will provide adequate vegetative cover for erosion protection on an embankment." UDEQ requests that natural analogs in the area be identified and documented to support predictions of adequate plant cover. As described in the response to Interrogatory 71/1, SWCA Environmental

Consultants (SWCA) assessed erosion under undisturbed conditions at Clive in June 2012 (SWCA 2012). Their observations were that the effects of wind and water erosion were limited. There was minimal evidence found of water erosion even on the sloped study plots. This is consistent with the Hansen, Allen, and Luce calculations of projected minimal sheet and rill erosion loss described in the response to Interrogatory 191/3 and the evaluation of the potential for gully erosion on the Federal Cell described in the response to Interrogatory 71/1.

The response to Interrogatory 71/1 describes the sequence of reclamation measures for quickly re-establishing natural conditions on the cover developed by SWCA (2013). Ecological and engineering measures described in the response to 171/1 will rapidly stabilize the cover in the short term and continue to provide long-term stabilization. As SWCA (2013) states, "functioning native ecosystems comprised of the borrow soils at the Clive site do not show erosion as the DRC suggests."

UDEQ expresses their concern about biological soil crust (BSC) at the Site. In particular, they are concerned with "high uncertainty regarding its characteristics at the Clive site." UDEQ requests that Energy*Solutions* "provide examples with quantitative data from sites in similar climate and with similar soils. These examples should show how biological soil crust is preserved or re-established, the timeline for re-establishment, and how presence (or not) of the biological soil crust affected erosion."

BSC is common at the Clive Site. An average of nearly 80 percent of the soil surface in the vicinity of the Clive Site is covered by BSC according to surveys done by SWCA (2013). Energy*Solutions* has developed a comprehensive plan (SWCA 2013) for establishment of BSC on the Federal Cell based on consideration of the literature (Belnap et al. 2001; Bowker 2007). Plans for recovery of the BSC will not be passive. Active measures will be taken to accelerate establishment, including topsoil inoculation with BSC organisms (Belnap et al. 2001; Bowker 2007) and stabilization of the soil surface by seeding with fast growing species. SWCA (2013) describes the inoculation process used to spread BSC organisms collected from undisturbed native soils on the topsoil (SWCA 2013), and the stabilization of the soil surface with fast growing species shown to enhance BSC rehabilitation (Bowker 2007). Recovery time for BSC at the Clive Site is projected by SWCA (2013) to be 3–5 years based on their Site analyses and the use of active assistance measures.

Lastly, UDEQ requests information from similar sites regarding "how presence (or not) of the biological soil crust affected erosion." SWCA (2013) has provided discussion of the literature describing the beneficial role of BSC in controlling soil erosion.

2.6 Interrogatory CR R313-25-7(2)-59/2: Bathtub Effect

DEQ Conclusion from April 2015 SER, Appendix C:

Until the issues are resolved regarding the design of the cover and infiltration rates (see the DU PA SER, Section 4.1.1.1 and Appendix B) the potential for bathtubbing effects cannot be ruled out. Therefore, this interrogatory remains open.

DEQ Critique of DU PA v1.4, Appendix 21: No further analysis has been performed since v1.2.

2.6.1 Interrogatory Response

Net infiltration in the Clive DU PA Model v1.4 is calculated using stochastic inputs. The implementation in the DU PA Model is described in detail in Appendix 5 of the *Final Report for the Clive DU PA Model, Clive DU PA Model v1.4* (Neptune 2015d). To evaluate the likelihood of the bathtub effect occurring, a distribution of net infiltration rates for the ET cover was developed from 1,000 realizations of the net infiltration model. The 99th percentile value of this distribution was 0.106 mm/yr. The design value for the saturated hydraulic conductivity of the clay liner below the waste is 1.0×10^{-6} cm/s (316 mm/yr) (Whetstone Associates 2011). At steady state under unit gradient conditions this hydraulic conductivity corresponds to the flux of water through the saturated clay liner.

Given the much greater capacity of the clay liner to allow water to flow through it in comparison to the 99th percentile of net infiltration rates, the bathtub effect is not possible. Any increase in saturated hydraulic conductivity of the clay liner below the waste due to naturalization will make the bathtub effect even less likely. The largest net infiltration rate at the base of the cover modeled using the Benson et al. (2011) approach for in-service cover properties was 1.31 mm/yr. Even for this unlikely conceptual model of clay liner properties, the maximum net infiltration is over 240 times smaller than the 316 mm/yr that can flow through the cover with its design value saturated hydraulic conductivity.

2.7 Interrogatory CR R313-25-7(3)-60/2: Modeled Radon Barriers

DEQ Conclusion from April 2015 SER, Appendix C:

As described under Interrogatory 05, based on several unresolved issues related to the ET cover, DEQ indicated in the DU PA SER Section 4.1.1.1 that the cover design was deficient and that it cannot determine the adequacy of this portion of the Clive DU PA. (See the description under Interrogatory 05 above for specific details.) Therefore, this interrogatory remains open.

DEQ Critique of DU PA v1.4, Appendix 5, Appendix 21: See Interrogatory 21 for discussion regarding approach and concerns related to modeling the radon barriers.

2.7.1 Interrogatory Response

This interrogatory points to issues raised in Interrogatories 05/2, 21/1, and 90/2. See the responses to Interrogatories 05/2, 21/1, and 90/2.

2.8 Interrogatory CR R313-25-7(1–2)-90/2: Calibration of Infiltration Rates

DEQ Conclusion from April 2015 SER, Appendix C:

As noted in Sections 4.1.1.1, 4.1.1.3, and 4.4 of the DU PA SER, several issues (including infiltration rates) regarding the ET cover remain unresolved. Therefore, this interrogatory remains open.

DEQ Critique of DU PA v1.4, Appendix 21: No further analysis has been performed on calibration of infiltration rates since v1.2.

2.8.1 Interrogatory Response

Issues regarding infiltration rates raised in Sections 4.1.1.1, 4.1.1.3, and 4.4 of the DU PA SER (SC&A 2015b) are:

Sensitivity analysis proposed by UDEQ

See the response to UDEQ Comment B.11.

Correlation between α and K_s parameters

See the response to Interrogatory 05/2.

Development of hydraulic parameter distributions

See the response to UDEQ Comment B.2.

Increased hydraulic conductivity of the clay liner over time is not accounted for in the model.

See the discussion on the clay liner properties in the response to Interrogatory 05/2.

Only a single value of K_s was used for the Surface and Evaporative Zone layers and a single value of alpha was used for the radon barriers.

See the response to UDEQ Comment B.2.

Disruption of cover due to erosion, frost, and biointrusion

See the discussion on biointrusion (Effect of Biologicals on Radionuclide Transport) in the response to Interrogatory 05/2.

See the discussion on calculations of frost depth in the response to Interrogatory 05/2.

See the discussion on cover disruption due to erosion in the response to Interrogatory 05/2.

2.9 Interrogatory CR R313-25-7(2)-150/3: Plant Growth and Cover Performance

DEQ Conclusion from April 2015 SER, Appendix C:

As discussed in the DU PA SER (Section 4.4.3), concerns remain regarding the potential impacts of biointrusion on infiltration and this interrogatory is open.

DEQ Critique of DU PA v1.4 and Appendix 21: See responses to Interrogatories 10 and 28 for further discussion.

2.9.1 Interrogatory Response

In this interrogatory, UDEQ references issues in Section 4.4.3 of the SER (SC&A 2015b). This section of the SER is titled "Effect of Biological Activity on Radionuclide Transport." SC&A (2015b) cite several examples of increased infiltration due to activity of ants and mammals. These examples, however, are not specific to the Clive Site. SC&A (2015b) criticizes the number of excavations and the mapping of roots at the Site conducted by SWCA (2013). Practical considerations, however, dictate that sampling be limited.

Based on site-specific information collected by SWCA (2013), their opinion is that, while greasewood will eventually become established at the Site, roots will follow available water and will remain within the Surface, Evaporative Zone, and Frost Protection Layers growing laterally along the clay barriers. For the flow modeling through the cover layers, a statistical distribution for the saturated hydraulic conductivity based on the in-service cover properties described by Benson et al. (2011) was used for the radon barriers. Use of these in-service hydraulic properties accounts for changes in the hydraulic properties of the radon barriers due to biotic activity.

For additional discussion of these issues, see the responses to Interrogatories 05/2 and 10/3.

2.10 Interrogatory CR R313-25-8(4)(d)-153/2: Impact of Pedogenic Processes on the Radon Barrier

DEQ Critique, v1.4 and Appendix 21: See responses to interrogatories 10 and 28 for further discussion. In addition, alterations in the hydraulic properties of cover soils are due primarily to changes in the size, shape, and connectivity of the pores in response to volume change. Changes in hydrologic conditions within the cover profile (e.g., wetting or drying, freezing or thawing) induce changes in pore water potential (aka pore water suction) that cause volume change. Decreases in pore water due to drying or freezing cause the soil to shrink, resulting in tensile stresses that form cracks and other macropores. Formation of macropores causes the saturated hydraulic conductivity and the van Genuchten α parameter to increase. The "macropores" formed by volume change are larger than the pores in the soil on completion of construction, but generally are not large cracks that would be visible in a transect or test pit excavated with a clay spade or similar tool.

Cover soils in more arid regions have a greater propensity for volume change and alterations in hydraulic properties because very large changes in pore water potential occur seasonally. Plants in arid regions have the ability to extract water to much higher potentials than plants in humid regions (Gee et al. 1999), resulting greater volume change and more significant structural changes. However, over time, cycling of pore water potential combined with the effects of biota intrusion result in similar alterations in hydraulic properties regardless of climate (Benson et al. 2007, 2011).

2.10.1 Interrogatory Response

See the response to Interrogatory 05/2: Evapotranspiration Cover (ET Cover), which includes a discussion of the conceptual model of soil formation at Clive based on field data analysis.

In this interrogatory, UDEQ attributes changes in hydraulic properties of a cover material to volume changes of the material: "alterations in the hydraulic properties of cover soils are due

primarily to changes in the size, shape, and connectivity of the pores in response to volume change."

Changes in volume due to expansion and shrinkage are characteristic of expansive clays. These clays that develop a blocky structure due to vertical shrinkage cracks formed during dry periods are described by Handy and Spangler (2007). Moisture cycles form a subangular blocky structure characterized by aggregates approximately 1 cm in size. Expansive clays are composed of a significant fraction of smectite group minerals. Volumetric shrinkage strain during drying was measured by Albrecht and Benson (2001) on eight natural clay soils through cycles of wetting and drying. These authors found that samples containing the larger percentages of smectite or mixed illite/smectite had the highest volumetric shrinkage strains and showed the most extensive cracking. The smallest shrinkage strains were measured for the soils with less smectite and more illite, kaolinite, and quartz.

The mineralogy of Unit 4 soil clay composition was determined by x-ray diffraction through analysis conducted by the University of Utah (Bingham Environmental 1996). The results shown in Table 4 indicate a zero composition of minerals in the smectite group or, as it was formerly named, montmorillonite. The absence of smectite minerals in the Unit 4 soil makes changes in soil structure attributed to wetting and drying cycles as suggested by UDEQ unlikely.

Table 4. Minerals in Unit 4 soil clays.

Mineral	Percent by Weight
Quartz	12
Plagioclase	2
K-Feldspar	3
Dolomite	4
Calcite	8
Aragonite	53
Kaolinite	2
Illite/Mica	1

2.11 Interrogatory CR R313-25-7(2)-175/1: Infiltration Rates for the Federal Cell Versus the Class A West Cell

DEQ Conclusion from April 2015 SER, Appendix C:

As DEQ noted in the Round 3 Interrogatories:

> *ES notes that this interrogatory is no longer relevant since the Federal Cell will use an ET cover. We agree with this position. However, a thorough discussion of the modeling of infiltration rates, with soil hydraulic conductivity values as provided in NUREG/CR-7028 (Benson et al., 2011), is expected in the report on the ET cover system.*

The role of hydraulic conductivity on infiltration rates is extensively discussed in the DU PA SER. See Section 4.1.1.1 and Appendix B. As specifically noted in Section 4.1.1.1:

> *There are still a number of unresolved issues with respect to the selection of parameter ranges, distributions, and correlations, as well as the modeling approach and predicted sensitivities. These concerns are detailed in Appendix B. Further, because the model-predicted infiltration rates may be sensitive to the hydraulic properties assigned to each ET layer, the α and K_{sat} values assumed for modeling moisture in each soil layer within the cover system must be correlated based on experimental data. Also, additional justification is required for the soil property values used in the model by* Energy*Solutions. Therefore, DEQ does not consider this portion of the performance assessment resolved.*

Therefore, this interrogatory remains open.

DEQ Critique of DU PA v1.4 and Appendix 21: See responses to Interrogatories 10, 21, 28, and 153 for further discussion.

2.11.1 Interrogatory Response

This interrogatory states that there are issues detailed in Appendix B. See the responses to SER Appendix B, Comments B.1 through B.9 and B.11.

For discussion of the use of correlated α and K_s parameter values for flow modeling, see the response to Interrogatory 05/2.

For discussion of the use of hydraulic parameter selection and distribution development, see the response to UDEQ Comment B.2.

2.12 Interrogatory CR R313-25-8(5)(a)-176/1: Representative Hydraulic Conductivity Rates

DEQ Conclusion from April 2015 SER, Appendix C:

At this time, DEQ does not accept the Energy*Solutions* position that infiltration results are insensitive to radon barrier changes. As discussed under Interrogatory CR R313-25-7(2)-05/2: Radon Barrier, an appropriate modeling analysis needs to be performed with DEQ agreement as to values of in-service hydraulic conductivity and correlation between K_{sat} and α (see Appendix E to the DU PA SER). Until that study is performed and the results analyzed, this interrogatory remains open. (See also Appendix B to the DU PA SER.)

DEQ Critique of DU PA v1.4 and Appendix 21: See responses to Interrogatories 10, 21, 28, and 153 for further discussion.

2.12.1 Interrogatory Response

The saturated hydraulic conductivity, K_s, was not included in the regression equation for net infiltration because it was found not to be a predictor (that is, not close to statistical significance). K_s is, however, included in the regression models for volumetric water content of the radon barriers.

Saturated hydraulic conductivity is the ratio of water flux to hydraulic gradient under saturated conditions. The hydraulic conductivity of an unsaturated soil is strongly dependent on the volumetric water content. As air enters the pores of a saturated soil, the hydraulic conductivity decreases rapidly. For example, a plot showing the relationship of average hydraulic conductivity to water content for the Unit 4 silty clay material modeled for the Surface and Evaporative Zone Layers is shown in Figure 18. This plot uses the mean value of K_s determined from site-specific core data and hydraulic function properties from the United States Department of Agriculture (USDA) Rosetta database (USDA 2017).

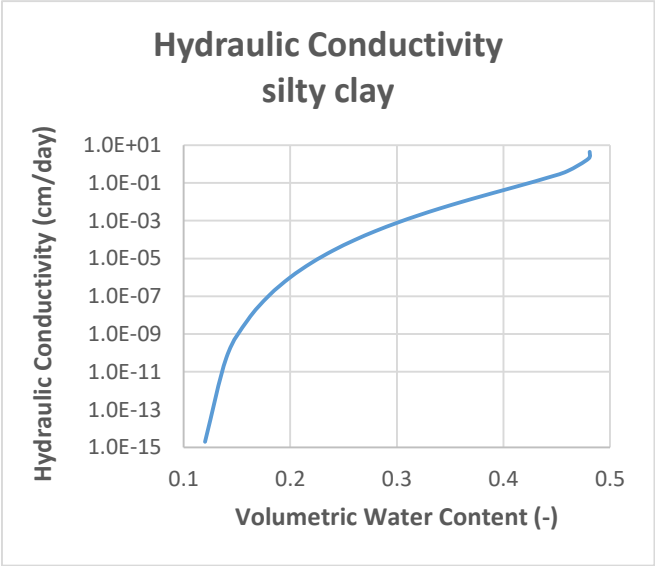

Figure 18. Relationship between hydraulic conductivity and water content used for Unit 4 material.

For this example, if the water content is slightly reduced from its saturated water content of 0.481 to a water content of 0.4, the hydraulic conductivity is greatly reduced from its saturated value of 4.46 cm/day to a value of 0.04 cm/day. This reduction of hydraulic conductivity with reduced water content is even more pronounced with coarser textured soils. In this example, a small reduction in water content was shown to produce a 100-fold reduction in hydraulic conductivity. Since most of the flow in the cover layers occurs under unsaturated conditions, it is not surprising that net infiltration is not sensitive to the value of saturated hydraulic conductivity.

Another reason for the lack of sensitivity of the value of the saturated hydraulic conductivity to net infiltration is likely the low moisture availability at the Site. Due to the climate there is not enough available water for saturated conditions to occur extensively. This can be illustrated with a simple comparison of precipitation volume to soil storage volume. If all of the water from the entire mean annual precipitation at Clive was instantly infused into the cover, the porosity of the layers could contain the saturation within the upper 19 inches of the cover, which is to the top one inch of the Frost Protection Layer.

Changes in the hydraulic conductivity of the radon barrier were accounted for in the flow modeling. A statistical distribution for the saturated hydraulic conductivity, K_s, of the radon

barriers was developed using values from a range of in-service ("naturalized") clay barrier K_s values described by Benson et al. (2011, Section 6.4, p. 6-12). Details of the hydraulic property distribution development of this distribution are described in the response to Interrogatory 21/2.

Correlation between the α and K_s parameters is discussed in the response to Interrogatory 05/2.

2.13 Interrogatory CR R313-25-7(2)-189/3: Modeling Impacts of Changes in Federal Cell Cover-System Soil Hydraulic Conductivity and Alpha Values

DEQ Critique of DU PA v1.4 and Appendix 21: See responses to Interrogatories 10, 21, 28, and 153 for further discussion. In addition, data from other facilities in the region near the Clive site also confirm that changes in the hydraulic properties of cover soils occur, and the effectiveness of a cover can change in response to changes in the hydraulic properties.

For example, Benson et al. (2008) report on an assessment of hydraulic properties in the fine-textured layers in the cover over the uranium mill tailings facility in the Monticello, Utah. The investigators found that the saturated hydraulic conductivity of the cover soils in the upper 1.5 meters increased by approximately 10x. Similarly, α increased by approximately 5x. Excavation of caisson lysimeters at the site also showed roots and cracks present in the radon barrier, which was 1.6–1.9 m bgs (Figure 10-1).

The radon barrier at the Grants, New Mexico, reclamation site was evaluated in the summer of 2016, 20 years after completion, by investigators sponsored by the U.S. Nuclear Regulatory Commission (NRC) and DOE's Office of Legacy Management (LM). At this site, the radon barrier is closer to the surface, with 12 inches of riprap and a sand bedding layer placed directly over the radon barrier. The capillary break provided by the riprap and the sand bedding layer were believed to prevent drying and cracking of the radon barrier.

Large block samples were collected from the radon barrier at Grants, New Mexico, for assessment of field-scale saturated hydraulic conductivity in the laboratory. Block samples were also collected from an analog site representing conditions anticipated in the long term. A summary of the hydraulic conductivities reported to date is included in Figure 189-1 below. All of the saturated hydraulic conductivities are greater than 10^{-6} cm/s. Most are within or close to the range described in NUREG/CR-7028 and are approaching the saturated hydraulic conductivity measured at the analog site. None are less than 1×10^{-7} cm/s as assumed for the lower radon barrier at Clive.

At the Cheney Disposal Facility near Grand Junction, Colorado, data from two large-scale lysimeters indicate that the percolation rate from the cover profile has increased substantially over time, most likely due to structural development within the frost protection layer and the radon barrier at the site. A summary of the water balance data from these lysimeters is shown in Table 189-1. This cover employs a rock armor layer, a sand bedding layer, and a frost protection layer over the radon barrier. Herbicide is used to prevent plant intrusion and root development. Thus, conditions at this site should minimize the possibility for pedogenesis and alterations in hydraulic properties. Initially, percolation was on the order of 1 mm/y and less than about 1% of precipitation. In less than a decade, however, the percolation rate has risen substantially and was nearly 20% of precipitation in Water Year 2016.

As illustrated in NUREG/CR-7028, changes in hydraulic properties occur at sites more arid and more humid than Clive. At the hyperarid Apple Valley site in the arid High Plains desert in

southern California, the saturated hydraulic conductivity of a clay barrier similar to the radon barrier at Clive increased from 1.5×10^{-8} to 1.2×10^{-5} cm/s, or 800x (Benson et al. 2011).

These examples illustrate that structural changes, alterations in hydraulic properties, and alterations in the water balance occur at other sites in the region near Clive, Utah, and at more arid locations. Accordingly, changes in the hydraulic properties should be anticipated in the cover proposed for the Clive site.

2.13.1 Interrogatory Response

In this interrogatory, UDEQ again states their perception that a correlation between the van Genuchten α parameter and the saturated hydraulic conductivity of cover materials should be included in the flow model. The lack of correlation between the α and K_s parameters for the Unit 4 soil is discussed in the response to Interrogatory 05/2.

In addition, UDEQ maintains that statistical distributions of hydraulic properties developed by Benson et al. (2011) should be used to represent the degradation of cover performance with time. The basis for this assertion is saturated hydraulic conductivity data and water balance estimates from other sites provided by UDEQ that in their words "confirm" the general application of a conceptual model of soil structure formation described in Benson et al. (2011).

UDEQ argues that, since soil structural changes and resulting changes in hydraulic properties and deep drainage are observed at these sites "in the region near Clive Utah," that these same changes should be expected at the Clive Site. The sites listed are the Monticello Mill Tailings Repository south of the town of Monticello, Utah (290 miles from Clive), the Blue Water disposal site near Grants, New Mexico (485 miles from Clive), the Cheney disposal site near Grand Junction Colorado (270 miles from Clive), and the Apple Valley Alternative Cover Assessment Program (ACAP) site referenced by Benson et al. (2011).

Of these sites, two do not have ET covers. At the Cheney site the upper layer is described as rock armor treated with herbicide to eliminate vegetation. At the Blue Water site the tailings are covered by a 1.7 to 2.6 ft radon barrier (DOE 2017). The radon barrier is overlain by a 4 to 12-inch thick layer of riprap. Neither of these sites features layers that would function as an ET cover.

No information was found on the full facility name, identity of the owner/operator, setting of the site, construction details, or operation of the site named Apple Valley in Benson et al. (2011). Searches were unable to find more than a general location for this site near Apple Valley, California, provided in Benson et al. (2011). The relevance of measurements of this site's performance to the Clive Site is uncertain without more information.

SWCA (2013) describe the Monticello site as having similar seasonal precipitation, rainfall patterns, and vegetation conditions (Waugh et al. 2008) to the Clive Site. However, SWCA (2013) describe three important differences between the sites:

1. Monticello receives approximately 50% greater average annual precipitation (15.4 in) than Clive.
2. The Monticello ET cover is comprised of clay-loam to sandy-loam soils that are less alkaline and more fertile than the saline, alkaline silty-clay soils at Clive (Waugh et al. 2008).
3. The native vegetation at Monticello is dominated by big sagebrush shrublands and grasslands that are more diverse and of larger stature—with greater target plant densities and cover for the ET cover—than those proposed at Clive.

Site-specific observations of soil formation at the Clive Site that differ significantly from those described in Benson et al. (2011) are discussed in the response to Interrogatory 05/2.

2.14 Interrogatory CR R313-25-7(2)-192/3: Implications of Great Salt Lake Freezing on Federal Cell Performance

DEQ Critique of DU PA v1.4, Appendix 2: In the Updated Site-Specific Performance Assessment (Energy*Solutions* 2013), Appendix E, Energy*Solutions* presents a calculation of frost depth at the Clive site based on the modified Berggren equation, which first presented by Berggren (1943), refined by Aldrich and Paynter in 1953, and later adopted by the U.S. Army Corps of Engineers and other agencies as their preferred method for frost depth determination (Departments of the Army and Airforce, 1988).

In their July 8, 2014 (Energy*Solutions* 2014), response to this interrogatory, Energy*Solutions* points to Appendix E to the Updated Site-Specific Performance Assessment (Energy*Solutions* 2013) for the calculation of the potential frost depth; however, that reference (nor any other estimation of frost depth) is not provided in v1.4, Appendix 2.

Therefore, this interrogatory will remain open until an estimate of the potential frost depth has been incorporated into DU PA Appendix 2, either by reference to or reproducing Energy*Solutions* 2013, Appendix E, or by providing a similar calculation of the potential frost depth. Additionally, if Energy*Solutions* 2013, Appendix E, is referenced or reproduced, any open interrogatories against Appendix E must be resolved before it is incorporated into DU PA Appendix 2.

DEQ Critique of DU PA v1.4, Appendix 21: An estimate of the potential frost depth has not been provided in Appendix 21.

2.14.1 Interrogatory Response

See the response to Interrogatory 05/2 for a description of frost depth calculations for the Clive Site.

2.15 SER B.1 Supplemental Interrogatory Comment 1

1) Demonstrate why 20 HYDRUS runs are sufficient to capture the parameter uncertainty.

DEQ Critique from April 2105 SER, Appendix B:

Energy*Solutions*' response provided to this comment did not address the comment satisfactorily.

DEQ understands that the regressions [Equations 39 and 40 of Appendix 5 to the depleted uranium performance assessment (DU PA) (Neptune 2014b)] were created as simplified surrogate models that relate percolation from the base of the cover and water content in each layer of the cover profile to hydraulic properties of the cover soils. This regression model was developed based on output from HYDRUS from 20 sets of input parameters.

Because only 20 cases were used for the simulations, the tails of the distributions describing the hydraulic properties are poorly sampled, and more extreme cases may be inadequately represented. Consequently, the regressions may represent average or mean conditions sufficiently but may not adequately represent the more extreme cases. No information has been provided to demonstrate that the extreme cases in the tails of the distributions are adequately represented by the regression, or that 20 cases are sufficient to capture the effects of the tails of the distributions. For heavy-tailed distributions such as those used for hydraulic properties, many more simulations would be needed to adequately represent events driven by properties associated with the tails of the distributions.

The predictions in Energy*Solutions* (2014) Figure 5 (see the discussion on Comment 7 below) suggest that the process of developing the regression model has resulted in predictions that are centered more around the mean behavior and that are insensitive to the tails. The percolation predicted from the regression varies within a narrow range of around 0.3 millimeters per year (mm/yr), whereas percolation predicted by HYDRUS predictions for all realizations ranges from approximately 0.01 mm/yr to 10 mm/yr. The response suggests that this insensitive behavior is due to the variance reduction in the hydraulic properties to account for spatial averaging, but another plausible reason is that the regression is based on mostly mean behavior and is relatively insensitive to extremes represented by the hydraulic properties in the tails of the distributions.

A well-documented justification is needed that demonstrates that Equations 39 and 40, based on predictions from 20 simulations using 20 sets of randomly sampled properties, adequately predict the percolation rate and the water contents for cases near the mean and more extreme cases in the tails of the distributions.

In addition, the analysis fails to adequately account for (1) correlations between parameters α and K_{sat} in the same soil layer, and (2) correlations between the values of each parameter within different soil layers. These deficiencies need to be resolved. DEQ also notes that the Energy*Solutions* response contains no substantive discussion of how and why scaling was conducted and how it impacts the results. This discussion must be provided.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 21 for a description of the HYDRUS model parameter uncertainty.

2.15.1 Interrogatory Response

In response to supplemental interrogatories submitted to Energy*Solutions* on August 11, 2014 (Energy*Solutions* 2014), additional capability was developed to allow for more HYDRUS simulations of the cover system to be completed within a practical time period. Fifty HYDRUS-1D simulations were conducted to evaluate the uncertainty in infiltration flux into the waste zone and water content within each ET cover layer as a function of hydraulic property uncertainty; these simulations were documented in DU PA v1.4 Appendix 5 (Neptune 2015c). Equation numbers 39 and 40 from Appendix 5 of DU PA v1.2 (Neptune 2015c) correspond to equation numbers 41 and 42 from Appendix 5 of DU PA v1.4 (Neptune 2015c).

The development of hydraulic property input statistical distributions for this modeling is described in the response to UDEQ Comment B.2. The values of α, n, and K_s used as inputs for each of the 50 simulations are listed in Table 9 of DU PA v1.4 Appendix 5 (Neptune 2015c) and are reproduced here in Table 6.

Simulations were run for 1,000 years. The mean of the fluxes into the top of the waste layer and the mean water contents for the Surface Layer, Evaporative Zone Layer, Frost Protection Layer, and Upper and Lower Radon Barriers over years 900 to 1000 were calculated.

The 50 HYDRUS-1D simulations resulted in a distribution of average annual infiltration into the waste zone, and average volumetric water contents for each ET cover layer. Infiltration flux into the waste zone ranged from 0.0067 to 0.18 mm/yr, with an average of 0.024 mm/yr, and a log mean of 0.018 mm/yr for the 50 replicates.

Multiple linear regression models were fit to the HYDRUS infiltration results, and water contents for each ET cover layer. The general form of the regression was:

$$Y = \beta_0 + \beta_1 * K_S + \beta_2 * \alpha + \beta_3 * n$$

Net infiltration is in units of mm/yr and volumetric water content is dimensionless. For the net infiltration flux regressions, K_s was dropped as a predictor due to poor fit of the models. The regressions were fit using the 'lm()' function in the software package R (R Core Team 2015), which uses least squares optimization for estimating parameters. All values of β coefficients are summarized in Table 5.

Table 5. Coefficients calculated from multiple linear regression models.

Coefficient	β_0	β_1	β_2	β_3
SurfaceWC	0.48155	0.00000	0.54920	-0.20020
EvapWC	0.57947	0.00000	0.73997	-0.24790
FrostWC	0.04282	0.00000	0.43297	0.01617
Rn1WC	0.14737	-0.00076	1.70702	0.06353
Rn2WC	0.14740	-0.00076	1.70648	0.06351
Flux (mm/yr)	-0.32921	N/A	5.56826	0.19538

Implementation in GoldSim

Average annual infiltration flux into the waste zone, and the volumetric water content of each ET cover layer, were calculated using Equations 41 and 42, developed from HYDRUS-1D simulation results (Neptune 2015c). GoldSim calculates values using Equations 41 and 42 from Appendix 5 of DU PA v1.4 (Neptune 2015c) for each ET cover layer.

These equations for solving infiltration and water content in GoldSim are:

$$Infil = \beta_0 + \beta_2 * \alpha + \beta_3 * n \tag{41}$$

$$WC = \beta_{i,0} + \beta_{i,1} * K_S + \beta_{i,2} * \alpha + \beta_{i,3} * n \tag{42}$$

where *Infil* is net infiltration in mm/yr, *WC* is average volumetric water content, and β values are linear regression coefficients with the subscript *i* corresponding to Surface, Evaporative Zone, Frost Protection, Upper Radon Barrier, and Lower Radon Barrier Layers. The necessary distributions in GoldSim are VG_logAlpha, VG_logN, and RnBarrierKsat_Natdist.

α and *n* are calculated from values drawn from distributions using:

$$\alpha = 10^{\text{VG_logAlpha}}, where\ \text{VG_logAlpha} \sim Normal(mean: -1.79, se: 0.121) \text{ and}$$

$$n = 10^{\text{VG}_{\text{logN}}}, where\ \text{VG}_{\text{logN}} \sim Normal(mean: 0.121, se: 0.019).$$

K_s is sampled using:

$$\text{RnBarrierKsat_Natdist} = K_s, \sim Lognormal(geom.mean: 3.37\ cm/day, geom.sd: 3.23\ cm/day), \text{ with right shift of 0.00432 cm/day.}$$

See the response to Interrogatory 05/2 regarding correlation of the van Genuchten α parameter and saturated hydraulic conductivity.

Figure 19 shows a comparison of the net infiltration results calculated using HYDRUS and using the regression equation in the Clive DU PA Model v1.4. Clearly, the comparison shows an excellent fit to the HYDRUS results, demonstrating that the use of a regression equation to approximate the HYDRUS simulations resulted in a successful model abstraction in this case.

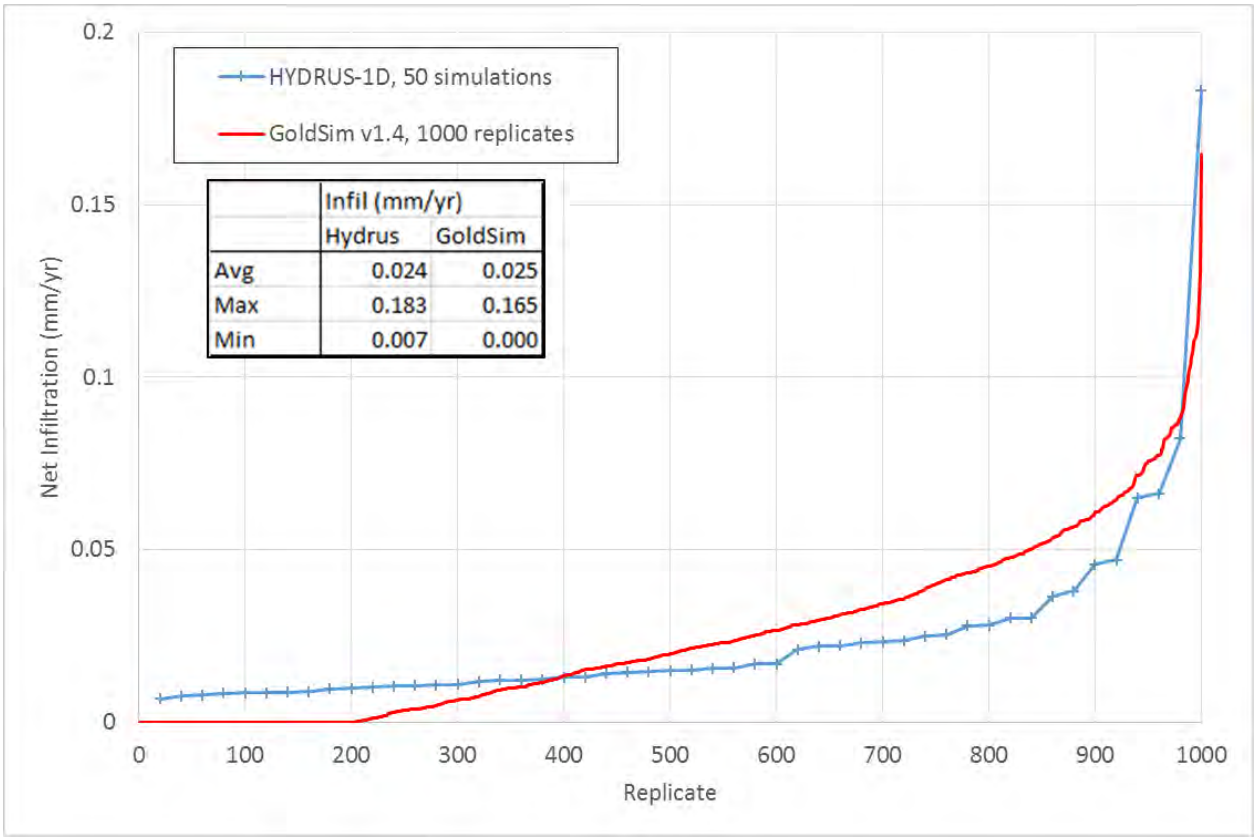

Figure 19. Comparison of 1,000 realizations of net infiltration using the linear model in GoldSim with the results of the 50 HYDRUS simulations of infiltration.

As described in Energy*Solutions* (2014), the discrepancy between the net infiltration rates obtained from the 20 HYDRUS simulations and the GoldSim estimated net infiltration using the regression model was due to not scaling the α and *n* distributions used as inputs for the HYDRUS simulations. This discrepancy has been resolved for the 50 HYDRUS simulations described in Appendix 5 of the DU PA Model v1.4 (Neptune 2015c), and the comparison between the HYDRUS results and the 1,000 realizations using the regression equation are shown here in Figure 19.

The 50 cases were run at sets of values chosen to explore the part of the input parameter space used for the DU PA Model, thus putting the effort and resources into the portion of the parameter space most important to support the model. The values chosen are directly from the distributions developed for Clive DU PA Model v1.4, and the use of values is adequate to expect to sample from the tails of the distributions. The model abstraction and connections to input parameter

distributions were described in detail earlier in this response, as well as the reasons for developing distributions on a scale appropriate for the PA Model.

UDEQ concludes this interrogatory stating that the "Energy*Solutions* response contains no substantive discussion of how and why scaling was conducted and how it impacts the results."

An explanation regarding how and why scaling was conducted in multiple sections of the responses. In addition, Section 1.1 of this document provides a high-level discussion, with examples.

In summary, the reason for "scaling" is to take the available information about the input parameters and use it to develop a distribution at a scale consistent with the scale represented by the PA Model. In other words, the random draws from the distributions should be values that are consistent with the scales they are supposed to represent (e.g., an extreme value possible from a point location at one point in time should not be used to represent a large spatial volume over a long period of time).

Available data often represent much smaller spatial volumes and time periods than are needed for the PA Model; therefore, the data should not be used directly to develop a distribution, but instead "scaling" should be employed to attempt to build a distribution representing the PA Model scale. Averaging is one simple method of scaling information up by aggregating information available at smaller scales.

Larger scales are typically associated with less variability, and thus narrower distributions, but the statistical method used for scaling should depend on the properties of the available data and on uncertainty in assumptions needed to justify the scaling. The end goal is distributions that produce draws representing reasonably realistic values to apply to the spatial volumes represented in the PA Model and long time periods over which they are held constant within a run of the PA Model.

2.16 SER B.2 Supplemental Interrogatory Comment 2

2) The Table 9 HYDRUS parameters do not appear to "bound" the α, *n*, and K_{sat} distributions. For example, in the distribution, K_{sat} ranges from 0.0043 to 52 cm/day, but in the 20 HYDRUS runs K_{sat} only ranged from 0.16 to 10.2 cm/day.

DEQ Critique from April 2015 SER, Appendix B:

Energy*Solutions'* response indicates that the input "values are considered sufficiently extreme to evaluate the influence of K_S on the HYDRUS model outputs, and hence to determine the influence of K_S on the water content and infiltration model outputs." The basis for the conclusion "considered sufficiently extreme" needs to be demonstrated rather than stipulated.

As cited in the response to Comment 1 (above), a well-documented justification is needed that demonstrates that Equations 39 and 40, based on predictions from 20 simulations using 20 sets of randomly sampled properties, adequately predict the percolation rate and the water contents for cases near the mean and more extreme cases in the tails of the distributions. This demonstration should also provide a physical basis for excluding some of the variability in key

hydraulic properties normally considered to affect percolation strongly, such as K_{sat} in the shallow cover-system layers (i.e., the Surface Layer and the Evaporative Zone Layer). Any exclusion of this parameter or its full range of variability from other aspects of modeling, correlation, or sensitivity analysis should also be justified. Although the Clive DU PA v1.2 appears superficially to have illustrated that the output was not sensitive to K_{sat}, this conclusion may be the result of predictions from a cover hydrology model for which unrealistic parameters were used as input (e.g., changing some parameter values but not others for a given soil layer). A separate quantitative demonstration is needed showing that Equations 39 and 40, based on the 20 sets of hydraulic properties used as input, are representative.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 21 for a description of the HYDRUS model input distribution, ranges and bounds.

2.16.1 Interrogatory Response

In response to supplemental interrogatories submitted to Energy*Solutions* on August 11, 2014, additional capability was developed to allow for more HYDRUS simulations of the cover system to be completed within a practical time period. Fifty HYDRUS-1D simulations were completed to evaluate the uncertainty in infiltration flux into the waste zone and water content within each ET cover layer as a function of hydraulic property uncertainty and were documented in DU PA v1.4 Appendix 5 (Neptune 2015c). See the response to UDEQ Comment B.1.

HYDRUS Hydraulic Property Input Parameters

Parameter values and parameter statistical distributions for the hydraulic properties of the cover layers shown in Figure 1 were developed based on site-specific data, engineering specifications, widely used soil hydraulic property databases, and consideration of the function of the layer. These are the parameters used for the hydraulic conductivity model described in Equations (1), (2), and (3) in Section 1.3 needed for the HYDRUS flow modeling.

Surface Layer and Evaporative Zone Layer

These two layers are composed of the same Unit 4 silty clay. The source of site-specific material properties for Unit 4 is Bingham Environmental (1991) (pp. B-20 and B-26). They report results from measurement of water retention for two of nine cores sampled from Unit 4 at the Site. The water retention relation is the correspondence between the tension of water held in the pores of the material and the water content of the material. These data are used to estimate the parameters of the van Genuchten-Mualem hydraulic conductivity model.

The functions of these layers, beyond supporting vegetation and providing erosion control, are to store water from precipitation events within the layers and slow deeper drainage so that the water is available for release to the atmosphere through evaporation and plant transpiration. The α and n values of the van Genuchten water retention model (Section 1.3) influence the capacity of the Unit 4 material used for the Surface and Evaporative Zone Layers to hold water. To provide a better estimate of the uncertainty of these Unit 4 properties, statistical distributions were developed for α and n to be used for inputs for the flow modeling.

To develop the distributions for flow model input, α and *n* values were taken from the distributions of the mean and the standard deviation for each parameter from the Rosetta model database of hydraulic parameters for the textural class of silty clay (USDA 2017). The standard deviations were converted to standard errors by dividing by √n, where *n* is the number of samples (28 in this case).

The Rosetta model provided estimates of van Genuchten water retention parameters, saturated hydraulic conductivity, and unsaturated hydraulic conductivity parameters. The Rosetta model is widely used and has been successful in many applications. In addition to other predictive features, the Rosetta model provides a database containing the class average values of soil hydraulic function parameters for the 12 USDA soil textural classifications. These average values are based on 2,134 soil samples for water retention and 1,306 soil samples for saturated hydraulic conductivity (USDA 2017). These data were obtained from the RAWLS, AHUJA, and UNSODA databases (USDA 2017).

To provide consistency with the conceptual model, probability distributions needed to be specified that matched the spatio-temporal scale of the model. The fitted regression models were used in the Clive DU PA GoldSim model, but the distributions of α and *n* were re-scaled to match the structure of the GoldSim model. Scaling in this way is inherently an averaging process, although some care needs to be taken to ensure that the immediate response reacts linearly to the inputs (expectation is a linear operator). The Rosetta database indicates that 28 samples were used to develop the mean and standard deviation estimates. Consequently, scaling was performed by dividing the standard deviation by the square root of 28, which represents using the standard error of the Rosetta data for the parameter distributions implemented in GoldSim. This provides an appropriate distribution for the Clive DU PA GoldSim model given the structure and scale of that model.

The distributions for A and N given in terms of log transforms of α and *n* were described in the response to UDEQ Comment B.1. Normal distributions of A and N were sampled 50 times, and then transposed from log space by calculating 10^A and 10^N to provide 50 sampled values of α and *n*. In addition, N was truncated such that it could not be less than or equal to 0.0. A correlation between K_s and α was not used. (See the response to Interrogatory 05/2.)

To manage computational burden, the saturated hydraulic conductivity, K_s, for the Surface Layer and Evaporative Zone Layer was assigned a single deterministic value of 4.46 cm/day based on the mean value determined from analysis of the Unit 4 cores (Equation 29 of Neptune (2015c)). See the response to Comment B.5.

Radon Barriers

An expanded assessment of the performance of the radon barriers was made possible by developing a distribution for the saturated hydraulic conductivity (K_s) of the radon barriers to use for the modeling. Development of this distribution is described in the response to Interrogatory 21/2.

For all HYDRUS simulations, the same K_s value was applied to both the Upper and Lower Radon Barriers. To manage computational burden, deterministic values for θ_r, θ_s, α, and *n* from Table 17 of Whetstone Associates (2011) were used for the radon barriers and are listed in Table 8 of Neptune (2015c). A correlation between K_s and α was not used (see the response to Interrogatory 05/2).

The equivalent of Table 9 of Appendix 5 of DU PA Model v1.2 (Neptune 2014) cited in the interrogatory is reproduced here from Appendix 5 of DU PA Model v1.4 (Neptune 2015c). This table, Table 6 below, contains the values of α, n, and K_s drawn from the distributions described above and used in 50 HYDRUS simulations of net infiltration and volumetric water content.

Table 6. Parameter sets of van Genuchten α, n, and K_s used for HYDRUS modeling.

Realization	α (1/cm)	n	K_s (cm/d)
1	0.013091	1.359766	3.285794
2	0.014317	1.371086	12.497148
3	0.010969	1.357776	3.736272
4	0.018089	1.342287	5.162964
5	0.019954	1.316356	2.325706
6	0.010797	1.279182	4.168751
7	0.016004	1.396199	2.595876
8	0.012816	1.308572	0.838501
9	0.014744	1.372326	2.055096
10	0.014791	1.360367	5.052781
11	0.020639	1.276159	3.234858
12	0.019501	1.327968	2.194697
13	0.015766	1.334194	1.307280
14	0.019048	1.373538	1.719640
15	0.018539	1.338996	1.635838
16	0.017045	1.267606	1.749758
17	0.019983	1.413655	5.126214
18	0.012494	1.326223	10.753272
19	0.019503	1.356646	1.845171
20	0.028186	1.378016	3.643845
21	0.010929	1.244500	6.738214

Realization	α (1/cm)	n	K_s (cm/d)
22	0.020973	1.282170	6.943533
23	0.017971	1.372107	1.099495
24	0.016549	1.467656	3.648668
25	0.012120	1.330512	6.338780
26	0.011984	1.382991	0.792890
27	0.012782	1.382761	7.005276
28	0.017094	1.275082	4.768674
29	0.013032	1.382671	9.861743
30	0.024165	1.349583	7.758327
31	0.016054	1.386282	1.478986
32	0.024889	1.310637	2.501489
33	0.017247	1.320670	2.459523
34	0.014338	1.265236	66.503659
35	0.016633	1.286526	31.683457
36	0.014343	1.383885	1.005712
37	0.022207	1.236303	3.733521
38	0.012511	1.317326	4.565641
39	0.018395	1.333180	6.167757
40	0.013735	1.294514	2.206236
41	0.015243	1.229113	4.106400
42	0.018063	1.282922	3.299065
43	0.017010	1.326811	32.484809
44	0.020072	1.323515	31.128008
45	0.015950	1.357247	2.326748
46	0.018944	1.252554	2.976567
47	0.015677	1.301147	1.241111
48	0.024293	1.287802	4.617869
49	0.018819	1.264178	0.737824
50	0.017781	1.263628	2.880623

The 50 random draws from the distribution for K_s have a minimum of 0.73 cm/day, a maximum of 66.5 cm/day, and a mean value of 6.76 cm/day. The maximum of 66.5 cm/day is greater than the maximum of the range reported by Benson et al. (2011) of 52 cm/day (6.0×10^{-6} m/s). Also note that the lowest K_s value drawn was 0.738 cm/day, a value more than 100 times larger than the minimum of the distribution.

The sensitivity of the modeled net infiltration rate to the value of the saturated hydraulic conductivity is discussed in the response to Interrogatory 176/1.

2.17 SER B.3 Supplemental Interrogatory Comment 3

3) NUREG/CR-7028 (Benson et al. 2011) gives the "in-service hydraulic conductivity" as ranging from 7.5×10^{-8} to 6.0×10^{-6} m/s [0.7 to 52 cm/day], with a mean of 4.4×10^{-7} m/s [3.8 cm/day]. Instead of using the provided distribution (i.e., log-triangular with a minimum, maximum, and most likely), ES/Neptune constructed a lognormal distribution with a mean and standard deviation of 0.691 and 6.396 cm/day, respectively. Provide the justification for this approach. For example, the selection of 0.0043 cm/day as the lower end of the K_{sat} distribution requires justification (Appendix 5, p.41). It is not clear why a design parameter value should be used when adequate field data are available. The number chosen by the Licensee for the lower end of the distribution range in the GoldSim implementation is 163 times lower than the lowest value in the range specified within the NUREG guidance (see Section 13.0 of Appendix 5, Unsaturated Zone Modeling to the Clive DU PA). We believe that use of the design parameter biases the K_{sat} distribution in a non-conservative manner.

DEQ Critique from April 2015 SER, Appendix B:

Energy*Solutions*' response to Comment 3 has not demonstrated that the distribution of K_{sat} used for the HYDRUS modeling adequately represents the range of conditions that might be realized for a "naturalized" cover, i.e., one that has undergone pedogenesis as described in NUREG/CR-7028 (Benson et al. 2011). To account for the higher K_{sat} in NUREG/CR-7028 (Benson et al. 2011), the lognormal distribution for K_{sat} was re-fit by the Licensee using an abnormally large log(σ) of 6.396. This provides an unrealistic distribution of K_{sat} that substantially overweights K_{sat} in the lower range.

This, in turn, has the general effect of artificially increasing apparent capillary barrier effects in the DU PA Model v1.2, i.e., at the interface between a relatively lower-permeability zone (the combined Surface Layer and the Evaporative Zone Layer, having a mean K_{sat} value in the DU PA Model v1.2 of 4.46 cm/day) and a relatively higher-permeability zone (the Frost Protection Layer, having a mean K_{sat} value in the DU PA Model v1.2 of 106.1 cm/day). When Energy*Solutions* assumes in HYDRUS that the K_{sat} value for the lower-permeability zone can be as small as 0.0042 cm/day, the ratio in hydraulic conductivity between the higher-permeability zone and the lower-permeability zone can thus be as large as 25,000. This creates in the model an extremely potent artificial, non-realistic capillary barrier at the Evaporative Zone Layer/Frost Protection Layer interface that, in an unrealistic way, reduces infiltration below that interface to extremely small or even negligible values.

The primary model hydraulic conductivity value for the higher-permeability zone in the DU PA Model v1.2, 106.1 cm/day, may already be unrealistic, since the assemblage of soil particles in the Frost Protection Layer is proposed to be a random, poorly-sorted mixture of grain sizes, with

smaller grains being as small as clay. The Frost Protection Layer is not characterized in terms of actual grain size distribution in the DU PA Model v1.2, other than to say that particle sizes can range from 16-inch diameter to clay size. The hydraulic conductivity assigned to it is arbitrary. The assigned value is representative of a sandy loam, which is a very poor representation of the proposed Frost Protection Layer. A mixture of poorly-sorted grain sizes, as found in the Frost Protection Layer, tends to greatly diminish the hydraulic conductivity of a soil compared to a relatively well-sorted mixture. Further exacerbating the problem in the DU PA Model v1.2 is that the hydraulic conductivity values assumed in HYDRUS for the lower-permeability zone are additionally allowed to be 163 times lower than the lowest specified value in the NUREG range for in-service hydraulic conductivity (Benson et al. 2011).

The rationale for dramatically increasing log(σ) to account for the higher K_{sat} associated with pedogenesis or "naturalization" has not been provided and is counterintuitive. The log(σ) should at least be similar for as-built and naturalized covers and may, in fact, be lower for naturalized covers because pedogenic processes ameliorate hydraulic anomalies inherent in the cover from construction. NUREG/CR-7028 (Benson et al. 2011) indicates that pedogenesis tends to transform in-service hydraulic conductivity values to as-built values found in a much higher, but a more restricted, range. The mean should shift upward during naturalization as structure develops, reflecting overall increase in K_{sat} and α rather than a broader range.

As noted previously, while the Clive DU PA Model v1.2 may have illustrated that the output was not sensitive to K_{sat}, this conclusion may be the result of predictions from a cover hydrology model for which unrealistic parameters were used as input. Insensitivity of infiltration to hydraulic conductivity would be expected if inappropriate input parameter values are used so as to create in the model an unjustified, artificial capillary barrier effect. Normally, in the absence of a capillary barrier, infiltration is very sensitive to hydraulic conductivity. As stated by Alvarez-Acosta et al. (2012):

> *A soil hydraulic property that is often a required input to simulation models is the saturated hydraulic conductivity, K_S. It is one of the most important soil physical properties for determining infiltration rate and other hydrological processes…. In hydrologic models, this is a sensitive input parameter and is one of the most problematic measurements at field-scale in regard to variability and uncertainty.*

Thus, the insensitivity of deep infiltration to K_{sat} reported in the Clive DU PA is not sufficient to dismiss the need for demonstrating the efficacy of the parameters used for the HYDRUS input in Appendix 5 to the DU PA Model v1.2.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 21 for a description of the Energy*Solutions* assumptions regarding the in-service versus naturalized parameters.

2.17.1 Interrogatory Response

In this interrogatory UDEQ questions the validity of the lognormal distribution fit by Neptune to the in-service barrier saturated hydraulic conductivity measurements from Benson et al. (2011). See the response to Interrogatory 21/2 for a description of the methods used for fitting the distribution for DU PA Model v1.4 (Neptune 2015c).

UDEQ states "Instead of using the provided distribution (i.e., log-triangular with a minimum, maximum, and most likely), ES/Neptune constructed a lognormal distribution with a mean and standard deviation of 0.691 and 6.396 cm/day, respectively."

Saturated hydraulic conductivity, K_s, is generally modeled with a lognormal distribution, as demonstrated through the figures and the reporting of the geometric mean, rather than the arithmetic mean, for this parameter in Benson et al. (2011). Therefore, developing a lognormal distribution for this parameter is consistent with previous work. Benson et al. (2011) provide a median and range of likely K_s values, but do not explicitly state that the distribution should be log-triangular. The information provided has been used for the median and the likely range, but fit to a lognormal distribution. This assumes that the ends of the "likely range" should be close to the 1st and 99th percentiles of the distribution, rather than a strict minimum and maximum that would be assumed using the suggested log-triangular distribution.

The lognormal distribution has many advantages over the log-triangular distribution. More mass of the distribution is concentrated close to the median; for the log-triangular distribution, more mass is located in the tails where values should be less likely. In practice, this means that the lognormal distribution will lead to draws that are closer to the median, while draws from the log-triangular distribution would lead to more draws that are at the extreme edges of the expected K_s values. The lognormal distribution does not exclude plausible K_s values.

Although Benson et al. (2011) provide a range of likely K_s values, they never state that it would be impossible for K_s to be smaller or greater than the ends of the reported range. In fact, throughout the document, the authors provide examples of other K_s values that are sometimes beyond the given range, i.e., the in-service K_s for Cedar Rapids is 0.06 cm/day. The lognormal distribution does not completely exclude values outside the range deemed plausible, while a log-triangular distribution completely excludes them. This is true for the low end of the distribution, as well as the high end, where the lognormal distribution has a long right tail, allowing for approximately 1% of K_s values to be greater than the upper end of the range specified by Benson et al. (2011). Finally, as stated previously, Benson et al. (2011) suggest a value for the median of the distribution. It is often assumed the mode of a triangular distribution is equal to the median, but this is not the case. The log of the median can be used as the mode on the log scale, but then the median on the original scale will be close to 6, instead of the goal of 3.8.

UDEQ also has concerns with the use of 0.00432 as a minimum K_s value. The lognormal distribution was not fit with the value of 0.0043 but this value was used to truncate the distribution after fitting so that lower values could not be drawn at random. The lower bound excludes K_s values below the design specification, and it barely affects the distribution. Without the lower bound and distribution shift, the probability of a draw being at or below the boundary of 0.0043 cm/day is less than 10^{-8}. Setting a lower bound does not mean that the distribution approaches that value, but it is a precaution to ensure it never goes below it, which is the use of the lower bound here.

UDEQ argues that "Energy*Solutions*' response to Comment 3 has not demonstrated that the distribution of K_{sat} used for the HYDRUS modeling adequately represents the range of conditions that might be realized for a "naturalized" cover, i.e., one that has undergone

pedogenesis as described in NUREG/CR-7028 (Benson et al. 2011)." In general, it appears that the distribution developed for K_s is not entirely understood. UDEQ claims that the work "provides an unrealistic distribution of K_s," but the distribution stems directly from the Benson et al. (2011) field data that they would like used. The lognormal distribution has a similar median value, 3.37 cm/day, and a similar range of values for the 1st to 99th percentile, 0.22 cm/day to 51.5 cm/day, compared to their range of 0.65 to 52 cm/day.

UDEQ then states "To account for the higher K_{sat} in NUREG/CR-7028 (Benson et al. 2011), the lognormal distribution for K_{sat} was re-fit by the Licensee using an abnormally large log(σ) of 6.396. This provides an unrealistic distribution of K_{sat} that substantially overweights K_{sat} in the lower range." See the response to Interrogatory 21/2 for a description of the lognormal distribution used for K_s in Appendix 5 of the Clive DU PA Model v1.4 (Neptune 2015c) developed based on the information in NUREG/CR-7028 (Benson et al. 2011). The distribution has a geometric mean of 3.37 and a geometric standard deviation of 3.23 (log(3.23) = 1.17). Therefore, the lognormal distribution used for the HYDRUS modeling to obtain the 50 realizations used for the model abstraction associated with the DU PA Model v1.4 has a log(σ) of 1.17, not 6.396. The 6.396 was used for the 20 HYDRUS realizations used for the model abstraction in Appendix 5 of the DU PA Model v1.2 (Neptune 2014). The distribution was revised when capability was developed to run many more HYDRUS simulations. See the response to UDEQ Comment B.2.

UDEQ then raises the issue of a capillary barrier at the interface between the bottom of the Evaporative Zone Layer and the top of the Frost Protection Layer. For the Frost Protection Layer, hydraulic properties for a sandy loam were used as taken from the HYDRUS-1D pull-down menu, which includes properties from the database of Carsel and Parrish (1988). The parameters for a sandy loam were chosen because this texture represents a mixture of particle sizes consisting of sand, silt, and clay in fractions representing the range seen in the Unit 3 material at the Site. This soil component fills the voids between the cobbles in the Frost Protection Layer and determines the water flow properties of this layer.

Single deterministic values were used for the hydraulic properties θ_r, θ_s, α, n, and K_s. The saturated hydraulic conductivity for the Frost Protection Layer was assigned a single, deterministic value of 106.1 cm/day based on the sandy loam textural class average from the Carsel and Parrish database. Statistical distributions were not developed for the hydraulic properties of this layer since the function of this layer is protection against freezing and biointrusion, and modeling uncertainty in the hydraulic properties of this layer would add significant computational burden to the modeling.

UDEQ states that the properties of this layer contribute to the layer behaving as a capillary barrier. A capillary barrier is a two-layered system consisting of a fine-grained layer overlying a coarse-grained layer. In their comments UDEQ is referring to the Surface and Evaporative Zone Layers as the upper layer and the Frost Protection Layer as the lower layer. They argue that the hydraulic properties of these layers lead to "an extremely potent artificial, non-realistic capillary barrier" at the interface between the Evaporative Zone Layer and the Frost Protection Layer.

The capillary barrier phenomenon occurs due to differences in the relationship between the hydraulic conductivity and the water tension of the two materials. Water moving in the unsaturated zone is at a negative pressure that can be referred to as tension. For water applied to the top of the fine layer in an initially dry profile at an initially large tension the fine-grained material will have a hydraulic conductivity larger than the coarse-grained material. Due to this difference, water can move down through the fine-grained layer but cannot enter the coarse-grained layer immediately. As more water moves into the fine-grained layer the water content in this layer increases and the corresponding water tension decreases. Water cannot enter the air-filled pores of the coarse-grained layer until the tension decreases to the water entry value of the coarse-grained layer. When this tension is reached, water infiltrates into the coarse-grained layer.

This phenomenon is commonly used in cover design to temporarily hold water in the upper layers by capillarity until it is released to the atmosphere through evaporation and transpiration (Morris and Stormont 1999). This is the same concept as the "store-and-release" cover described by Benson et al. (2011): "The storage layer resides below the topsoil (approx. 300 mm thick) and above a capillary break or foundation layer (if present)."

The hydraulic property values and statistical distributions assigned to the Evaporative Zone and the Frost Protection Layers are reasonable estimates based on site-specific information and commonly used soils databases. Given these property assignments, the Frost Protection Layer behaves hydraulically by enhancing storage in the Evaporative Zone in a realistic manner, not as "an extremely potent artificial, non-realistic capillary barrier."

UDEQ states further in Comment B.3 with respect to capillary barriers, "When Energy*Solutions* assumes in HYDRUS that the K_{sat} value for the lower-permeability zone can be as small as 0.0042 cm/day, the ratio in hydraulic conductivity between the higher-permeability zone and the lower-permeability zone can thus be as large as 25,000." The basis of this comment is not clear. The saturated hydraulic conductivity of the Frost Protection Layer in the flow model is 106.1 cm/day, while the saturated hydraulic conductivity of the Surface and Evaporative Zone layers is 4.46 cm/day. This is a ratio of 24 to 1 not 25,000 to 1.

UDEQ comments on the analysis of flow modeling results that the magnitude of net infiltration is not sensitive to the magnitude of the saturated hydraulic conductivity of the radon barriers. There are a number of factors that contribute to this. The sensitivity of the modeled net infiltration rate to the value of the saturated hydraulic conductivity is discussed in the response to Interrogatory 176/1.

2.18 SER B.4 Supplemental Interrogatory Comment 4

4) Provide justification for using the Rosetta database, as appropriate for an engineering earthen cover.

DEQ Critique from April 2015 SER, Appendix B:

This interrogatory asked for justification for using the Rosetta database for an *engineered earthen cover*. The response goes to great length comparing the attributes of the Rosetta database to other databases, none of which are populated with data for engineered earthen

covers. Most of the databases are for agricultural soils, many of which have been tilled. Their relevance to an engineered earthen cover has not been demonstrated. The response has shown, however, that many of the mean values of hydraulic properties used as input are, to some extent, in reasonable agreement with those associated with engineered earthen covers, as described in NUREG/CR-7028 (Benson et al. 2011). On the other hand, as discussed in the Supplemental Interrogatory Comment 3 (see Section B.3), the low-end value in the range of hydraulic conductivity used in the GoldSim model is 163 times lower than the lowest specified value in NUREG/CR-7028 for in-service hydraulic conductivity. The low-permeability tail of the distribution is overweighted, and variability is not properly accounted for.

One response to the interrogatory, if it could be substantiated using data, would be that the Rosetta database is not based on engineered earthen cover soils and should not be assumed to be representative, but point-wise comparisons between hydraulic recommended properties in Rosetta and those in NUREG/CR-7028 demonstrate that the mean hydraulic properties are similar in both cases. However, as pointed out above, the variability assumed in the hydraulic properties chosen to represent the soils in the DU PA Model v1.2 is not appropriately characterized, and this limitation in the model biases the modeling results greatly.

While it is true that engineered soils undergo pedogenesis and become more like natural soils over time, it is important to follow NUREG/CR-7028 guidelines. The fact that the GoldSim model uses values for its K_{sat} distribution that, at the low end, are two orders of magnitude lower than specified in NUREG/CR-7028, and that the low-permeability range of values is overweighted, does not lead to confidence that the GoldSim model is set up appropriately.

Furthermore, in the GoldSim model as implemented, it is assumed for the input parameter values that there is no correlation between log(α) and log(K_{sat}). When databases based on natural soils are used, it is important to account for correlation between these two parameters. Strong correlation between log(α) and log(K_{sat}) (with $R^2 = 0.9$) has been established for the largest database in North America, as well as for the largest database in Europe [see Sections 4.1.1.1 and 4.4.1 of the safety evaluation report (SER)]. The two correlation equations are quite similar. Furthermore, a mathematical relationship similar to the correlation equations has been developed from fundamental soil physics theory by Guarracino (2007).

Failure to account for this correlation, or other, significant correlations (e.g., correlation in individual parameter values between different cover-system soil layers), leads to unrealistic modeling. As stated in GoldSim's User Manual, Appendix A: Introduction to Probabilistic Simulation (GTG 2013):

> *Ignoring correlations, particularly if they are very strong (i.e., the absolute value of the correlation coefficient is close to 1) can lead to physically unrealistic simulations. In the above example, if the solubilities of the two contaminants were positively correlated (e.g., due to a pH dependence), it would be physically inconsistent for one contaminant's solubility to be selected from the high end of its possible range while the other's was selected from the low end of its possible range. Hence, when defining probability distributions, it is critical that the analyst determine whether correlations need to be represented.*

The response has also clarified that the Surface Layer and Evaporative Zone Layer were each assigned a geometric mean hydraulic conductivity of 5×10^{-7} meters per second (m/s). This hydraulic conductivity is considered unrealistically low for in-service near-surface layers (e.g., < 10 feet deep) that will be densely structured due to wet-dry cycling, freeze-thaw cycling, and biota intrusion by roots, insects, etc. This unrealistically low K_{sat} at or near the surface may have

choked off infiltration in the HYDRUS model and exacerbated runoff, thereby limiting deeper ingress of meteoric water in the profile and under-predicting percolation. As discussed in Section 4.1.1.1 of the SER, the unrealistically low near-surface K_{sat} value, combined with the unrealistically high Frost Protection Layer K_{sat} value, which is inputted into the model, would tend to create in the model an unrealistic, artificial capillary barrier at the top of the higher permeability layer that would inappropriately render modeled values of infiltration extremely low. Soils at the surface develop significant structure and generally are much more permeable than those much deeper in the profile. Energy*Solutions* will need to provide additional evidence that this assumed hydraulic conductivity did not artificially bias the HYDRUS modeling.

The response to Comment 4 also indicates that NUREG/CR-7028 recommends using a single measurement from a single site to define α. This is an incorrect interpretation of the design recommendations in NUREG/CR-7028. The recommendation in NUREG/CR-7028 to use α = 0.2 1/kilopascal (kPa) applies when reliable site-specific information is not available and when a single typical value (not a range of values) is desired. It is based on an interpretation of the dataset presented in NUREG/CR-7028 as accounting for scale-dependent hydraulic properties. The HYDRUS modeling in Appendix 5 used an α that is approximately one order of magnitude lower than the recommendation in NUREG/CR-7028. This α is based in part on historic measurements made at Colorado State University on core samples obtained at the Clive site by Bingham Environmental (1991), which are known to be too small and too disturbed to adequately represent in-service conditions. The relevancy of this historic data from Bingham Environmental is dubious, at best.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 21 for a description of the Energy*Solutions* assumptions regarding the in-service versus naturalized parameters.

2.18.1 Interrogatory Response

The class average values of soil hydraulic function parameters for the 12 soil textural classifications in Rosetta were based on 2,134 soil samples for water retention, and 1,306 soil samples for saturated hydraulic conductivity (Schaap et al. 2001). These data were obtained from the RAWLS, AHUJA, and UNSODA databases (Schaap et al. 2001). Given the stronger economic incentive for characterizing agricultural land than for rangeland, the more extensive soils databases are derived from data obtained from agricultural lands. Soil textural classifications are determined by particle size distributions, not by land use, so these databases have utility for non-agricultural application. Since the objective of the revegetation plan (SWCA 2013) is to develop a sustainable, steady-state condition that mirrors the natural system, few inputs used in the hydrologic modeling would be related to engineered properties.

The available Unit 4 soil texture data indicate that the sample represents an extreme of the range of particle sizes that compose the silty clay textural class. Distributions were developed for the van Genuchten α and *n* parameters for the Surface and Evaporative Zone Layers that represented the entire range of the silty clay class by using the mean and standard deviation values provided by the Rosetta database.

The Benson et al. (2011) report published by the NRC (NUREG/CR-7028) provides recommendations for ranges of hydraulic parameters that may be used to represent in-service conditions of store-and-release and barrier layers in covers.

The Surface and Evaporative Zone Layers in the Clive ET cover system correspond to store-and-release layers. The α and *n* values of the van Genuchten water retention model strongly influence the capacity of the Unit 4 material in the Surface and Evaporative Zone Layers to hold water. To provide a better estimate of the uncertainty of these Unit 4 properties, statistical distributions were developed for α and *n* to be used for inputs for the flow modeling. To develop the distributions for flow model input, α and *n* values were taken from the distributions of the mean and the standard deviation for each parameter from the Rosetta model database of hydraulic parameters for the textural class of silty clay (USDA 2017). The standard deviations were converted to standard errors by dividing by √n, where *n* is the number of samples (28 in this case). Values of the van Genuchten parameter α for these two layers were drawn from a statistical distribution with a mean of 0.016 1/cm. The value for α recommended for in-service layers by Benson et al. (2011) (p. 10-4) is 0.2 1/kPa, which corresponds to a value of 0.02 1/cm, similar to the mean used for the infiltration simulations. The distribution used for the van Genuchten *n* parameter for the flow model simulations had a mean of 1.32. The value for *n* recommended for in-service layers by Benson et al. (2011) (p. 10-4) is 1.3.

To manage computational burden, the saturated hydraulic conductivity, K_s, for the Surface Layer and Evaporative Zone Layer was assigned a single deterministic value of 4.46 cm/day (5.16×10^{-5} cm/s) based on the mean value determined from analysis of the Unit 4 cores (Equation 29 of Neptune (2015c)). The hydraulic properties for Units 3 and 4 are based on laboratory measurements by the Colorado State University (CSU) Porous Media Laboratory for the moisture retention and hydraulic conductivity of core samples from Units 3 and 4 at the Clive Site (Bingham Environmental 1991). The Unit 4 material used for the Surface and Evaporative Zone Layers is classified as a silty clay. The average saturated hydraulic conductivity assigned to a silty clay is 0.48 cm/day from the Carsel and Parrish (1988) database and 9.61 cm/day from the Rosetta database (USDA 2017). The value used for K_s is clearly realistic as it was derived from site-specific data and falls between estimates from two widely used soil hydraulic parameter databases. Comparison with results obtained by Benson et al. (2011) can be made with mean values of the K_s of store-and-release layers of in-service covers listed in Table 6.6 of Benson et al. (2011). The geometric mean of these results is 8.7×10^{-7} m/s or 7.5 cm/day. This value is less than twice the value used for the infiltration modeling.

A distribution for the saturated hydraulic conductivity (K_s) of the radon barriers was developed to use for the modeling. The resulting distribution described in the response to Interrogatory 21/2 is:

> $Ks \sim Lognormal(geom.mean: 3.37\ cm/day, geom.sd: 3.23\ cm/day)$, with a right shift of 0.00432 cm/day.

The value for K_s recommended by Benson et al. (2011), p. 10-3, for modeling "typical conditions" of in-service cover layers is 5×10^{-7} m/s (4.32 cm/day), which is well within the distribution used for the Clive DU PA infiltration modeling.

The minimum value of 0.00432 cm/day, corresponding to the design specification for the radon barriers (Whetstone Associates 2011), was used as a shift. Note that the minimum value was not used to fit the distribution, but simply to constrain the distribution by not allowing K_s values

smaller than that. UDEQ suggests that truncating the distribution at the design K_s value "overweights" the low end of the distribution. This is not correct, as the shift only makes it impossible to choose a value for K_s that is less than the design value.

Single values of α and *n* determined from site-specific measurements were used for the radon barrier in the infiltration modeling to manage computational burden. A value of 0.003 1/cm was used for α and a value of 1.17 was used for n. These values were used in previous modeling by Whetstone Associates (2011). Benson et al. (2011) describe α as varying between 0.001 1/cm and 0.032 1/cm. A range from 1.2 to 1.4 is recommended by Benson et al. (2011) for the n parameter. The value used for the infiltration modeling is slightly below the low end of that range.

Correlations between hydraulic parameters were not included in the distribution development. See the response to Interrogatory 05/2 for a discussion of why hydraulic parameter correlations are not included.

In this comment UDEQ has raised a number of objections to the choice of parameter values and statistical distributions used for the Clive DU PA infiltration modeling. These objections appear to be based on the belief that the recommendations contained in NUREG/CR-7028 (Benson et al. 2011) should be rigidly applied to the Clive Site. Hydrogeologic models, however, are site-specific. Climate conditions and soil formation processes at the Clive Site contradict the assumptions of rapid soil structure formation in the cover layers observed by Benson et al. (2011) at other sites and demonstrate the inapplicability of the conceptual model to the Clive Site. The one-size-fits-all generalization of hydraulic properties does not appropriately represent the unique conditions at the Clive Site. See the response to Interrogatory 05/2: Evapotranspiration Cover (ET Cover) and the response to Interrogatory 153/2.

For discussion of capillary barrier behavior in the cover system, see the response to Comment B.3.

In this interrogatory UDEQ again questions the quality of the hydraulic property measurements made by the Groundwater and Porous Material Laboratory at Colorado State University. See the discussion under Naturalized Cover in the response to Interrogatory 21/2.

2.19 SER B.5 Supplemental Interrogatory Comment 5

5) a) Provide additional explanation/justification for the assumed surface boundary condition and the sensitivity of the HYDRUS results to the boundary conditions.

   b) Also, why is a linear regression the optimal surface response for the design?

DEQ Critique from April 2015 SER, Appendix B:

The interrogatory asked for additional justification for the assumed surface boundary condition. Energy*Solutions*' response explains how the boundary condition was created but does not provide justification for the boundary condition. Two shortcomings need to be addressed explicitly.

First, the repetition of the same 100-year periods 10 times to represent the climatic conditions over a 1000-year period of climatic input will need to be justified quantitatively. For all practical purposes, this simulation strategy will provide essentially the same output for each 100-year period in the record. This demonstration should show that the meteorological conditions over a 1000-year period, including extreme events expected over a 1000-year period, can be represented adequately using a sequence of repeated 100-year records. Normally, longer periods of time involve greater variability in the data. This requested demonstration should also show that the impacts of these extremes on the hydrological response of the cover are adequately represented.

Second, the justification should show that the hydrological behavior at the upper boundary (i.e., surface of the cover) is reasonable and within expected norms. This has not been demonstrated in Appendix 5 (Neptune 2014b), and the unrealistically low K_{sat} assigned to the Surface Layer (see Comment 4) in combination with likely capillary-barrier effect artifacts in the model may have choked off infiltration into the cover profile. At a minimum, water-balance graphs should be presented for typical and wet years showing the temporal behavior of each of the primary cumulative water-balance variables for the cover (e.g., precipitation, runoff, soil water storage, evapotranspiration, percolation). These graphs, and their associated discussion, should demonstrate that the surface boundary is represented adequately and that predictions are within expected norms.

The absence of climate change considerations should also be presented in the context of the most recent climate science, which does show systematic shifts in climate throughout North America within the next 10,000 years, if not sooner. An explanation should also be provided as to why climate change is not relevant at the Clive site when it has been considered in performance assessments for other disposal facilities in the region (e.g., the Monticello U mill tailings disposal facility).

Energy*Solutions*' response also provides an extensive discussion to justify the efficacy of Equations 39 and 40 in Appendix 5. However, these outcomes may have been biased by the unrealistically low K_{sat} assigned to the Surface Layer and Evaporative Zone Layer (see Comment 4), which, in combination with likely capillary-barrier effect artifacts in the model, may have choked off infiltration into the cover profile. The efficacy of Equations 39 and 40 should be revisited once the impacts of the unrealistically low K_{sat} assigned to the Surface Layer and Evaporative Zone Layer (see Comment 4) have been investigated.

As an alternative to the linear regression, DEQ/SC&A fit an exponential equation to the van Genuchten α, *n*, and K_{sat} input data and the HYDRUS-calculated fluxes (Figure B-1). The triangles shown in Figure B-1 are the fluxes calculated using the following exponential fit: $\text{Flux} = 45.465 \times \alpha^{1.4408} \times n^{-1.332} \times K_{sat}^{-0.445}$. For large fluxes, the exponential fit does not appear to be much better than the linear fit, but for small fluxes (which tend to result when the van Genuchten α is small), the exponential fit is much better than the linear fit.

DEQ Critique of DU PA v1.4, See Interrogatory 21 for a description of the Energy*Solutions* assumptions regarding the linear regression of the GoldSim versus HYDRUS infiltration rates.

DEQ Critique of DU PA V1.4, Appendix 21: No changes have been made with respect to the treatment of the surface boundary conditions.

2.19.1 Interrogatory Response

a) Atmospheric Boundary Conditions

The methods used to develop atmospheric boundary conditions applied to the top of the Surface Layer in the HYDRUS models were described in *Unsaturated Zone Modeling for the Clive PA, Clive DU PA Model v1.4* (Neptune 2015c). Precipitation, surface runoff, and evaporation under time-varying climate conditions are boundary condition information required by HYDRUS. The data required for the atmospheric boundary condition includes daily values of precipitation, potential evaporation, and potential transpiration to represent the time-variable boundary conditions on the upper surface of the cover. The long-term evaluation period for this analysis makes it necessary to generate a representative climate record with a longer term than any existing daily data record. The model is deliberately run for a long period of time (1,000 years) in order to reach a near-steady state net infiltration rate that is not influenced by the initial conditions.

The WGEN model (Richardson and Wright 1984) was used to generate a 100-year synthetic precipitation record for the Site. The WGEN model is a component of the widely used HELP model (Schroeder et al. 1994a; Schroeder et al. 1994b). A 100-year precipitation record was generated using the monthly average values from measurements at the Site based on 17 years of observations. Meteorological measurements at the Site have been shown to be consistent with observations at National Oceanographic and Atmospheric Administration (NOAA) stations (Whetstone Associates 2011). Use of the WGEN model is consistent with U.S. NRC guidance (Meyer et al. 1996). These authors found a good comparison between observed and WGEN simulated monthly average precipitation and histograms of daily precipitation for an arid site example.

Daily potential evapotranspiration (PET) was calculated with values of daily maximum (T_{max}), minimum (T_{min}), and mean (T_{mean}) temperatures and extraterrestrial radiation using the Hargreaves method. This approach is used extensively in accepted modeling platforms such as the Soil and Water Assessment Tool (Neitsch et al. 2011) and is also documented in the HYDRUS manuals (Šimůnek et al. 2013). The use of appropriate meteorological data and accepted methods for estimating daily boundary condition values supports the confidence in the application of these boundary conditions. Repetition of a long-term daily record to provide a boundary condition for an even longer-term simulation is often necessary for the large timescales required by PA models. Examples can be found in EPA (2002) and Levitt (2011).

UDEQ argues that “an explanation should also be provided as to why climate change is not relevant at the Clive site when it has been considered in performance assessments for other disposal facilities in the region.” This response provides a brief discussion of potential climate change impacts on unsaturated zone hydrology taken from a more detailed consideration of issues involved with representing global climate change in performance assessment models by Crowe et al. (2017).

In evaluating the influence of climate change on the unsaturated zone, the standard approach in past performance assessments is to assume bounding or worse-case effects of future climate

changes through model evaluations of the wettest and coolest glacial climate in order to maximize future precipitation and infiltration. While potentially useful, these bounding/conservative approaches do not consider the range of possible site-specific effects from both long-term and abrupt anthropogenic driven climate change. Instead, climate scenarios used in performance assessments evaluate natural variations in past climate associated with glacial and interglacial conditions. Further, the timing of future climate change or climate-driven events are not assessed; transition to a glacial climate is *assumed* during the isolation period of disposed waste.

The earth is currently in an interglacial period and the timing of the inception of the next glacial period is critically important for forecasting future climate states. Climate modeling studies coupling changes in the earth's orbital configurations with variable atmospheric CO_2 content demonstrate conclusively that the earth is very unlikely to return to a glacial state when CO_2 concentrations remain above pre-industrial levels (~ 280 parts per million; current levels exceed 400 parts per million). A return to pre-industrial concentrations will likely require in excess of 50,000 years and may require hundreds of thousands of years even if current emissions were to drop dramatically.

The most likely scenario for the future global climate is continuation of the current interglacial climate under conditions of variable but progressive global warming. Previously used assumptions in performance assessments of bounding glacial climates (coldest/wettest conditions) are no longer applicable and under some conditions may require design of overly protective and costly closure covers to reduce infiltration.

UDEQ maintains that "unrealistically low K_s" values have been assigned to the surface layer material in the flow model. This value comes from testing of core samples from the Clive Site. See the response to UDEQ Comment B.4 for further discussion. UDEQ argues that "likely capillary-barrier effect artifacts in the model, may have choked off infiltration into the cover profile." The hydraulic property values and statistical distributions assigned to the Evaporative Zone and the Frost Protection Layers are reasonable estimates based on site-specific information and commonly used soils databases. Given these property assignments, the Frost Protection Layer behaves hydraulically by enhancing storage in the Evaporative Zone in a realistic manner. See the response to UDEQ Comment B.3 for further discussion on capillary barriers.

UDEQ has been provided with annual averages for water balance components of precipitation, runoff, evapotranspiration, storage, and deep drainage. UDEQ claims that these water balance plots are not adequate and have produced numerous examples of daily water balance plots. Daily water balance is not the appropriate scale for evaluating a performance assessment model. See the response to Interrogatory 21/2 for a discussion of evaluation of flow model water balance.

b) Use of Linear Model for Abstraction

UDEQ then discusses comparisons between linear and quadratic regression models developed previously from the results of the 20 HYDRUS realizations.

In response to supplemental interrogatories submitted to Energy*Solutions* on August 11, 2014 (Energy*Solutions* 2014), additional capability was developed to allow for more HYDRUS simulations of the cover system to be completed within a practical time period. Fifty HYDRUS-1D simulations were conducted to evaluate the uncertainty in infiltration flux into the waste zone and water content within each ET cover layer as a function of hydraulic property uncertainty; these simulations were documented in DU PA v1.4 Appendix 5 (Neptune 2015c). Therefore, modeling of net infiltration and cover layer water content in Clive DU PA v1.4 is based on 50 realizations/cases, not the 20 referred to in the interrogatory.

Predictions of average annual net infiltration from regression models with only linear terms, or with quadratic terms, are compared to the net infiltrations actually obtained from HYDRUS (Figure 20). The predictions from the regression models use the same input values used for the 50 HYDRUS cases (i.e., the predictions are simply the fitted values from the fitting of the regression model to the data from HYDRUS).

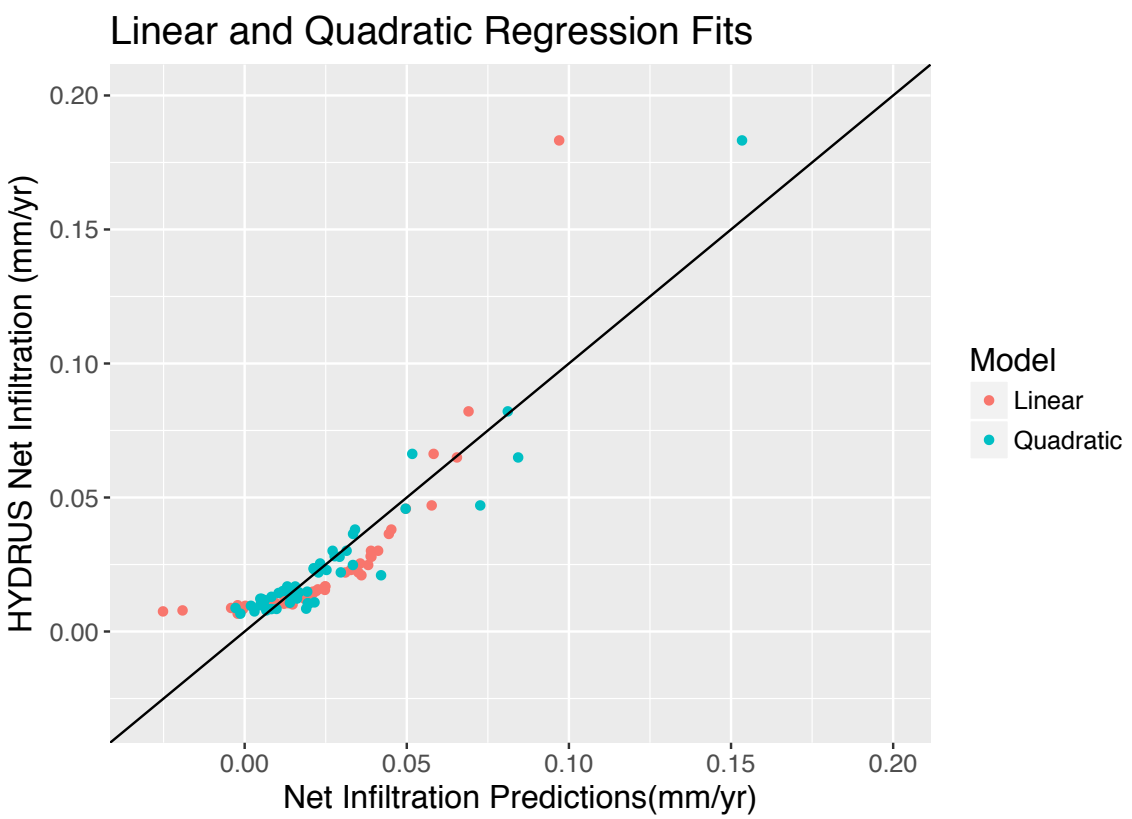

Figure 20. A comparison of predictions (fitted values) from the linear and quadratic regression models, against the HYDRUS results for net infiltration used in the model fitting.

As seen in Figure 20, there is curvature in the HYDRUS net infiltrations that is not fully captured in the fitted regression models, even with quadratic terms. However, HYDRUS is a complicated process model, and an abstraction of reality itself, and the goal of the abstraction is not to capture

the HYDRUS net infiltration response surface perfectly, but to provide reasonable infiltration rates into GoldSim.

The ranges of the predictions from the two regression models are very similar, with most values between 0 and 0.05 (Figure 21). The predictions from the model with only linear terms tend to be slightly larger than those from the quadratic model by about 0.02 to 0.05, but the differences are so small that they are not practically meaningful. The small differences in predictions suggest both models are reasonable; the linear regression model was chosen for implementation in DU PA Model v1.4 because it is simpler and matches model form and is also used for water content across layers. Additional discussion of the predictions from the regression model with only linear terms is provided in the response to Interrogatory 21/2.

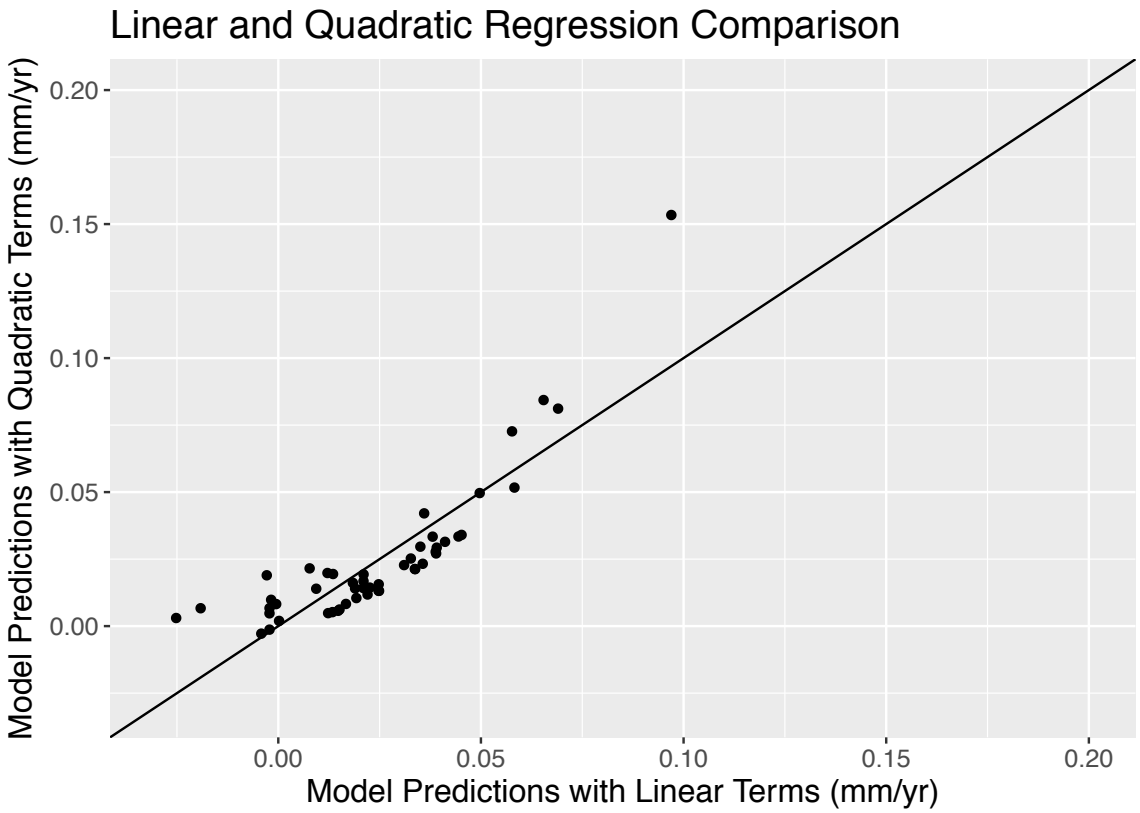

Figure 21. A comparison of predictions from the linear and quadratic regression models based on the input values used for the 50 HYDRUS runs.

As described in Section 1.1 and in the responses to Interrogatory 21/2 and Comment B.1, the goal of the model abstraction is to develop linear regression models to predict reasonable net infiltration rates and water contents for use in the DU PA Model v1.4. This comment (B.5) refers to an "exponential fit" based on the results from an original 20 HYDRUS runs associated with DU PA Model v1.2; the specific fit referenced is not relevant to the DU PA Model v1.4 because of changes to distributions and the use of 50 HYDRUS cases for the model abstractions described previously in this response.

The model form suggested by UDEQ is one of many possible reasonable alternatives and, as expected, does capture some of the curvature in the HYDRUS results not captured by the linear regression model used for DU PA Model v1.4. However, as described in other responses, the goal of the model abstraction is to produce reasonable values of net infiltration and water content to use for GoldSim realizations, not to match the HYDRUS results as closely as possible; HYDRUS is itself a model of reality with its own approximations and assumptions.

For comparison, model form suggested by UDEQ was refit using the 50 HYDRUS realizations for v1.4. The predicted values for net infiltration are very similar between the two models (Figure 22), with the linear regression model predictions covering a slightly larger range of infiltrations and having slightly higher infiltrations in the middle of the range covered. The small differences in predictions suggest both models are reasonable; the linear regression model was chosen for implementation in DU PA Model v1.4 because it is simpler and matches the model form also used for water content across layers. Additional discussion of the predictions from the regression model with only linear terms is provided in the response to Interrogatory 21/2.

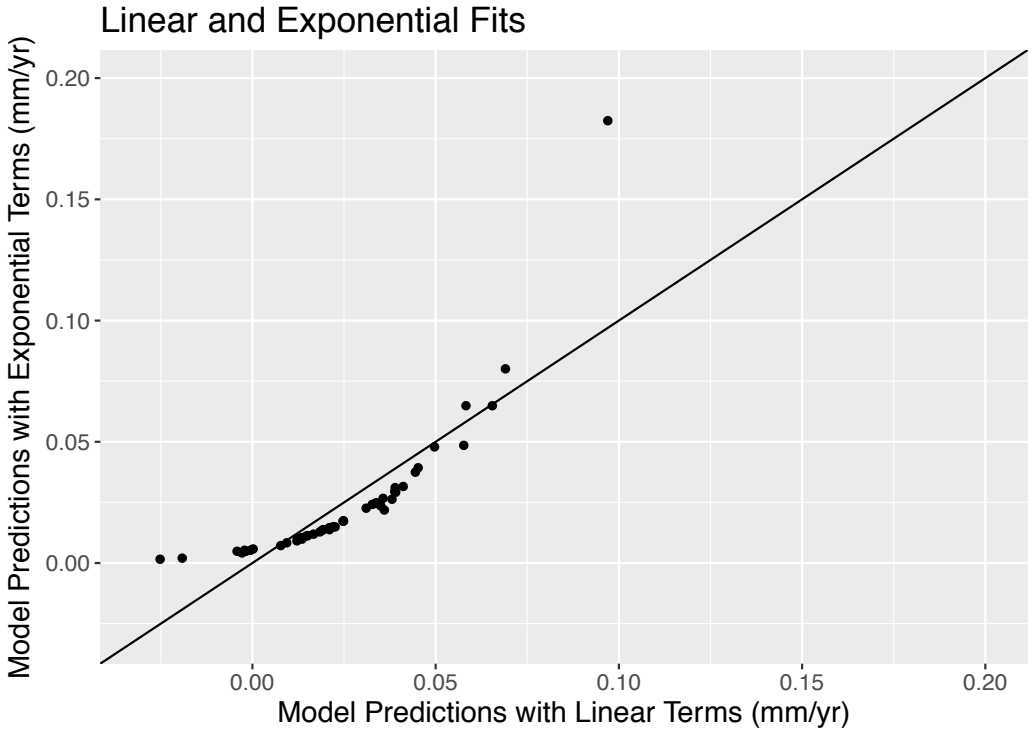

Figure 22. Comparison of predicted net infiltration rates at the inputs used with the 50 HYDRUS runs for the linear regression model and the "exponential" model suggested by UDEQ.

2.20 SER B.6 Supplemental Interrogatory Comment 6

6) To summarize the 20 HYDRUS results, Appendix 5, Section 12.9 states: "*Infiltration flux into the waste zone ranged from 0.007 to 2.9 mm/yr, with an average of 0.42 mm/yr, and a log mean of 0.076 mm/yr for the 20 replicates*." In addition to this statement, provide the results for each HYDRUS run so that the results can be matched to the input data.

DEQ Critique from April 2015 SER, Appendix B:

This interrogatory requested that the results be provided for each HYDRUS run so that the results can be matched to the input data. The response included a spreadsheet summarizing percolation from the base of the cover and water contents from the HYDRUS analysis. However, the output from HYDRUS was not provided.

The output from HYDRUS should be included in the report and presented in a manner consistent with the practice associated with design and evaluation of water-balance covers (i.e., ET covers). Water-balance graphs should be reported showing the key water-balance quantities, and discussion should be provided that demonstrates that the predictions are within expected norms for water-balance covers. This type of presentation and discussion has not been provided in Appendix 5 or in subsequent responses to interrogatories.

Energy*Solutions*' response also discusses graphs in an attached spreadsheet and indicates that these graphs demonstrate that there is no relationship between percolation from the base of the cover and K_{sat} of the radon barrier. This finding may have been biased by the unrealistically low K_{sat} assigned to the Surface Layer and Evaporative Zone Layer (see Comment 4), which, in combination with likely capillary-barrier effect artifacts in the model, may have choked off infiltration into the cover profile. This issue needs to be reevaluated once the impact of the K_{sat} assigned to the near-surface layers has been addressed.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 21 for a description of the adequacy of the HYDRUS model output.

2.20.1 Interrogatory Response

In response to supplemental interrogatories submitted to Energy*Solutions* on August 11, 2014, additional capability was developed to allow for more HYDRUS simulations of the cover system to be completed within a practical time period. Fifty HYDRUS-1D simulations were completed to evaluate the uncertainty in infiltration flux into the waste zone, and water content within each ET cover layer as a function of hydraulic property uncertainty, and were documented in DU PA v1.4 Appendix 5 (Neptune 2015c). See the response to UDEQ Comment B.1 (Section 2.15.1).

The input parameters for the 50 realizations were provided in Appendix 5 of DU PA Model v1.4 (Neptune 2015c) and are reproduced in this document in Table 6. Flow model results for use in the GoldSim model consisted of the average annual fluxes into the top of the waste layer and average annual water contents for the Surface Layer, Evaporative Zone Layer, Frost Protection Layer, and Upper and Lower Radon Barriers averaged over the years 900 to 1000 of the simulation. The outputs from HYDRUS for each realization are provided in Table 7. The results of these 50 realizations were used to fit regression equations for net infiltration and water content for the DU PA Model v1.4.

Table 7. Results of 50 flow realizations described in Appendix 5 of DU PA Model v1.4.

Realization	Net Infiltration (mm/yr)	Volumetric Water Content (-)				
		Surface	Evaporative Zone	Frost Protection	Upper Radon	Lower Radon
1	0.0107	0.22	0.25	0.07	0.25	0.25
2	0.0123	0.21	0.25	0.07	0.24	0.24
3	0.0085	0.21	0.25	0.07	0.25	0.25
4	0.0236	0.22	0.26	0.07	0.25	0.25
5	0.0279	0.23	0.27	0.07	0.27	0.27
6	0.0079	0.23	0.27	0.07	0.24	0.24
7	0.0230	0.21	0.25	0.07	0.26	0.26
8	0.0098	0.23	0.26	0.07	0.26	0.26
9	0.0146	0.21	0.25	0.07	0.26	0.26
10	0.0131	0.22	0.25	0.07	0.25	0.25
11	0.0221	0.24	0.28	0.07	0.26	0.26
12	0.0281	0.23	0.26	0.07	0.27	0.27
13	0.0144	0.22	0.26	0.07	0.26	0.26
14	0.0380	0.22	0.25	0.07	0.27	0.27
15	0.0254	0.22	0.26	0.07	0.27	0.27
16	0.0122	0.24	0.28	0.07	0.26	0.26
17	0.0663	0.21	0.25	0.07	0.27	0.27
18	0.0084	0.22	0.26	0.07	0.24	0.24
19	0.0364	0.22	0.26	0.07	0.27	0.27
20	0.1832	0.22	0.26	0.08	0.28	0.28
21	0.0075	0.24	0.28	0.07	0.24	0.24
22	0.0248	0.24	0.28	0.07	0.25	0.25
23	0.0301	0.22	0.25	0.07	0.28	0.28
24	0.0458	0.20	0.24	0.07	0.27	0.27
25	0.0084	0.22	0.26	0.07	0.24	0.24
26	0.0109	0.21	0.24	0.07	0.27	0.27

Realization	Net Infiltration (mm/yr)	Volumetric Water Content (-)				
		Surface	Evaporative Zone	Frost Protection	Upper Radon	Lower Radon
27	0.0104	0.21	0.25	0.07	0.24	0.24
28	0.0117	0.24	0.28	0.07	0.25	0.25
29	0.0106	0.21	0.25	0.07	0.24	0.24
30	0.0821	0.22	0.26	0.08	0.26	0.26
31	0.0220	0.21	0.25	0.07	0.27	0.27
32	0.0649	0.23	0.27	0.07	0.27	0.27
33	0.0168	0.23	0.26	0.07	0.26	0.26
34	0.0067	0.24	0.28	0.07	0.22	0.22
35	0.0101	0.23	0.27	0.07	0.23	0.23
36	0.0149	0.21	0.25	0.07	0.27	0.27
37	0.0210	0.25	0.29	0.07	0.26	0.26
38	0.0086	0.22	0.26	0.07	0.24	0.24
39	0.0233	0.22	0.26	0.07	0.25	0.25
40	0.0096	0.23	0.27	0.07	0.25	0.25
41	0.0088	0.25	0.29	0.07	0.25	0.25
42	0.0151	0.23	0.27	0.07	0.25	0.25
43	0.0155	0.22	0.26	0.07	0.23	0.23
44	0.0301	0.23	0.27	0.07	0.24	0.24
45	0.0168	0.22	0.25	0.07	0.26	0.26
46	0.0142	0.24	0.28	0.07	0.25	0.25
47	0.0122	0.23	0.27	0.07	0.26	0.26
48	0.0471	0.24	0.28	0.07	0.26	0.26
49	0.0157	0.24	0.28	0.07	0.27	0.27
50	0.0130	0.24	0.28	0.07	0.25	0.25

UDEQ requests plots of flow model water balance components on a daily basis. See the discussion of the applicability of daily water balance plots to PA models in the response to Interrogatory 21/2.

UDEQ questions the outcome from the fitting of the regression equation that net infiltration rates are not sensitive to the magnitude of the saturated hydraulic conductivity of the radon barriers. See the response to UDEQ Comment B2 (Section 2.16.1) for discussion of this issue.

2.21 SER B.7 Supplemental Interrogatory Comment 7

7) The HYDRUS and GoldSim calculated infiltration rates (and perhaps other intermediary results) need to be provided in the report, so that the reviewers do not have to delve into the code's output files. For example, provide dot plots of the infiltration rates through the surface layer and/or provide a statistical summary of the infiltration rates that were sampled in GoldSim.

DEQ Critique from April 2015 SER, Appendix B:

This interrogatory requested that the percolation rates reported by HYDRUS be presented directly in the report. The response includes Figure 4, which shows "infiltration" in mm/yr for various layers in the cover and Figure 5, which shows "infiltration" (interpreted as percolation from the base of the cover) from HYDRUS and predicted with the regression equation, i.e., Equation 39 in Appendix 5.

The quantities shown in Figure 4 need more explanation. Infiltration is defined as the flux of water across the atmosphere-soil interface in response to precipitation. Water movement below the surface is a volumetric flux, and the flux from the base of the cover and into the waste is the percolation rate for the cover. Do these quantities represent the net flux from the base of each layer in the cover? The "infiltration" for the surface layer report in Figure 4 also raises concern, as the results indicate that the unrealistically low K_{sat} assigned to the Surface Layer and Evaporative Zone Layer (see Comment 4), in combination with likely capillary-barrier effect artifacts in the model, may have choked off infiltration into the cover profile and unrealistically limited downward movement of water. A discussion of the HYDRUS predictions in the context of cumulative water-balance quantities and expected norms for water-balance covers could address this issue.

As indicated in the discussion associated with Comment 1, the predictions shown in Figure 5 illustrate that the percolation rate from the regression used in GoldSim is considerably different from the predictions made with HYDRUS and is essentially insensitive to the hydraulic properties used as input. The lack of sensitivity is attributed to the reduction in log-variance to address spatial averaging, but another plausible explanation is that Equation 39 reflects central conditions adequately but extreme conditions in the tailings inadequately. Yet another plausible explanation is the likely capillary-barrier effect artifacts in the model, which would minimize or possibly even exclude infiltration of water to greater depths, so long as evaporation could remove it from the upper two soil layers. Furthermore, evapotranspiration rates in the model are likely too high, since they do not account for accumulation of gravel at the surface over time, which would tend to greatly diminish evaporation. A quantitative demonstration and explanation is needed to address this issue.

The response should also indicate how and why temporal scaling was incorporated into the hydraulic properties, as indicated by the term "spatio-temporal" used in the response to the interrogatory. Temporal scaling should account explicitly for the temporal evolution of the distribution of hydraulic properties due to pedogenic effects. No discussion has been provided regarding a temporal evolution of hydraulic properties. If temporal scaling has not been incorporated, then scale matching should be described as spatial rather than spatio-temporal.

Energy*Solutions*' response should also indicate why conventional spatial averaging procedures for correlated hydraulic properties were not used in the spatial scaling process from point scale measurements in the Rosetta database to grid scale in the model. Spatial scaling from a point measurement to model grid scale will need to account for upscaling of the mean to address measurement bias as well as downscaling of the log-variance in a manner consistent with the spatial correlation structure of engineered but degraded-over-time in-service earthen cover soils. The response should indicate how these factors are addressed by reducing the log-variance by the square root of the sample size in the Rosetta database.

The discussion below illustrates DEQ's mathematical (as opposed to hydrogeologic) concerns with the way infiltration is being abstracted into GoldSim from the HYDRUS results.

1) The linear regression equation that has been programmed into GoldSim does not give results that are consistent with what is calculated by HYDRUS (i.e., for a given pair of α and *n*, the regression equation result in GoldSim does not approximate the HYDRUS result). This is demonstrated by Figure B-1 (See DEQ Critique to Supplemental Interrogatory Comment 5).
2) As acknowledged by Energy*Solutions* in its responses to Supplemental Interrogatories 1 and 2, due to scaling effects the ranges for α and *n* that have been programmed into GoldSim are more narrow than those in HYDRUS (i.e., in HYDRUS, α ranges from 0.001883 to 0.3021, but in GoldSim, α only ranges from 0.005 to 0.0493; likewise, in HYDRUS, *n* ranges from 1.029 to 1.883, but in GoldSim *n* only ranges from 1.060 to 1.540). See Figure B-2 and Figure B-3 for complementary cumulative distribution (CCD) comparisons that were prepared by SC&A utilizing Energy*Solutions* HYDRUS results and the Neptune (2014b), Table 1 GoldSim α and *n* distributions.

The CCD comparison in Figure B-4 shows the effect of these two mathematical considerations on the resulting GoldSim infiltration rate. This infiltration CCD is very similar to Figure 5 of the Energy*Solutions* Response to Supplemental Interrogatories, except that it is rotated 90 degrees.

Note that GoldSim was not re-run for these analyses. Instead, the GoldSim equations were programmed into an Excel Crystal Ball file, and 10,000 realizations were run. Also, the reason the GoldSim CCDs are smoother than the HYDRUS CCDs is that the GoldSim CCDs have 10,000 points, whereas the HYDRUS CCDs have only 20.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 21 for a description of the adequacy of the GoldSim and HYDRUS model output.

2.21.1 Interrogatory Response

In this comment UDEQ first references the regression models for net infiltration developed from the HYDRUS simulations with 20 realizations from Appendix 5 of v1.2 of the Clive DU PA Model (Neptune 2014). As described previously, in response to supplemental interrogatories submitted to Energy*Solutions* on August 11, 2014 (Energy*Solutions* 2014), additional capability was developed to allow for more HYDRUS simulations of the cover system to be completed within a practical time period. Fifty HYDRUS-1D simulations were conducted to evaluate the uncertainty in infiltration flux into the waste zone and water content within each ET cover layer as a function of hydraulic property uncertainty; these simulations were documented in DU PA v1.4 Appendix 5 (Neptune 2015c). Therefore, net infiltration and cover water content values

used in Clive DU PA v1.4 are based on 50 realizations/cases, not the 20 referred to in this comment.

UDEQ requests that HYDRUS and GoldSim calculated infiltration rates be provided in a report and that a statistical summary of the infiltration rates that were sampled in GoldSim be provided. The input parameters for the 50 realizations were provided in Appendix 5 of DU PA Model v1.4 (Neptune 2015c). Infiltration rates used in GoldSim can be calculated using the regression model in Appendix 5 (Neptune 2015c). The net infiltration rates calculated in the 50 HYDRUS realizations are given in Table 7 of this document. A statistical summary of net infiltration calculated in the 50 realizations is given in Section 12.9 of Appendix 5 (Neptune 2015c).

UDEQ shows comparisons between the van Genuchten α and n values generated using the distributions for these parameters from the GoldSim model and the values used for the 20 HYDRUS simulations in their Figures B-2 and B-3. In addition, UDEQ shows a comparison in their Figure B-4 between values of net infiltration generated using the regression model and the values resulting from the 20 HYDRUS realizations. These comparisons for input parameters and net infiltration clearly differ.

UDEQ has suggested a number of causes for these differences but, as described in Energy*Solutions* (2014), these differences were due to not scaling the α and n distributions used as inputs for the HYDRUS simulations. The proper scaling has been applied for the 50 HYDRUS simulations described in Appendix 5 of the DU PA Model v1.4 (Neptune 2015a).

The same comparisons using v1.4 distributions for α and n are shown in Figure 23 and Figure 24, corresponding to the v1.2 comparisons in UDEQ's Figures B-2 and B-3. Comparisons between the complementary cumulative distribution functions for the 50 net infiltration values from the HYDRUS realizations and 1000 values generated from the regression model used in GoldSim are shown in Figure 25. These results demonstrate that proper scaling of the input parameter distributions has resulted in consistency between HYDRUS inputs and outputs and the simplified model used in GoldSim for net infiltration.

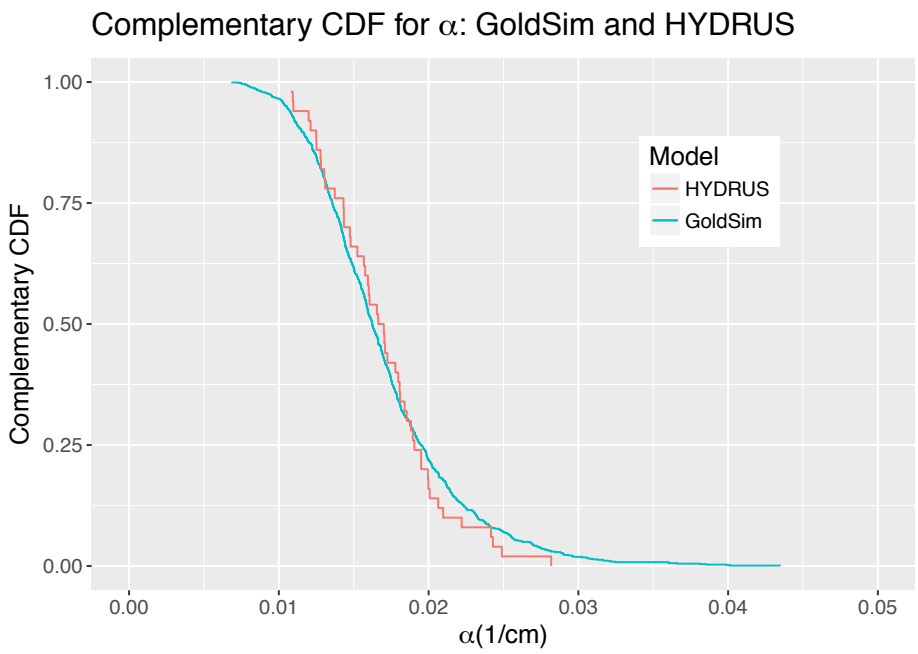

Figure 23. Re-creation of information in UDEQ Figure B-2 showing complementary cumulative distribution functions (CDFs) for the 50 α values used in the HYDRUS realizations and 1000 values drawn from the distribution used in GoldSim for the Clive DU PA Model v1.4.

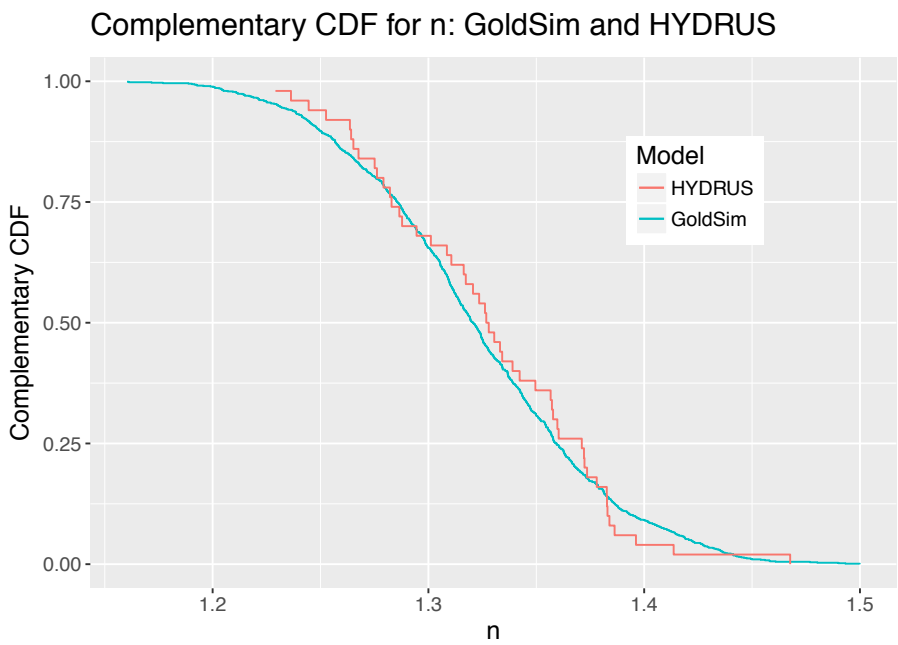

Figure 24. Re-creation of information in UDEQ Figure B-3 showing complementary cumulative distribution functions (CDFs) for the 50 n values used in the HYDRUS realizations and 1000 values drawn from the distribution used in GoldSim for the Clive DU PA Model v1.4.

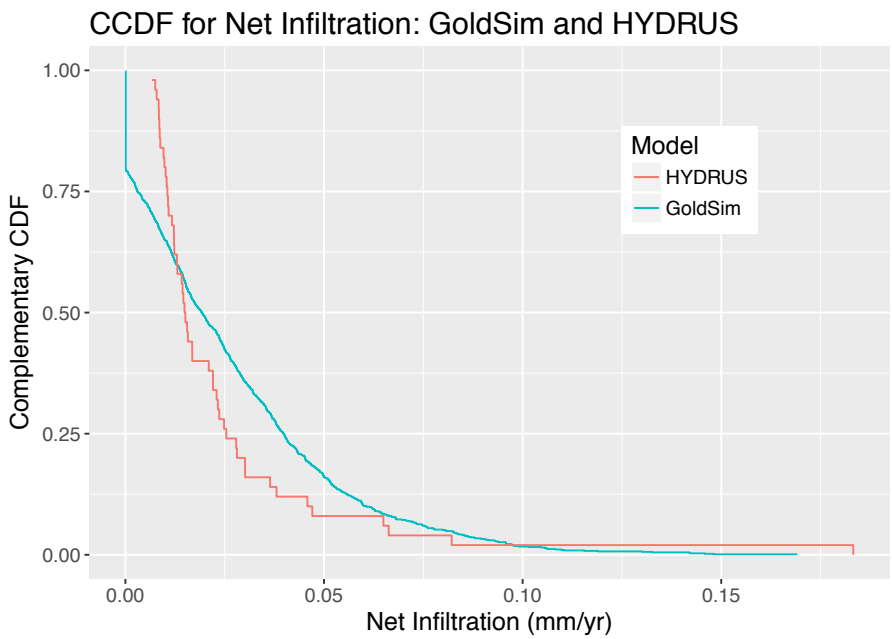

Figure 25. Re-creation of information in UDEQ's Figure B-4 showing complementary cumulative distribution functions (CDFs) for the 50 net infiltration values from the HYDRUS realizations and 1000 values drawn from the distribution used in GoldSim for the Clive DU PA Model v1.4.

UDEQ then argues "Furthermore, evapotranspiration rates in the model are likely too high, since they do not account for accumulation of gravel at the surface over time, which would tend to greatly diminish evaporation. A quantitative demonstration and explanation is needed to address this issue."

The accumulation of gravel at the surface at the Clive Site is highly unlikely. Recent field studies (Neptune 2015b) provide evidence that the Site is within a region of significant eolian activity (wind driven) evidenced by locally thick accumulation of gypsum dunes west and southwest of the Site and a laterally continuous layer of suspension fallout silts preserved beneath the modern surface throughout the Clive Site. The eolian deposits in the upper part of the stratigraphic section represent a 10,000-year record of deposition and soil formation (Neptune 2015b). Observations of Holocene eolian silt throughout the Clive Site support a conceptual model of long-term eolian deposition on a stable surface that promotes and preserves concurrent eolian deposits which are only slightly modified by slow processes of soil formation. See the response to Interrogatory 05/2 for further discussion of eolian deposits and soil formation at the Site.

UDEQ requests clarification of the term "spatio-temporal scaling" used in reference to distribution development for hydraulic properties. UDEQ suggests that "temporal scaling should account explicitly for the temporal evolution of the distribution of hydraulic properties due to pedogenic effects," and "If temporal scaling has not been incorporated, then scale matching should be described as spatial rather than spatio-temporal."

UDEQ's conceptual model of significant soil structural changes occurring during the performance period of the Clive DU PA Model is inconsistent with field observations at the Site. For a discussion of soil formation at the Site, see the response to Interrogatory 05/2.

As described in Section 1.1 and Appendix 14 of the DU PA Model v1.4 (Neptune 2015e), the temporal scale represented in a distribution should align with the scale represented by a value from the distribution in the PA Model. The PA Model takes a single draw from each of the relevant hydraulic property distributions at the beginning of a model realization and typically uses that value for the entire realization of the model (over all time represented by the model). From a temporal perspective, the values should be judged to be reasonable and to be held constant over long time periods, and therefore should not reflect extremes that are only realistic at smaller time scales.

Thinking about plausible long-term averages for the values representing the spatial volumes of the PA Model is the easiest way to judge reasonableness of the distribution relative to time. However, this is challenging because it is clearly impossible to collect data over 100s or 1000s of years into the future to capture potential soil forming effects when developing the distribution of a long-term average. Therefore, temporal scaling is more abstract than the methods discussed for spatial scaling, and actually uses spatial variability as a surrogate for variability that might be observed over time. For example, using data from different locations and regions captures conditions in different materials that may be observed at one location over time through soil forming effects. Therefore, the heterogeneity over space is used as a surrogate for heterogeneity over time for the volumes represented by the PA Model; this is necessary if distributions are to be based on empirical information because it is not possible to collect the data needed to capture the heterogeneity over time into the future. Therefore, while the scaling does appear to be simply "spatial scaling" on the surface, it is not a misnomer to call it spatio-temporal scaling because both scales are always simultaneously considered even if most of the information available is spatial. The resulting distributions should be evaluated relative to both dimensions by asking "does the distribution provide values that are plausible when applied to the spatial volumes of PA cells over long periods of time?"

The "conventional spatial averaging procedures" referred to by UDEQ are useful when extensive spatially referenced point-scale data are collected from the area of interest (the Site) and the goal is to aggregate or "upscale" the point-scale data to reflect information at many larger grid cells representing aggregated material over the same spatial area as covered by the point-scale data. There are two main reasons this approach is not realistic for distribution development for the DU PA Model: (1) the Rosetta data are not site-specific (i.e. not from Clive) and therefore are not spatially referenced to the volumes of soil represented by cells of the PA Model, and (2) the volumes and time periods represented by cells of the PA Model are very large relative to the areas over which data are collected.

The Rosetta database represents a diverse collection of measurements from samples at different locations and different points in time, with no spatial reference to the Clive Site. As described in Section 1.1 and Appendix 14 of the DU PA Model v1.4 (Neptune 2015e), and in other responses related to "scaling," the goal is to capture values in the distributions that are deemed plausible considering they must represent large volumes of soil and long periods of time. Measurements

from single locations included in the Rosetta database will capture extreme values that would not be representative of aggregated measurements representing large volumes of material, and therefore the standard deviation of the raw measurements should not be used as the standard deviation of the final distribution for the PA Model. Instead, the distributional goals for the PA Model require aggregation over potential values from single locations and times that could be observed at the Site to develop a distribution reflecting plausible aggregated values given the current state of knowledge.

Given the lack of site-specific data and spatially explicit information, a reasonable and simple way to proceed is to base the distribution on the average over the values from a variety of conditions found in the Rosetta database. The goal is then to develop a distribution capturing plausible values of averages of the input variables to apply over the spatial areas and time periods used in the PA Model. An elegant way to obtain such a distribution is use of fundamental statistical results regarding the distribution of plausible averages that could have been obtained under many different random samples of point-locations and times (the sampling distribution of the average), and its estimated standard deviation (the standard error of the average). That is, based on the available data, statistical theory can be used to develop a distribution describing other averages that could have been obtained had sampling differed. The sampling distribution can also be thought of as communicating the uncertainty in the estimated mean. Greater variability in the raw data or less information in available data (e.g., smaller sample sizes) leads to more uncertainty, and therefore a larger standard error of the average.

A reasonable distribution is a normal distribution with standard deviation equal to the standard error of the average based on the Rosetta database, calculated as the sample standard deviation divided by the square root of the sample size. This is not the only approach that could be used to distribution development, but its simplicity is appropriate given the distributional goal and available information. The approach essentially assumes that the available data represent a collection of measurements from point locations randomly selected (in space and time) from the Site over the next 10,000 years. The sampling locations and occasions are assumed to be far enough apart that they can be assumed to be independent. Then, the sampling distribution of the average reflects plausible spatio-temporal averages that are reasonable to apply over the Site and over the length of time the model is run. For the Clive DU PA Model v1.4 distributions, the distributions for α, n, and K_s are developed on the log scale where the underlying population distribution of Rosetta values is more symmetric, further justifying the use of the normal distribution to approximate the sampling distribution of the average.

2.22 SER B.8 Supplemental Interrogatory Comment 8

8) a) Demonstrate that the fitted equations for water content and infiltration (Appendix 5, Equations 39 and 40, and Table 10) give “reasonable” results when compared to HYDRUS.

   b) For example, provide an explanation for why K_{sat} is insensitive to the infiltration rates.

DEQ Critique from April 2015 SER, Appendix B:

This interrogatory asked for demonstration that Equations 39 and 40 provide realistic predictions relative to the predictions from HYDRUS. Energy*Solutions*' response provides a number of graphs showing that the predictions in the Clive DU PA Model v1.2 using Equations 39 and 40 are similar to those from HYDRUS in the sense of the mean but exhibit less variability than the predictions in HYDRUS. The reduced variability in the percolation predicted by Equation 39 is attributed to the reduction in log-variance to address spatial averaging, but another plausible explanation is that Equation 39 reflects central conditions adequately, but extreme conditions in the tailings inadequately. A quantitative demonstration and explanation is needed to resolve this issue.

This interrogatory also asked for an explanation of the lack of sensitivity of percolation rate to K_{sat}. The response on pages 25 and 26 (un-numbered figures) shows that water is isolated in the surface layer. However, using an unrealistically low K_{sat} for the Surface Layer and Evaporative Zone Layer, in combination with likely capillary-barrier effect artifacts in the model (see Comment 4), may have choked off infiltration into the cover profile and trapped water at the surface, thereby limiting downward movement of water unrealistically and artificially impacting the significance of K_{sat} of the radon barrier. A discussion of the HYDRUS predictions in the context of cumulative water-balance quantities and expected norms for water-balance covers could address this issue.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 21 for a description of the verification of the HYDRUS results.

2.22.1 Interrogatory Response

UDEQ requests a comparison between the regression models in the GoldSim DU PA Model for net infiltration and water content with the HYDRUS simulation results for these parameters. The request refers to "Appendix 5, Equations 39 and 40, and Table 10." Equations 39 and 40 are found in Appendix 5 of the DU PA Model v1.2 (Neptune 2014). As described in the response to UDEQ Comment B. 1, improved regression models were provided based on 50 HYDRUS simulations in Appendix 5 of the DU PA Model v1.4 (Neptune 2015c). These models correspond to Equations 41 and 42 in v1.4. The regression equation coefficients are provided in Table 10 of both documents. This comparison of net infiltration between the regression models and HYDRUS results is discussed in the response to Comment B.1.

A comparison between measurements of the water content of the Evaporative Zone Layer Unit 4 soil and water contents obtained from the regression model is discussed in the response to UDEQ Comment B. 9.

UDEQ raises a concern about the sensitivity of modeled net infiltration to the value of the saturated hydraulic conductivity. See the response to Interrogatory 176/1 for a discussion of the sensitivity of the net infiltration at the Clive Site to the values of the saturated hydraulic conductivity of the cover layers.

In this interrogatory UDEQ argues that the values of the saturated hydraulic conductivity assigned to the Surface and ET Zone Layers are unrealistically low and that hydraulic properties

used create an artificial and unrealistic capillary barrier. See the response to UDEQ Comment B.4 for a discussion of Surface and ET Zone Layer saturated hydraulic conductivities.

See the response to UDEQ Comment B.3 for a discussion of capillary barrier effects.

2.23 SER B.9 Supplemental Interrogatory Comment 9

9) Compare the moisture contents calculated using the fitted equations to the Bingham (1991, Table 6 and/or Appendix B) Clive site measured Unit 4 moisture contents, and rationalize any differences.

DEQ Critique from April 2015 SER, Appendix B:

The comparison with HYDRUS is remarkably good. However, the comparison with Equation 39 is not good. Equation 39 seems to predict θ between 0.27 and 0.31 for nearly all cases, whereas the data are over a much broader range.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 21 for a description of the adequacy of the goodness of fit against the Bingham (1991) data.

2.23.1 Interrogatory Response

UDEQ requested a comparison between the regression model for water content in Appendix 5 of DU PA v1.2 (Neptune 2014) with the water content data for Unit 4 material acquired by Bingham Environmental (1991). Comparisons were made between the regression model for the Evaporative Zone Layer and Unit 4 water contents listed in Table 6 of Bingham Environmental (1991). The Surface Layer was not selected for this comparison because it has a reduced porosity due to the gravel admixture.

Gravimetric water contents for Unit 4 soils, at depths less than or equal to 2 feet (near the depth of the Evaporative Zone Layer (0.5 to 1.5 ft)), were taken from Bingham Environmental (1991), (Table 6, pdf p. 42-43). Six values matched the depth constraint and those data are presented in Table 8. Volumetric water contents for these six samples were calculated by multiplying the gravimetric values by the bulk density of 1.397 g/cm^3 reported on the Adobe pdf page 174 of Bingham Environmental (1991) for sample GW19A-B1 (Unit 4 sample).

Table 8. Water Content Data from Table 6 of Bingham Environmental (1991).

Bingham 1991 data					
DH ID	**Sample ID**	**Depth (ft)**	**Unit**	**Grav. WC %**	**Vol. WC**
GW-17A	L-1	2	4	27.8	0.39
GW-19B	L-1	2	4	17.5	0.24
SLC-203	NA	2	4	21.7	0.30
SLC-204	NA	2	4	15.3	0.21
SLC-205	NA	2	4	20.7	0.29
SLC-206	NA	2	4	19.6	0.27
Avg				20.43	0.285
Min				15.30	0.214
Max				27.80	0.388

Volumetric water contents calculated using the regression model were extracted from the GoldSim DU PA Model v1.2 by adding a result element for the Expression "WaterContentETCover_regr". Then the model was run for 1,000 simulations to generate 1,000 values of water content for the Evaporative Zone Layer (Unit 4 soil).

Volumetric water contents from the regression model used in GoldSim (1000 replicates), from HYDRUS (20 replicates), and from the six measured values from Table 8, are shown in Figure 26. For the x-axis, each of the 6 values in Table 8 were plotted at increments of ~ 167 in order to show the data on the x-axis with 1,000 values (for the GoldSim results). Similarly, the HYDRUS-1D values were plotted at increments of 50. As shown in Figure 26, the volumetric water contents calculated with the fitted equation in GoldSim are well-bounded by the Bingham data from Table 8. The mean volumetric water content value in Table 8 is 0.285 while the mean from the GoldSim model 1,000 replicates is slightly higher at 0.294. The mean value of the 20 HYDRUS-1D replicates is 0.286, effectively identical to the Bingham Environmental (1991) samples.

UDEQ states that, while the comparison of the sampled water contents with the HYDRUS results is remarkably good, the comparison with Equation 39 (regression model) is not good. They state that "Equation 39 seems to predict θ (water content) between 0.27 and 0.31 for nearly all cases, whereas the data are over a much broader range." This observation on their part is incorrect. Examination of the results from the regression model (labeled "GoldSim") in Figure 26 show water content values ranging from slightly greater than 0.1 to a maximum of 0.35. It is also important to keep in mind that the parameter input distributions to the regression model have been upscaled to specify the model at the appropriate spatial scale of the Site and the temporal scale of the model. Using proper upscaling the regression model output represents

uncertainty in the system's average response rather than the variability of data collected at points in time and space.

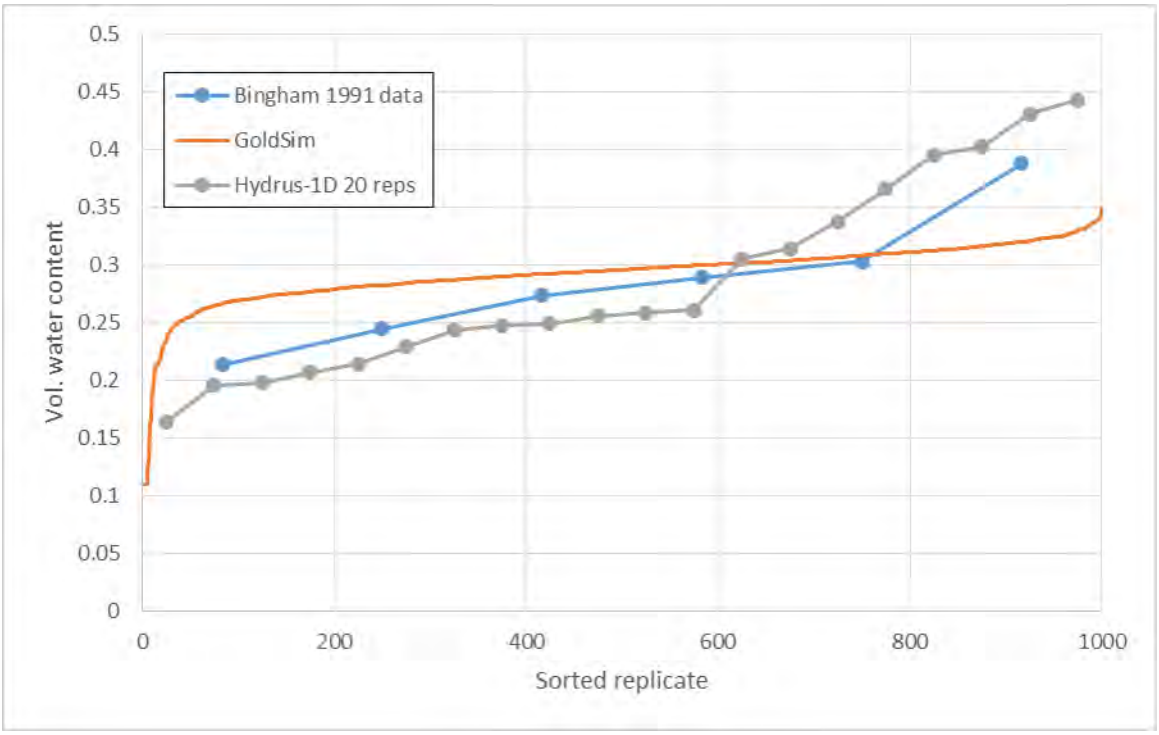

Figure 26. Comparison of Bingham Environmental (1991) water content data with water content calculated using the regression equation for the DU PA GoldSim model and with the results of the 20 HYDRUS simulations.

2.24 SER B.11 Supplemental Interrogatory Comment 11

DWMRC provided Energy*Solutions* with an Excel file, "Clive Hydrus Sensitivity Recommend REV2.xlsx," which contains suggested or proposed combinations of input values for the HYDRUS runs used to support the Clive DU PA.

DEQ Critique from April 2015 SER, Appendix B:

DEQ requested a sensitivity analysis for a reasonable range of parameters to evaluate whether the model responds within expected norms for a water-balance cover. This request has been made in part because Appendix 5 provides inadequate documentation to demonstrate the efficacy of the HYDRUS model and its realism relative to expected norms for a water-balance cover.

Moreover, Appendix 5 indicates that predictions made by the model are insensitive to hydraulic parameters (notably K_{sat}) generally known to have a strong influence on predictions made by HYDRUS and similar models. For example, the unrealistically low K_{sat} for the Surface Layer and Evaporative Zone Layer (see Comment 4) may have choked off infiltration into the cover profile and trapped water at the surface, thereby limiting downward movement of water unrealistically and artificially impacting the significance of K_{sat} of the radon barrier. As explained throughout

this document, there are significant concerns that the HYDRUS model may not be realistic and may be biasing the analyses in the performance assessment. An assessment of the efficacy of the HYDRUS model in the context of expected norms is essential to resolve this issue.

Energy*Solutions*' response goes to great length to dismiss the requested sensitivity analysis as not based on reasonable soil properties and as being inconsistent with a performance assessment approach. The response justifies the criticism of the soil properties by citing databases for soil properties unrelated to engineered earthen covers (e.g., the National Resource Conservation Service database) or data reports known to contain measurements on samples that are too small to represent in-service conditions and collected with antiquated techniques that are known to cause disturbance of soil structure (e.g., the 1991 Bingham Environmental report).

Despite these criticisms, the requested analyses apparently were conducted, but the output was not included or presented comprehensively in the responses. The findings from these simulations should be tabulated and reported, and water-balance graphs should be prepared and discussed in the context of the mechanisms known to influence the hydrology of water-balance covers. A thoughtful discussion would help justify the use of the HYDRUS model and build confidence in the output.

DEQ Critique of DU PA v1.4, Appendix 21: See Interrogatory 21 for a description of the adequacy of the range, distribution and bounds on the HYDRUS input data. The type of output that should be provided is also presented.

2.24.1 Interrogatory Response

UDEQ requested responses to 10 supplemental interrogatories on August 11, 2014. Comment 11 in Appendix B of the SER (SC&A 2015a) contains Comment 10 of the 10 supplemental interrogatories.

In this interrogatory, UDEQ provided a table with sets of flow model input parameters for the cover layers. Single values were specified for the van Genuchten *n* parameter, the residual water content, and the saturated water content. These same values were to be applied to all layers. Values of the van Genuchten α parameter and the saturated hydraulic conductivity, K_s, were given for each layer in categories labeled "low," "typical," and "high." The values for α and K_s for the radon barrier and the Frost Protection Layer were identical. UDEQ requested that HYDRUS simulations be conducted using multiple combinations of parameter values for a total of nine simulations.

For each simulation, UDEQ instructed the modelers to "run 'warm up' simulation 5 times back to back beforehand using meteorological year having annual precipitation closest to long-term average. Use heads from end of this 5 yr simulation as initial conditions for the performance simulation."

Energy*Solutions* expressed their concern with this approach but did fulfill UDEQ's request to run the requested simulations. Energy*Solutions* provided the following response (Energy*Solutions* 2014).

> In general, Energy*Solutions* strongly disagrees with the request of running highly speculative, unsupported, one-off cases suggested in the subject request. This is not consistent with the intent of the Utah regulation nor the meaning or application of a "*sensitivity analysis.*" In practice, an appropriate sensitivity analysis would consider only combinations of input values that are plausibly visible at the site under study. Whereas the concept of plausibility in this context is applied based on available data and professional judgment, the values that are suggested in the subject document (and repeated above) are <u>not</u> plausible for this site.
>
> Energy*Solutions* also disagrees with the intent given that the site will return to natural conditions. In fact, the Division-suggested input values <u>do not</u> match natural conditions, whereas the probability distributions used in the Clive DU PA Model provide reasonable bounds for site conditions projected into the future given the available information and data.
>
> There are significant limitations in assessing the effects of parameter and conceptual uncertainty using deterministic modeling with specified (discrete) cover designs and bounding transport parameters and assumptions. Any more comprehensive sensitivity analysis for the infiltration modeling should not be based on selective, unrepresentative, and non-systematic changes in physical properties of cover materials.
>
> In accordance with well-documented NRC guidance, the probabilistic approach models future conditions by projecting current knowledge/conditions as reasonably as possible while capturing uncertainty in the parameters or assumptions of the model. This is distinctly differentiated from "*conservative*" (i.e., supposedly biased towards safety) modeling that is occasionally seen, typically using point values for parameters (implying a great deal of confidence; i.e., no uncertainty, or conditioning). This type of conservative modeling is often termed "*deterministic*" modeling, and has often been used to support compliance decisions. However, supposed conservatism in parameter estimates (or distributions) is often difficult to judge in fully coupled models in which all transport processes are contained in the same overall PA model. More importantly perhaps, actual conservative dose results from PA models do not support the full capability of a disposal facility, which leads to sub-optimal decisions for disposal of legacy waste and for the nuclear industries that need a disposal option. Conservative, deterministic models may have utility at a "*screening*" level, and they are often useful during probabilistic model building, but they do not provide the full range of information that is necessary for important decisions such as compliance or rule-making (cf., Bogen (1994), Cullen (1994)).
>
> Analysis of non-representative, arbitrarily selected one-off cases that are based on unrealistic conditions easily lead to misinterpretation of the performance of the disposal system.

What is proposed by the Division is not a sensitivity analysis. Rather, the Division proposes an analysis of separate implausible combinations of input parameter values. Some details are provided below:

Saturated Hydraulic Conductivity (Ks)—Surface Layer

The surface layer in the ET cover functions as a store and release layer. Proposed values for this layer are 86.4 cm/day for a low value, 864 cm/day for a typical value, and 864 cm/day for a high value. The typical and high values proposed exceed the values for the K_s of sand provided in both the Rosetta (USDA 2017) and the Carsel and Parrish (1988) databases (712.8 cm/day and 643 cm/day respectively) and are not appropriate for characterizing a silty clay.

These values are also inconsistent with the measurements provided by Benson et al. (2011) for store and release covers. Table 6.6 of Benson et al. (2011) contains geometric mean values of measurements of in-service K_s for store and release covers at 10 sites. The geometric mean values of K_s ranged from 0.65 cm/day to 45.79 cm/day with a geometric mean of all sites of 7.5 cm/day. The proposed low value is an order of magnitude larger and the typical and high values are more than two orders of magnitude larger than the mean of the measured values.

The National Resources Conservation Service (NRCS) Web Soil Survey (WSS) (http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm) provides online access to Soil Reports containing soil property data. The most extensive surface soil type at the Clive Site corresponding to Unit 4 is classified as the Skumpah by NRCS. NRCS assigns K_s values for the upper 5 feet of the Skumpah ranging from 3.6 cm/day to 35 cm/day. These K_s values represent natural conditions.

Again, these values are orders of magnitude lower than the proposed values.

α Values—Surface Layer

The α values recommended for the low, typical, and high cases for the Surface Layer are 0.3 1/kPa (0.03 1/cm). These values are too large when compared to the values of 0.00295 1/cm and 0.0012 1/cm measured by Bingham Environmental (1991) on two cores taken from Unit 4 at the site.

All Hydraulic Model Parameters —Frost Protection Layer

All hydraulic parameter values for the Frost Protection Layer are set to the identical values recommended for the radon barriers. These two materials are quite different, and treating them as identical is unrealistic; even after naturalization the Frost Protection Layer will not reach the conditions of the current radon barrier. This would artificially induce more flow through the frost layer, but would not represent the naturalized system.

Added Gravel

For the HYDRUS simulations a mean value of 0.48 for the porosity of the Unit 4 silty clay used for the Surface Layer was obtained from the Rosetta database (USDA 2017). The effect of the addition of 15 percent gravel to the Surface Layer on porosity was calculated using ideal packing equations (Koltermann and Gorelick 1995), giving a value of 0.41. If adding gravel and naturalizing the layer have compensating effects, then the saturated water content should have remained 0.48. Their recommended value is 0.4, nearly identical to what we used.

The influence of change in soil structure on saturated hydraulic conductivity of the radon barriers was included in the Clive DU PA Model by sampling from a distribution of saturated hydraulic conductivity developed from measurements of barrier layers in service covers (Benson et al. 2011).

Warm-up Simulations

UDEQ included requests for "warm up" simulations. Specifically, the request was "For each case above, run 'warm up' simulation 5 times back to back beforehand using meterological year having annual precipitation closest to long-term average. Use heads from end of this 5 yr simulation as initial conditions for the performance simulation."

The 20 HYDRUS-1D simulations were conducted with, essentially, a 900-year warm-up period, which is a considerably longer time period than the 5 average years requested by the Division. Neptune used a 100-year synthetic record that was repeated 10 times to generate a 1,000-year record of atmospheric boundary conditions. All 20 simulations were run for 1,000 years but only the time series of average water content and infiltration for the last 100 years were used as results. This was done because the initial conditions for all simulations were set to a water potential of -200 cm, which is wetter than steady-state conditions. The long simulation time allowed for equilibration to steady-state. So, essentially, there is a 900-year warm up period. Figure 27 shows the time series of infiltration through the ET cover and into the waste zone. It is apparent that, even after 900 years, the line is not quite flat, indicating that our infiltration estimates are slightly over-estimated.

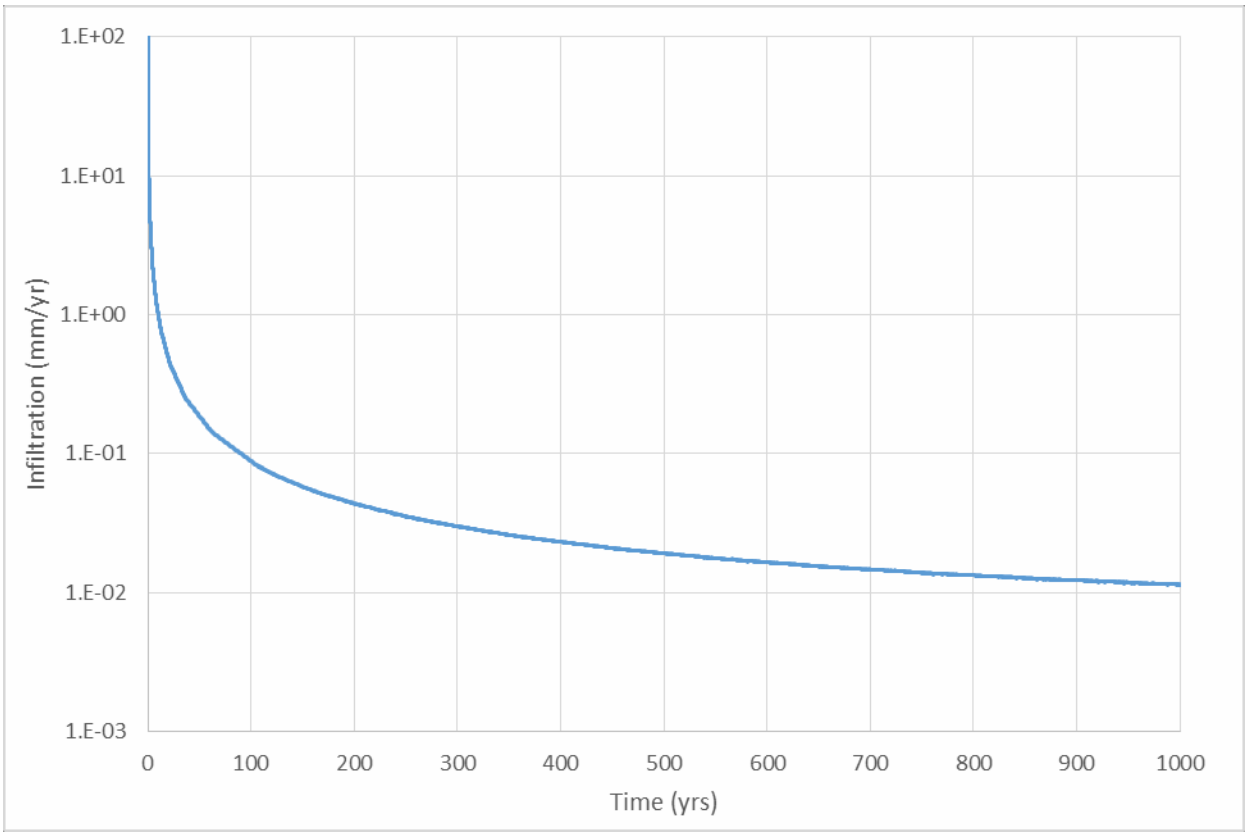

Figure 27. Time series of infiltration into the waste zone for one of the 20 HYDRUS-1D simulations.

Nevertheless, the nine HYDRUS-1D simulations requested by the Division were run and results showing the range from minimum to maximum infiltration (into the waste zone), along with the results from the original 20 HYDRUS-1D simulations, are shown in Figure 27. Despite the implementation of the high K_s values requested by the Division, infiltration in the new nine simulations is generally lower than for the original 20 HYDRUS-1D simulations. This is largely due to setting residual water content to zero, which effectively increases the water holding capacity of each soil layer.

Overall, the Clive DU PA Model provides a reasonable range for the input parameters for the hydraulic properties given the currently available data and information, and the HYDRUS runs for the nine additional combinations of single values for inputs adds no further insight.

Additional issues raised in Supplemental Interrogatory Comment B.11 are: observed insensitivity of net infiltration to the value of the saturated hydraulic conductivity, a capillary barrier formed by the upper cover layers, criticism of the NRCS soil properties data base, and criticism of sampling and testing methods used by the CSU Porous Media laboratory.

Sensitivity of Net Infiltration to Saturated Hydraulic Conductivity

See the response to Interrogatory 176/1.

Capillary Barrier Effects

See the response to UDEQ Comment B.3.

Antiquated Techniques for Sampling and Analysis of Core

See the response to Interrogatory 21/2.

3.0 Conclusion

Many issues relating to ET cover design and modeling are interwoven throughout the UDEQ interrogatories discussed in this document. The following summarizes critical aspects of these responses:

Geologic and Depositional Setting

- Observations of eolian (wind carried) silt deposited in the last 10,000 years across the Clive Site support a conceptual model of long-term eolian deposition on a stable surface that promotes and preserves concurrent eolian deposits that are only slightly modified by slow processes of soil formation. Based on these observations, modeling substantial cover material hydraulic property changes within 5 to 10 years after construction as presented in Benson et al. (2011) and in Appendix E of SC&A (2015a) is not appropriate for the Clive Site.
- UDEQ attributes changes in hydraulic properties of a cover material to volume changes of the material. Smectite minerals responsible for shrink/swell behavior in clays attributed to wetting and drying cycles are absent from the Unit 4 clay soils at the Site.
- Sites listed by UDEQ as being comparable to Clive are the Monticello Mill Tailings Repository south of the town of Monticello, Utah (290 miles from Clive), the Blue Water disposal site near Grants, New Mexico (485 miles from Clive), the Cheney disposal site near Grand Junction Colorado (270 miles from Clive), and the Apple Valley Alternative Cover Assessment Program (ACAP) site referenced by Benson et al. (2011). These sites are not comparable for a number of reasons including different cover types, different soils, and different ecology.

Disruptive Processes

- Based on data collection and analysis and the proposed cover design, SWCA evaluated the potential for disturbance by plant roots, mammals, and ants to result in increased infiltration (SWCA 2013) and determined that soil disturbance and increased infiltration due to biotic activity would be minute. Their evaluation does not support UDEQ's assertion that biointrusion of plants and animals will substantially increase infiltration.

- SWCA (2013) conclude from their observations at the Clive Site and ecological analog sites that the low fertility and alkalinity of the soils and the aridity of the climate limit the growth of plants at the Site and would inhibit the development of large deep-rooted plants in the cover. The Clive and Monticello Sites are not comparable with respect to rooting depths.
- The frost depths calculated as part of this analysis show results that are consistent with the depths of cover and frost protection proposed in the ET Cover design. Disruption of the cover due to freeze/thaw is not likely.

Flow Model Input Parameter Distribution Development

- Probability distributions used in a PA model incorporate uncertainty in the mean rather than variability among values from different point locations and times. The distribution should represent plausible means for the entire volume of material over the time frame of the model, rather than variability among measurements taken from individual locations within a site. Practically, this often translates into using standard errors for the estimated mean over a larger scale to define distributions, rather than standard deviation of available small-scale measurements. The relevant question to ask is "Does the distribution cover all plausible values of the input variable that could be representative of the large volume of material represented by the PA Model cell over long periods of time?"
- Parameter values and parameter statistical distributions for the hydraulic properties of the cover layers were developed based on site-specific data, engineering specifications, widely used soil hydraulic property databases, and consideration of the function of the layer.
- Estimates of the uncertainty in the hydraulic function α and n values of Unit 4 materials used for the surface and evaporative zone layers of the ET cover were obtained by using α and n values from distributions (mean and standard deviation) for each parameter from the Rosetta database of hydraulic parameters for the textural class of silty clay.
- The radon barrier saturated hydraulic conductivity distribution was based on 1st, 50th, and 99th target percentiles elicited from Benson et al. (2011) to capture plausible values for in-service (degraded) barriers that could apply to the entire cover described by the distribution. To manage computational burden, deterministic values for θ_r, θ_s, α, and *n* from previous site-specific modeling were used for the radon barriers.
- Distributions were developed using the open-source statistical software package R (R Core Team 2017), which functions to facilitate fitting of distributions to target quantiles, or percentiles.
- The net infiltration through the clay liner in the flow model is identical to the value of the net infiltration at the bottom of the radon barriers. This value is drawn from the net infiltration distribution which is based on measurements of in-service barriers from Benson et al (2011). Thus, the modeling approach does take into account clay liner degradation.

Model Abstraction—Development of Simplified Models for GoldSim

- The goal of "model abstraction" in the context of PA modeling is to build a relatively simple statistical model to approximate the relationship between the input parameters and an output of interest obtained from a sophisticated, and usually computationally intensive, process-based model. Using the flow modeling as an example, the goal of the statistical effort is to build a statistical model to capture the main structure in the relationship between input parameters and results produced by HYDRUS (needed as an input to the GoldSim model). The statistical model is then used to predict HYDRUS-like outputs within GoldSim.
- Fifty HYDRUS-1D flow simulations were conducted to evaluate the uncertainty in net infiltration into the waste zone and water content within each ET cover layer as a function of hydraulic property uncertainty. Model input parameter distributions and HYDRUS flow model results were fit with multiple linear regression models to develop simplified models for the GoldSim PA model.
- Comparisons showed consistency between α and n inputs to the HYDRUS model and α and n generated from the distributions for these parameters used in the GoldSim model. Similarly, the net infiltration values from the HYDRUS realizations were consistent with values generated using the regression equation in the GoldSim model.
- A linear regression model was chosen to represent net infiltration for implementation in the DU PA Model because it was simpler and matched the model form also used for water content across layers.
- The saturated hydraulic conductivity, K_s, was not included in the regression equation for net infiltration because it was found not to be a predictor (that is not close to statistical significance).
- Contrary to the opinion of UDEQ, there is not evidence of a strong linear relationship between α and K_s that should be incorporated into PA distributions, particularly for the Unit 4 soil within the silty clay soil textural class found at the Clive Site. These parameters are demonstrated to be statistically independent, implying they are theoretically uncorrelated and distributions can be developed separately for each parameter.

Other Issues

- The hydraulic property values and statistical distributions assigned to the Evaporative Zone and the Frost Protection Layers are reasonable estimates based on site-specific information and commonly used soils databases. Given these property assignments, the Frost Protection Layer behaves hydraulically by enhancing storage in the Evaporative Zone in a realistic manner, not as described by UDEQ as "an extremely potent artificial, non-realistic capillary barrier."
- Steady-state annual averages of net infiltration and water content from the HYDRUS simulations are the model results used to develop statistical distributions of these

parameters for inputs to the GoldSim model for the Clive DU PA. Daily water balance is not the appropriate scale to evaluate a performance assessment model.

- Common, accepted methods were used for developing atmospheric boundary conditions for the HYDRUS flow model.
- Given the much greater capacity of the clay liner to allow water to flow through it in comparison to the 99th percentile of net infiltration rates, the bathtub effect is not possible.

4.0 References

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Erosion Responses for the Clive DU PA Model

23 February 2018

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ACRONYMS AND ABBREVIATIONS

CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CWCB	Colorado Water Conservation Board
DEQ	(Utah) Department of Environmental Quality
DOE	(United States) Department of Energy
DU	depleted uranium
DWMRC	Division of Waste Management and Radiation Control
ecdf	empirical cumulative distribution function
EPA	(United States) Environmental Protection Agency
ET	evapotranspiration
HAL	Hansen, Allen, and Luce
HMR	Hydrometeorological Report
LEM	landscape evolution model
LLRW	low-level radioactive waste
MPV	maximum possible velocity
NOAA	National Oceanographic and Atmospheric Administration
NRC	(United States) Nuclear Regulatory Commission
NRCS	Natural Resources Conservation Service
PA	performance assessment
PDF	probability density function
PMP	probable maximum precipitation
PPA	probabilistic performance assessment
PSB	Prototype Surface Barrier
RCRA	Resource Conservation and Recovery Act
RHEM	Rangeland Hydrology and Erosion Model
RML	Radioactive Material License
RUSLE	Revised Universal Soil Loss Equation
sd	standard deviation
SER	Safety Evaluation Report
SWCA	SWCA Environmental Consultants
SWCC	soil water characteristic curve
UDEQ	Utah Department of Environmental Quality
UMTRCA	Uranium Mill Tailings Radiation Control Act
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation

This document addresses Category 2, Erosion of the DU PA Version 1.4 Interrogatories (Utah DEQ 2017). There are two open interrogatories and seven new interrogatories within this category. Background information on the statistical approaches applied for the probabilistic PA model is provided in Section 1.1 of NAC_0108, *ET Cover Design*. Section 1.2 of that document also provides a summary of the cell design, climate, and vegetation.

1.0 Overview and Conceptual Model

There are three water erosion processes considered for the Site: sheet erosion, rill erosion, and gully erosion (channel formation). Sheet erosion is the detachment of soil particles by water flowing overland as a sheet. During rainfall events when rainfall exceeds infiltration, runoff can occur, acting to erode cover materials. Sheet erosion is a process that extends over the entire area of the cover. If flow concentrates on the surface, shallow channels called rills can also be formed. Gully erosion is a process that occurs when flowing water forms larger narrow channels. Gully erosion typically results in a gully that has an approximate "V" cross section that widens and deepens with time until the gully stabilizes. The rate of erosion loss from all of these processes depends on the steepness and length of the slope, soil texture, vegetation, and cover surface characteristics, as well as rainfall intensity.

The stability of the cover with respect to erosion is evaluated for the Clive DU PA using several modeling approaches. The Universal Soil Loss Equation (USLE) (USDA 1978) is used for estimating losses due to sheet and rill erosion, and the permissible velocity method described in NUREG-1623 (NRC 2002) is used for evaluating the potential for gully erosion. The USLE provides estimates of long-term annual soil loss produced by rain drop impact and runoff. This method is recommended by the EPA for evaluation of cover stability (EPA 1991) and is a standard used across the United States. The NRC has recommended several methods for evaluating the potential for gully erosion on soil covers for waste embankments (NRC 2002).

Modeling of sheet and rill erosion losses from the cover was done with USLE. The USLE uses a conceptual model to evaluate stability that is described by Israelsen et al. (1984) as "if adequate protection is provided to control sheet erosion, then rills and gullies will never form from rainfall." The USLE procedure is based on the Universal Soil Loss Equation—a combination of parameters representing rainfall intensity, soil erodibility, slope length, slope steepness, cover and management factors, and conservation practices. Values for the parameters are obtained from tables and charts (or the computer program) applicable to the location, site-specific materials, and cover design.

The annual erosion loss rates estimated by USLE for the cover were corroborated using the Rangeland Hydrology Erosion Model (RHEM) (Nearing et al. 2011). RHEM is a process-based runoff and erosion model developed specifically for rangeland applications.

The evaluation of design elements for long-term cover stability by the NRC (NRC 2002) is based on the conceptual model that gully erosion differs from other design considerations in that the development of gullies and the process of erosion are cumulative and can progress with subsequent storm events. The method adopted by the NRC to provide long-term stability is to design stable slopes that prevent the initiation of gullies by a single, very large storm event. By

designing to an unusually large single event, smaller more frequent events will have no significant cumulative impact on stability.

NUREG-1623 (NRC 2002) details methods, guidelines, and procedures for designing erosion protection for earthen covers at uranium mill tailings sites that apply to the Federal Cell at the Clive Site. The stability of a design is evaluated by comparing the velocity of flow from an extreme precipitation event on the embankment slopes to the maximum flow a channel can carry without causing gullies. Site-specific information used to calculate the velocity on the embankment includes the probable maximum precipitation intensity, catchment area, slope, and a roughness coefficient.

Modeling of erosion in a borrow pit at the Site provided a line of evidence in addition to the erosion modeling using USLE and the NRC gully projection method (NRC 2002) that demonstrates the stability of the proposed ET cover design. Although the borrow pit is an approximation to the embankment, this analysis using the landscape evolution model SIBERIA provides insight into erosion projected out to 10,000 years.

2.0 UDEQ Interrogatory Responses

This section contains responses for Open Interrogatories CR R313-25-8(4)(a)-71/1 and CR R313-25-7(2)-191/3, as well as New Interrogatories CR R313-25-25(4)-197/1, CR R313-25-25(4)-198/1, CR R313-25-25(4)-199/1, CR R313-25-25(4)-200/1, CR R313-25-25(4)-201/1, CR R313-25-25(4)-202/1, and CR R313-25-25(4)-205/1.

2.1 Interrogatory CR R313-25-8(4)(a)-71/1: Biotic Processes in Gully Formation

DEQ Conclusion from April 2015 SER, Appendix C:

…the DU PA SER, Section 4.4.2 concluded the following:

> *Before the DU PA can be determined to be adequate,* Energy*Solutions needs to clarify certain issues relating to Appendix 10 to the DU PA Model v1.2 (…)... DRC is currently reviewing a license amendment request*[5] *to use an ET cover of similar design to that proposed for the Federal Cell in the DU PA. Any recommendations and conclusions from that review must be applied to the proposed Federal Cell as well.*

Therefore, this interrogatory remains open.

DEQ Critique of DU PA v1.4, Appendix 5, Appendix 21: No further analysis has been performed pertaining to biotic processes in gully formation since v1.2.

2.1.1 Interrogatory Response

This interrogatory points to soil erosion issues raised in Section 4.4.2 of the Safety Evaluation Report (SC&A 2015a). UDEQ expresses concerns that gullies will form and enhance radon diffusion, deep infiltration, and contaminant transport. Energy*Solutions* plans both ecological and engineering measures to address these concerns by minimizing gully formation.

Note that this interrogatory also attempts to link two distinct cell design reviews. Since issuance of the 2015 SER, Energy*Solutions* has begun construction of rock armor cover on the CAW cell. More importantly, the DU PA models the Federal Cell's ET cover as designed. CAW cover licensing is separate and distinct from the Federal Cell. Since their geometry differs, any attempt to couple or join the reviews is unsupported and arbitrary. Therefore, this aspect of the question is moot.

Ecological Measures

SWCA Environmental Consultants (SWCA) assessed erosion under undisturbed conditions at Clive in June 2012 (SWCA 2012). Eight study plots and one soil borrow area were identified and the location of wind and water erosion features were mapped. Each study plot was 0.25 ac (1000 m^2) with three plots located on hills. All plots were within the elevational range of the Clive Site.

SWCA observed that the effects of wind and water erosion were limited. There was minimal evidence found of water erosion even on the sloped study plots. This is consistent with the Hansen, Allen, & Luce (HAL) calculations of projected minimal sheet and rill erosion loss described in the response to UDEQ Interrogatory 191/3. The site-specific SWCA studies indicated that a cover would remain stable with the established native vegetation and biological soil crust mimicking undisturbed conditions.

SWCA has developed a sequence of reclamation measures for quickly re-establishing natural conditions for the cover that will minimize erosion (SWCA 2013). During the first two years the cover will be stabilized by seeding with fast-growing species. Establishment of these species will also exclude invasive annuals. The planned seed mix includes native perennial shrubs, forbs, and bunchgrasses that will become established during years three through five. The soil surface will be treated with local biological soil crust to speed up crust recovery during these years. Biological soil crusts are known to reduce wind and water erosion (Belnap and Gillette 1998; Belnap et al. 2001). The upper Unit 4 soil layer of the cover will be mixed with 15 percent gravel and the side slopes with 50 percent gravel as additional measures to prevent erosion. Observations at a number of other sites have shown that a gravel admixture reduces erosion and promotes evapotranspiration (SWCA 2013). SWCA (2013) concludes:

> The proposed ET cover designs and associated installation procedures comply with UAC R313-25-8(4)(a) and (b); UAC R313-25-18; UAC R313-25-19; UAC R313-25-20; UAC R313-25-8(4)(d); and UACR313-25-22 by establishing a stable and functioning system comprised of native vegetation and soil biota that minimizes any near-term episodic erosional exposure of contaminated materials. A functioning native ecosystem also provides long-term soil stabilization via soil development, plant roots in upper soil layers, and biological soil crusts.

Engineering Measures

Calculations to evaluate the stability of the cover design with respect to rill and gully erosion for the Class A West cell were provided in Appendix D of Energy*Solutions* (2015). Similar calculations for gully erosion potential for the Federal Cell are presented here.

Methods for evaluating the design basis for erosion of soil covers for waste embankments are given in NUREG-1623 (NRC 2002). This report details methods, guidelines, and procedures for designing erosion protection for earthen covers at uranium mill tailings sites that apply to the Federal Cell at the Clive Site.

The evaluation of design elements for long-term cover stability is based on the view taken by NRC (2002) that gully erosion differs from other design considerations in that the development of gullies and the process of erosion are cumulative and can progress with subsequent storm events. The method adopted by the NRC to provide long-term stability is to design stable slopes that prevent the initiation of gullies by a single, very large storm event. By designing to an unusually large single event, smaller more frequent events will have no significant cumulative impact on stability.

The potential for gully erosion on the Federal Cell was evaluated using the permissible velocity method described in NUREG-1623 (NRC 2002).

Slope Description

The Federal Cell is designed as a covered embankment with relatively steeper sloping sides nearer the edges. The upper part of the embankment referred to as the top slope has a slope of 2.4 percent, while the side slope is steeper with a slope of 20 percent. The length of the side slope is 175 ft. Top slopes of the embankment have different lengths. The longest top slope length is 521 ft.

Flow Concentration

The peak flow unit discharge, Q (cubic feet per second per foot [cfs/ft]), is calculated using the Rational Formula (NRC 2002):

$$Q = F \times c \times i \times A$$

where

- F is flow concentration factor,
- c is dimensionless runoff coefficient,
- i is rainfall intensity (inches/hour [in/hr]), and
- A is catchment area (acres).

A default value of 3 is recommended in NRC (2002) for the flow concentration factor, F. A value for the runoff coefficient of 0.5 is recommended for a graveled surface in Table 4.6 of NUREG 4620 (NRC 1986). The rainfall intensity used for the projection is 18.4 inches for the top slope and 19.8 inches for the side slope at the Clive Site. See the response to UDEQ Interrogatory 201 for a description of the calculation of these values. The catchment area is the area of a 1-ft wide strip along the length of the slope. Using these values, the peak flow unit discharge, Q, for the top slope and side slope are found to be 0.328 and 0.122 cfs/ft respectively.

Flow Depth

The flow depth, y, is then calculated using the Manning equation for normal depth on a one-foot-wide strip of the slope. This equation is given by NRC (2002) as

$$y^{5/3} = {Qn}\Big/{\left(1.486\, S^{1/2}\right)}$$

where

y	is flow depth (ft),
n	is Manning n, and
S	is slope (ft/ft).

A value of 0.05 is used for the Manning's n based on the calculation method of Bray for natural channels described in Coon (1998).

Using the previously calculated values for Q and the Manning's n, flow depths were calculated to be 0.205 ft for the top slope and 0.060 ft for the side slope.

Maximum Permissible Velocity

A value of 5.0 ft/s was chosen as the maximum permissible velocity (MPV) based on the characteristics of the channel. This is the value listed for gravel in Table CH13-T103 of Colorado Water Conservation Board (CWCB 2006) and in Table 4.7 of Nelson et al. (1986). The NRC (2002) method requires that the MPV be adjusted to account for the flow depth. Correction factors developed by Chow are provided in Appendix A of NRC (2002). The correction factor for flows less than 0.25 ft in depth is 0.5. The adjusted MPV values for both the top slope and the side slope are adjusted to 2.5 ft/s.

Actual Flow Velocity

The actual flow velocity is determined by dividing the discharge by the flow depth:

$$V_a = {Q}/{y}$$

Using this equation, the top slope and side slope velocities are 1.60 ft/s and 2.03 ft/s.

These velocities for the top slope and side slope do not exceed the adjusted MPV, so the design is acceptable (see Table 1). Both slope scenarios using the ET cover system provide acceptable protection against gully erosion using these criteria by limiting the potential of gully formation from high velocity channelization.

Table 1. Gully erosion potential—permissible velocity analysis for Federal Cell.

Slope Description	Length (ft)	Slope (ft/ft)	i (in/hr)	c	Q (cfs/ft)	y (ft)	V_a (ft/s)	MPV (ft/s)	Reduction Factor	Adjusted MPV (ft/s)
Top Slope	521	0.024	18.3	0.5	0.328	0.205	1.60	5.0	0.5	2.5
Side Slope	178.5	0.20	19.8	0.5	0.122	0.060	2.03	5.0	0.5	2.5

Borrow Pit Model

Modeling of gully formation in a borrow pit at the Site provides another line of evidence in addition to the sheet erosion modeling using USLE and the NRC gully projection modeling using the permissible velocity method (NRC 2002) that demonstrate the stability of the proposed ET cover design. (See the response to UDEQ Interrogatory 191/3.) Although the borrow pit is an approximation to the embankment, the intent of this analysis is to provide insight into erosion projected out to 10,000 years.

The SER (SC&A 2015a) states in Section 4.4.2 that results from the borrow pit modeling described in Appendix 10 of Neptune (2014) indicate that at 10,000 years about 1 percent of the surface will have gullies greater than or equal to 1 meter and suggest that, if this is the correct interpretation of the results, the influence of gully formation on radon release and infiltration should be minimal. Appendix 10 of the DU PA Model v1.2 presented a sampling of the results of the 1,000 simulations, while the results from all 1,000 simulations were provided in Appendix 10 of the DU PA Model v1.4 (Neptune 2015a).

See the response to UDEQ Interrogatory 199 regarding issues raised in Section 4.4.2 of the SER on the comparability of geometry and materials of the borrow pit and the embankment.

Section 4.4.2 of the SER noted that the description of how the results of the borrow pit erosion modeling were used in the DU PA Goldsim Model needed clarification. A detailed description of the analysis of erosion modeling results and their implementation in the GoldSim model was included in Appendix 10 of the DU PA Model v1.4 (Neptune 2015b).

Lack of evidence of significant erosion activity at the Site, planned ecological remediation of the soils used to construct the cover, and erosion models that demonstrate the stability of the cover support the prediction that erosion of the embankment will be minimal and will not enhance radon fluxes or deep infiltration.

2.2 Interrogatory CR R313-25-7(2)-191/3: Effect of Gully Erosion

DEQ Conclusion from April 2015 SER, Appendix C:

In conclusion, the analysis performed by HAL may or may not be correct, but before DEQ can accept it, each value selected and used in the analysis needs to be justified. Energy*Solutions*/HAL also needs to address how the embankment will be re-vegetated, how much re-vegetation is necessary and how much is expected, and how long is it expected to take. Therefore, this interrogatory remains open.

DEQ Critique of DU PA v1.4 and Appendix 21:

Gravel Surface

Gravel embedded in the upper layer may migrate upward over time due to environmental effects, such as freeze/thaw or wet/dry cycling phenomena, bringing some particles to the surface. At the same time, eolian erosion and deposition is likely to occur on the cover, potentially "silting in" gravel particles that move to the surface. Formation of a "gravel mulch" layer (i.e., a clean coarse layer of gravel at the surface) that would impede evaporation is unlikely. A more likely phenomenon is formation of a desert pavement, with finer sands, silts, and clay particles embedding around gravel particles. These finer materials provide a capillary conduit for evaporation.

This phenomenon is observed at sites where riprap or cobbles are used as cover. Fines deposit in the pores between the large particles, gradually accumulating and filling the pores. These fines serve as a seed bed and as a capillary conduit, allowing water to flow upward. This was very clear in the armored surfaces at both Uranium Mill Tailings Radiation Control Act (UMTRCA) covers studied in 2016 for the NRC and DOE-LM. An example from the Uranium Mill Tailings Reclamation site in Grants, New Mexico, is shown in Figure 191-1 below. Roots and structure in the radon barrier are being mapped as shown in Figure 191-1(a) and brush growing in an adjacent area of the riprap surface layer is shown in Figure 191-1(b).

The best approach to understand this issue, and to develop a suitable conceptual model for Clive, is to seek out analogs in the area where undisturbed fluvial surficial soils exist with appreciable gravel. Studying the surface of these soils will provide evidence regarding the long-term surface characteristics that can be anticipated at Clive.

Gravel Fraction to Address Erosion

The appropriate gravel fraction necessary to prevent erosion has not been defined with precision, nor has a validated methodology been developed to determine the appropriate gravel fraction as a function of site-specific conditions. Models have been developed, but they have not been validated in the field. For example, Smith and Benson (2016) used the model SIBERIA to evaluate erosion from a top deck with a gravel amendment, but the model was not validated in the field.

The gravel admixtures used at Hanford and Monticello have been effective in controlling erosion. No major erosion issues have been encountered at either site on the shallow top decks. Riprap is used on the steeper side slopes on both sites. There have been no quantitative field studies to evaluate the reduction in erosion achieved with the gravel admixture on the top deck at either site.

Gravel Fraction to Control or Prevent Biointrusion

There should be no expectation that 15% gravel, or even 50% gravel, will preclude biointrusion. As noted previously, plants readily germinate and root in riprap layers when silt accumulates in the pores (Figure 191-1). Vegetation is likely to be more robust in a gravel-amended surface layer with smaller particles and more fine-textured particles.

Burrowing animals will readily penetrate a layer containing gravel particles, and plants will readily grow in a fine-textured layer with as much as 50% gravel. Biointrusion design to prevent burrowing requires particles larger than the breadth of the animal (precludes particles from being moved through a burrow), and a gradation that results in pore sizes smaller than the breadth of the animal (prevents burrowing between particles).

Homogenization

Pedogenic phenomena are known to create structure and alter the hydraulic properties of earthen cover materials. There is no evidence in the literature that layering in covers diminishes with time or that a homogeneous profile develops. For example, distinct layering has been observed in recent excavations into UMTRCA covers that are 20 years old (Figure 191-2). Structure has developed in these layers, and the hydraulic properties have changed, but the profile is not homogeneous. A model for Clive should include a layered profile with appropriate hydraulic properties assigned to each layer that reflect realistic development of structure.

2.2.1 Interrogatory Response

UDEQ raises a number of issues in this interrogatory, beginning with design for slope stability.

Erosion Analyses

The first request from UDEQ is to provide the rationale for selection of the Revised Universal Soil Loss Equation (USLE) (USDA 1978) and the Rangeland Hydrology and Erosion Model (RHEM) (Nearing et al. 2011) parameters used for erosion modeling. A detailed response to this request was developed by Hansen, Allen, and Luce (HAL 2018). A summary of their final report is provided here. The complete report is provided in Appendix A.

Universal Soil Loss Equation (USLE) Parameters

The USLE estimates average annual soil losses from erosion. While the USLE equations are the same as the Revised Universal Soil Loss Equations (RUSLE), the use of the acronym RUSLE could imply the use of the software program developed by the USDA for factor determination. In order to clarify the methodology used in the analysis, all references are to USLE. The software package was not used because factors from a Utah-specific publication were available for the analysis as described below.

The USLE methodology is commonly used to determine the long-term stability of slopes and is an industry-standard method for design of erosion control. Guidance given by the EPA states that "The U.S. Department of Agriculture's (USDA's) Universal Soil Loss Equation is recommended as the tool to evaluate erosion potential" (EPA 1991). The basis for this approach is that "if adequate protection is provided to control sheet erosion, then rills and gullies will never form from rainfall" (Israelsen et al. 1984). The USLE equation is defined as:

$$A = R*K*LS*C*P$$

where

- A is the average soil loss per unit area, expressed in tons/acre/year,
- R is the rainfall/runoff factor, which is the number of rainfall units for rainfall energy and runoff and snowmelt,
- K is the soil erodibility factor in tons per acre per year per unit of R,
- LS is the topographic factor (length and steepness of the slope),
- C is the cover and management factor, which is the ratio of soil loss from an area with a given cover and management relative to that from an identical area in continuous fallow, and
- P is the supporting conservation practice factor, in this case assumed to be equal to 1.

This procedure and site-specific factors are described in "Erosion and Sedimentation in Utah—A Guide for Control" (Israelsen et al. 1984) and "Design Hydrology and Sedimentation for Small Catchments" (Haan et al. 1994).

R Factor

The R factor (6) is selected based on the Utah-specific Iso-Erodent (R) mapping provided in the Utah Water Research Laboratory report (Israelsen et al. 1984) which is provided in Figure 1.

K Soil Erodibility Factor

The K values (0.18 and 0.07 for top slope and side slope, respectively) are based on the Unit 4-specific material characteristics with the top slope gravel admixture and characteristics for the side slope gravel admixture, together with the Wischmeier nomograph as described in the methodology presented in the Israelsen and Hann procedures and shown in Figure 2. A particle size analysis using the hydrometer method was performed on the Unit 4 clay to determine the percent silt and very fine sand (see Figure 2) for use with the Wischmeier nomograph.

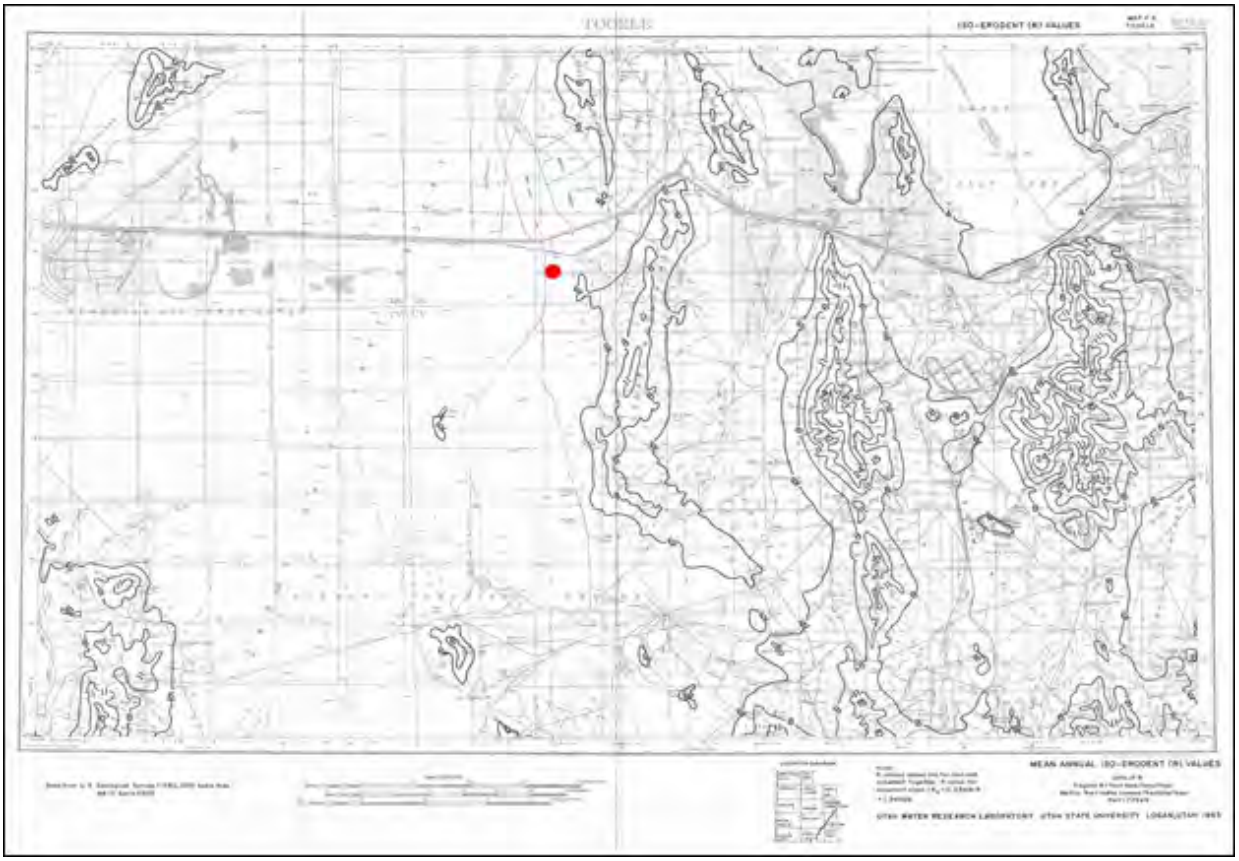

Figure 1. Utah-specific Iso-Erodent (R) mapping provided in the Utah Water Research Laboratory report (Israelsen et al. 1984).

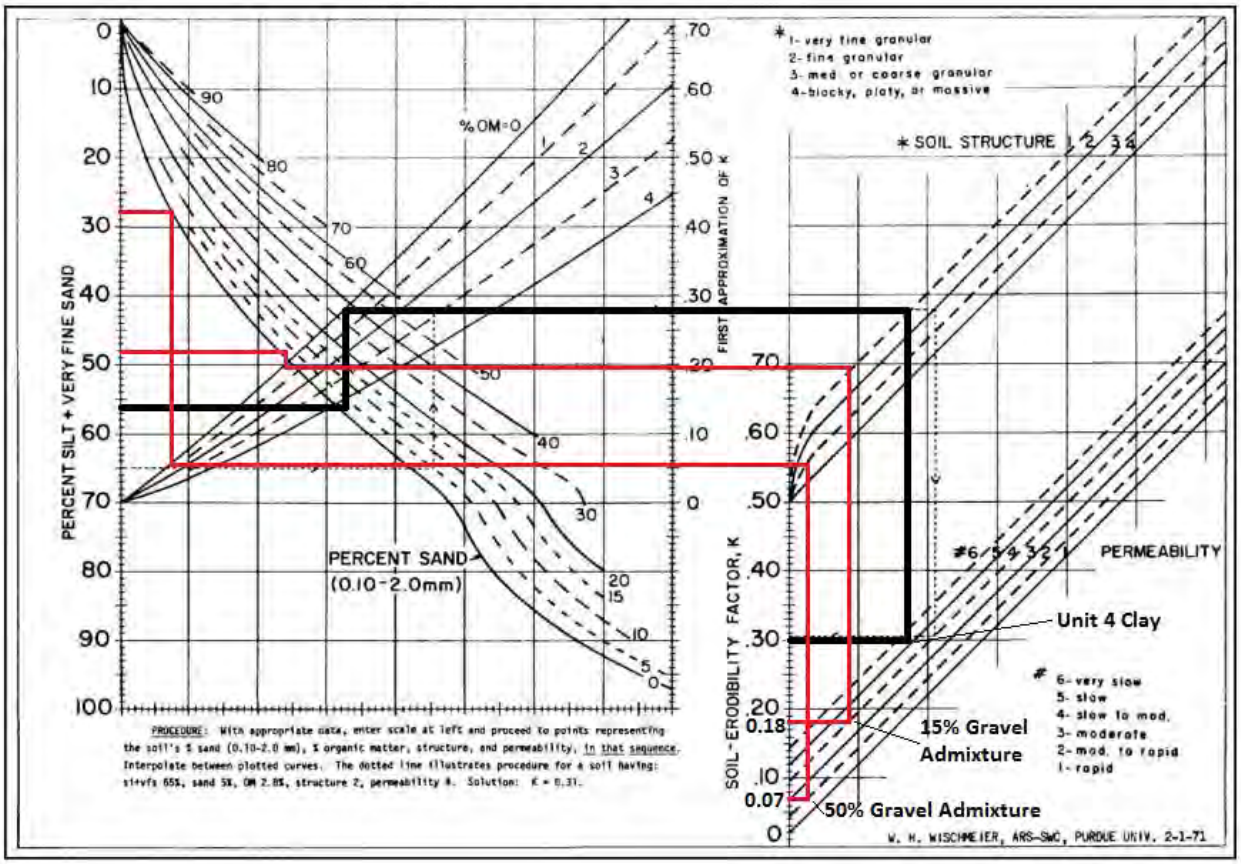

Figure 2. Wischmeier nomograph (Haan et al. 1994; Israelsen et al. 1984).

C Factor (VM Factor)

The C parameters used in the equation for both the 4% and 20% slopes were based on Table 9 and Table 10 of the US Department of Agriculture Handbook Number 537, "Predicting Rainfall Erosion Losses, A Guide to Conservation Planning" (USDA 1978), and are shown in Figure 3. The C factor for the top slopes (0.2) is based on the sparse vegetative cover naturally found in the areas immediately surrounding the Clive facility (Table 10 of Handbook Number 537, No Appreciable Canopy, Type G with 20% ground cover) and the Unit 4 gravel admixture. The C factor for the side slope is based on the higher percentage of gravel in the Unit 4 gravel admixture (50% gravel). The 50% gravel admixture on the side slopes results in a pseudo-gravel mulch once some of the fines have been removed. Therefore, a C factor of 0.02 was selected (Table 9 Handbook Number 537, Crushed Stone ¼ to 1½ in, Mulch Rate of 240 tons/acre, Land Slope of 21–33%, with a length limit of 200 feet).

Results

Soil loss calculated using these parameters in the USLE equation for the top slope and side slope are shown in Table 2.

TABLE 9.—*Mulch factors and length limits for construction slopes*[1]

Type of mulch	Mulch Rate	Land Slope	Factor C	Length limit[2]
	Tons per acre	*Percent*		*Feet*
None	0	all	1.0	—
Straw or hay,	1.0	1-5	0.20	200
tied down by	1.0	6-10	.20	100
anchoring and				
tacking	1.5	1-5	.12	300
equipment[3]	1.5	6-10	.12	150
Do.	2.0	1-5	.06	400
	2.0	6-10	.06	200
	2.0	11-15	.07	150
	2.0	16-20	.11	100
	2.0	21-25	.14	75
	2.0	26-33	.17	50
	2.0	34-50	.20	35
Crushed stone,	135	<16	.05	200
¼ to 1½ in	135	16-20	.05	150
	135	21-33	.05	100
	135	34-50	.05	75
Do.	240	<21	.02	300
	240	21-33	.02	200
	240	34-50	.02	150
Wood chips	7	<16	.08	75
	7	16-20	.08	50
Do.	12	<16	.05	150
	12	16-20	.05	100
	12	21-33	.05	75
Do.	25	<16	.02	200
	25	16-20	.02	150
	25	21-33	.02	100
	25	34-50	.02	75

TABLE 10.—*Factor* **C** *for permanent pasture, range, and idle land*[1]

Vegetative canopy		Cover that contacts the soil surface						
			Percent ground cover					
Type and height[2]	Percent cover[3]	Type[4]	0	20	40	60	80	95+
No appreciable		G	0.45	0.20	0.10	0.042	0.013	0.003
canopy		W	.45	.24	.15	.091	.043	.011
Tall weeds or	25	G	.36	.17	.09	.038	.013	.003
short brush		W	.36	.20	.13	.083	.041	.011
with average								
drop fall height	50	G	.26	.13	.07	.035	.012	.003
of 20 in		W	.26	.16	.11	.076	.039	.011
	75	G	.17	.10	.06	.032	.011	.003
		W	.17	.12	.09	.068	.038	.011
Appreciable brush	25	G	.40	.18	.09	.040	.013	.003
or bushes, with		W	.40	.22	.14	.087	.042	.011
average drop fall								
height of 6½ ft	50	G	.34	.16	.08	.038	.012	.003
		W	.34	.19	.13	.082	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.078	.040	.011
Trees, but no	25	G	.42	.19	.10	.041	.013	.003
appreciable low		W	.42	.23	.14	.089	.042	.011
brush. Average								
drop fall height	50	G	.39	.18	.09	.040	.013	.003
of 13 ft		W	.39	.21	.14	.087	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.084	.041	.011

Figure 3. Table 9 and Table 10 of the US Department of Agriculture Handbook Number 537, "Predicting Rainfall Erosion Losses, A Guide to Conservation Planning" (USDA 1978).

Table 2. Effects of erosion—average soil loss analysis using USLE. Soil loss is calculated for the top slope with Unit 4 clay with 15% gravel admixture and side slope with Unit 4 clay and 50% gravel admixture.

Slope Segment	R (ft tons/ ac/hr)	K (tons/ac/EI)	L (ft)	S (%)	C	A (tons/ac/yr)		Total Soil Loss (mm/year)
Top Slope (4%)	6	0.18	942 (4%)	4%	0.2	0.25	0.24 overall	0.026
Side Slope (20%)	6	0.07	188 (20%)	20%	0.02	0.19		

The Rangeland Hydrology and Erosion Model (RHEM) Model Parameters

The RHEM model was used in HAL's interrogatory response entitled "DRC RFI Section 4.0 Erosion" completed in 2013 to corroborate the results of the USLE analysis (Appendix D of Energy*Solutions* (2013)). This comparison showed a total loss from the embankment of 0.026 mm/yr from the USLE analysis and 0.016 mm/yr from the RHEM analysis. Since 2013, the RHEM on-line model has been updated. The latest version of the model (Version 2.3) lacks some of the functionality of the earlier model.

Specifically, slope lengths cannot be directly input as they were previously, so a direct comparison with the calculation using USLE is not possible. This appears to be due to an error within the program since the descriptions of the model available on the website include slope length as an input parameter option. Attempts to reach the contacts listed for the RHEM model in order to resolve the issue were unsuccessful. The model defaults to a slope length of 50 meters (164 feet).

Additional parameter options for cover characteristics appear to have been added since 2013, including options for a distinction between foliar cover and basal plant cover as well as rock cover, litter cover, and biological soil crust cover. Since the tool is a web-based model and not stand-alone software, the version of the online tool used in the 2013 analysis is no longer available. The parameters described in the 2013 interrogatory for vegetative conditions, slope grades, climate station, soil texture class, and slope lengths are still valid for the analysis completed at the time but the results reported therein can no longer be validated.

Gravel Surface

Next UDEQ discusses the use of local analogs to study soils with gravel surfaces. There are no questions or requests raised.

Gravel Fraction to Address Erosion

Then UDEQ goes on to argue that the appropriate gravel fraction necessary to prevent erosion has not been defined with precision. Further, a validated methodology has not been developed to determine this. Refer to the response to UDEQ Interrogatory 198/1 for further discussion.

Gravel Fraction to Control or Prevent Biointrusion

The next issue raised is a statement by UDEQ that gravel will not prevent biointrusion. This observation is accurate but not relevant, as gravel used in the cover design is not assumed or intended to inhibit biointrusion. In fact, as described in the revegetation plan developed by SWCA (2013), one function of gravel mulch over the soil surface is to increase moisture retention and seed establishment.

The proposed cover design uses the frost protection zone to provide the function of a biointrusion barrier. This layer is described by SWCA (2013) as "18 inches (46 cm) of 10–16 inches (25–41 cm) gravel and cobble mixture in-filled with small gravel, sand, and other fines (cobble and gravel to 16 inches [40.6 cm] diameter)." Please see the response to UDEQ Interrogatory 05/2 for discussion of evaluation of the extent of expected biointrusion at the Site.

Homogenization

The last issue of this interrogatory raised by UDEQ is that the hydraulic parameter distributions and correlations used for modeling of flow in the cover system based on the recommendations of Benson et al. (2011) were not implemented in the way that was intended by UDEQ.

Contrary to UDEQ's claim in this alternative modeling of net infiltration and water content of the cover layers requested by UDEQ, Energy*Solutions* did in fact use the recommendations from Section 10.2 "Parameters for Performance Assessments" in Benson et al. (2011), cited as the source of recommendations in Appendix E of the SER (SC&A 2015b). These recommendations for hydraulic parameters are:

- The saturated hydraulic conductivity of fine-textured earthen storage and barrier layers can be assumed to range between 1×10^7 m/s and 5×10^6 m/s.
- The porosity of earthen storage and barrier layers will likely range between 0.35 and 0.45.
- The α-parameter in the van Genuchten equation, which is used to describe the soil water characteristic curve (SWCC) for hydrologic simulations, varies between 0.01 and 0.33 kPa^{-1} for field-scale barrier and storage layers.
- The n-parameter in van Genuchten's equation, which is used to describe the SWCC for hydrologic simulations, varies over a very small range (typically between 1.2 to 1.4).

Except for the n-parameter, where UDEQ provides no reference as to which layer the recommendation refers, parameter value recommendations for all other parameters are applied to both barrier and storage layers without distinction. For the proposed Federal Cell cover design, the layers of the evapotranspiration (ET) cover are all either storage or barrier layers; however, UDEQ's recommended method makes no differentiation between the layers with respect to hydraulic parameters. The only distinguishing characteristics between depth zones of a variably saturated flow model are the values of the hydraulic parameters. If a saturated hydraulic conductivity value, for example, is drawn from a statistical distribution developed according to the method of Benson et al. (2011), then that value will be assigned according to that method to all cover layers in the model. Thus, the flow model of the cover will be homogeneous with respect to hydraulic conductivity. UDEQ objects to this homogeneity in hydraulic properties in this interrogatory, but that is the only viable outcome possible when applying the Benson et al. (2011) method to the ET cover.

2.3 Interrogatory CR R313-25-25(4)-197/1: Properties of Embankment Side Slope Materials

Interrogatory Statement:

Please explain and justify how, from an erosion perspective, the properties of Unit 4 material "are sufficiently similar" to the Federal Cell side slope, which consists of a mixture of Unit 4 soil with 50% gravel, to support this "sufficiently similar" modeling assumption. Also, please explain how the properties of Unit 4 material are sufficiently similar to Class A waste, which would be included over the DU waste. See also Interrogatory 203/1 below.

2.3.1 Interrogatory Response

In this interrogatory UDEQ preferentially extracts two from a number of assumptions provided in Appendix 10 of the Clive DU PA Model Final Report v1.4 (Neptune 2015a) as the basis for applying the results from modeling of a borrow pit face at the Site to the projection of erosion on the Federal Cell embankment. While there are differences in the characteristics of the borrow pit and the embankment, this analysis provides another line of evidence in addition to the more conventional modeling used to demonstrate the stability of the proposed ET cover design described below. Notably, the multiple lines of evidence provide good agreement that the proposed ET cover design will provide adequate erosion resistance.

Landscape evolution models such as SIBERIA are still in an early stage of scientific development. Accordingly, the methods for building confidence in model results that are commonly used in environmental modeling, such as rigorous calibration, sensitivity analyses, and uncertainty analyses, are difficult to apply. These models, however can be used in an exploratory context to gain insight into processes (Skinner et al. 2017) and to provide additional evidence to support the results of cover stability analyses using methods recommended by EPA and NRC. Calculations to evaluate the stability of the cover design with respect to gully erosion for the Class A West cell were provided in Appendix D of Energy*Solutions* (2015). Similar calculations for the Federal Cell are presented in the response to UDEQ Interrogatory 71/1.

2.4 Interrogatory CR R313-25-25(4)-198/1: Gravel Content of Embankment Materials

Interrogatory Statement:

Please provide the design bases and justification for the amount and sizing of the gravel in the top and side slopes of the Federal Cell. The proposal for the gravel admixture in the top slope (15%) appears too small. Also, please provide evidence for existing semi-arid or arid sites where only 15% gravel has been added to form a successful cover-system surface layer for a landfill.

Please describe actual analog sites where 50% gravel for side slopes has been demonstrated to be effective against erosion.

2.4.1 Interrogatory Response

A detailed response to this interrogatory was developed by Hansen, Allen, and Luce (HAL 2017a). A summary of their final report is provided here. The complete report is provided in Appendix B.

The design basis for the amount of gravel to add to the soil in the top and side slopes was first determined based on the analysis of the long-term sustainability of the slopes exposed to sheet erosion over time. The methods that were used are the Universal Soil Loss Equation (USLE) (USDA 1978) and the Rangeland Hydrology and Erosion Model (RHEM) (Nearing et al. 2011). These methods produce an estimate of the average annual soil loss in terms of tons per acre per year. With the gravel admixed into the Unit 4 clay soil, average annual soil losses were calculated to be about 0.24 tons/acre/year using USLE, which was also closely matched by the RHEM. This amount of loss is almost 10 times less than what has been recommended in EPA

guidance for covers for hazardous waste facilities. A more detailed discussion of the methodologies and results is provided in the response to UDEQ Interrogatory 191/3.

Once the slope was determined to be stable from an average soil loss perspective, checks on the gully erosion potential were completed based on the calculation of predicted velocities by comparing them to the maximum permissible velocity according to the method presented in NUREG-1623, "Design of Erosion Protection for Long-Term Stabilization" (NRC 2002). This second assessment based on an extreme intense rainfall event is recommended in NUREG-4620 (Nelson et al. 1986) because of the potential for significant damage to cover systems from such large events. In fact, this extreme intense rainfall event is known as the Probable Maximum Precipitation (PMP) and is so extreme that "the point precipitation data base, even if maximized for PMP moisture potential, shows no observed values even close to the 10-inch PMP estimate (the generalized, local storm PMP estimates in Utah)" (Jensen 1995). Additionally, the methodology applies a flow concentration factor (F) of three (NRC 2002). Therefore, the extreme event that is many times the highest ever recorded rainfall intensity in the area is also compounded by an additional safety factor of a multiplier of three. The end result of this process is an analysis that is meant to produce an extremely conservative value.

Flow velocities on the top and side slopes of the CAW embankment during the PMP event were predicted to be 2.37 and 2.07 ft/sec, respectively, as discussed in more detail in the response to UDEQ Interrogatory 191/3. The acceptable Maximum Permissible Velocity (MPV) was selected from tables provided in NUREG/CR-4620 (Nelson et al. 1986). Under this method the slope is stable if the calculated velocity (V, the velocity resulting from a PMP in this application) is less than the MPV. By contrast, if velocities exceed the MPV, the slope will experience excessive erosion that will lead to the formation of gullies. HAL found that the calculated velocities resulting from the PMP did not exceed the prescribed permissible velocity.

Reference Review

The methods discussed above have been published and/or accepted by the EPA (1989) and the US Nuclear Regulatory Commission (Nelson et al. 1986; NRC 2002). Other methods referred to in the interrogatory, on the other hand, have not been adopted, published, or referred to in guidance by federal agencies. While the works cited are part of productive ongoing academic research and study, they are not conclusive in their findings and should instead be the focus of additional research. A summary of each is provided below:

- "Gravel Admixtures for Erosion Protection in Semi-Arid Climates," *Erosion of Soils and Scour of Foundations* (Anderson and Stormont 2005). This paper was published as part of the proceedings of sessions of the Geo-Frontiers 2005 Congress held in Austin, Texas. Along with other conference proceedings articles, these early attempts to define a process for admixture design are helpful in that they outline practical steps to determine gravel size, gravel percentage, and admixture thickness. This approach, however, has limitations that result from the lack of empirical evidence to back up the steps and applications of many of the equations presented in the paper. The paper states that "the design method for gravel admixtures presented here may serve as an outline for further erosion investigations and provide guidance for future designs of gravel-soil admixture layers." Therefore, the paper was not meant to be used as a proven method for admixture design but rather as a starting point for further research and investigation.

- "Design of Erosion Protection at Landfill Areas with Slopes Less than 10%" (Anderson and Wall 2010a). Much of the background discussion of this paper is the same as Anderson and Stormont (2005). The methodology presented is similar to the steps provided in Anderson and Stormont (2005) with some changes. Again, the paper does not claim this to be a proven method but indicates the authors are taking steps to test its outcomes. Anderson and Wall (2010a) state "the procedure described here is being applied to a landfill cover soon to be constructed in southern Nevada. The Nevada project will provide the first large scale application of the procedure." HAL was unable to find information regarding empirical data on a smaller scale nor was final information on the results of the large scale Nevada project able to be found. Without this information or additional discussion in the paper, the limits of the equation and how the criteria for success or failure are defined remain unknown. For example, assuming the Nevada project site is shown to be successful with the 40% gravel admixture, there is nothing that would indicate if a lower percentage of gravel admixture, such as 25%, would also be adequate. Additionally, the suitability of the design and how success is defined is not sufficiently described in the paper to know whether the absence of observed gully erosion constitutes a successful design or if it is acceptable to have the formation of rills and gullies as long as the depth does not exceed the admixture layer thickness calculated using the method. This is an important distinction since the end result of the design process presented in the paper is the calculation of the thickness of the admixture layer which is presented as being dependent on the percentage of gravel in the admixture. This specific paper does not provide limits or conclusive guidance to the reliability of the method and therefore should serve as the starting point for further investigation and research.

- "Erosion Protection at Landfill Slopes Greater than 10%" (Anderson and Wall 2010b). This paper focuses on riprap on side slopes. The design proposed by Energy*Solutions* does not include riprap side slopes; therefore, this paper does not apply.

- "Long-Term Cover Design for Low-Level Radioactive and Hazardous Waste Sites as Applied to the Rocky Flats Environmental Technology Site Solar Evaporation Ponds" (Stenseng and Nixon 1995). The paper describing the design used at the Rocky Flats Environmental Technology Site was included as part of the proceedings from the 50th Industrial Waste Conference held in May 1995. The paper includes a brief description of the design basis for the 5% top slopes and 20% side slopes and the 40% gravel admixture. The admixture gravel content appears to have been selected instead of calculated as the result of a defined process. While instructive regarding the specific cover design discussed in the paper, no additional guidance is provided to guide application at other sites.

- "Ecology, Design and Long-Term Performance of Surface Barriers: Applications at a Uranium Mill Tailings Site" (Waugh and Richardson 1997). This paper is similar to the Stenseng and Nixon paper discussed previously in that it contains a summary of the design parameters but does not provide a specific and applicable methodology for the design of a soil gravel admixture with regard to erosion protection.

Sites with Top Slopes Comprised of 15% Gravel Admixture

There are some examples of sites that have employed slopes with 15% admixture and that give some measure of proof that a 15% admixture can be effective at controlling erosion. A test site was established at Hanford that is referred to as the Hanford Prototype Surface Barrier (PSB). The purpose of the PSB test site was to evaluate surface barrier constructability, construction costs, and physical and hydrologic performance at field scale (DOE 2016). This field-scale test cover was installed in 1994 and is comprised of a top erosion protection layer made up of a silt loam admixed with 15% pea gravel. The top slope of 2% in this case is slightly less than the top slopes of 2.5% and 4% proposed for the Federal Cell, but is an example of a cover system that relies on the same amount of gravel admixture. A review of the data collected at the site through 2015 (DOE 2016) concludes that:

> The 19-year PHB record showed practically no evidence of wind or water erosion of the ETC barrier, despite 3 years of triple the mean annual precipitation; three simulated 1000-year-return, 24-hour precipitation events; and an intense, controlled fire that burned off all vegetation across half the barrier surface….Even in the absence of vegetation (e.g., following a fire), the pea gravel added to the silt loam protected the barrier surface from wind and water erosion….Overall, the monitoring results have confirmed that the PHB design is resistant to water and wind erosion and that resistance is expected throughout the barrier's 1000-year design life.

Another test site using the same cover system was established at Hill Air Force Base in 1994, though little information has been published about that site to date.

Sites with Side Slopes Comprised of 50% Gravel Admixture

No sites were found that have used a gravel admixture on side slopes at or above 20%. Similarly, there were no methodologies found that specifically address the calculation of gravel admixtures for slopes greater than 10%, other than the general methods found in NUREG-1623 and NUREG/CR-4620 (Nelson et al. 1986; NRC 2002). For slopes over 9%, Simanton et al. (1984) found that the rate of water erosion decreases exponentially with increasing rock fragment cover. The effect of biological soil crust is also difficult to quantify. These crusts are expected to become established along the slopes as has been observed along natural slopes in the Clive area. The required lengthy post-closure care period provides the greatest opportunity for verification of the design methodology described previously by Simanton et al. (1984).

The design process completed to determine the acceptability of the 50% gravel admixture on the 20% side slopes is in accordance with EPA and Nuclear Regulatory Commission guidance. These guidance procedures contain no requirements that existing sites be used as evidence to support proposed designs. While it is acknowledged that such evidence would be helpful, each site is different and contains unique design constraints based on physical layout, climate, material availability, and project goals that make determinations based on sound methodologies necessary.

2.5 Interrogatory CR R313-25-25(4)-199/1: Uncertainties in Erosion Modeling

Interrogatory Statement:

Please provide quantitative estimates of the uncertainties involved using the borrow pit model as an analog for estimating erosion of the Federal Cell, including use of RHEM to develop input parameters for SIBERIA, and modeling uncertainties inherent in the selection of SIBERIA.

2.5.1 Interrogatory Response

Landscape evolution models (LEMs) were developed and applied for a face of a borrow pit at the Clive Site in order to predict the response of the pit face and upslope land surface to water erosion during runoff events. The models provide a quantitative description of the evolution of slopes and channels over time. While the embankment upper cover layers and the borrow pit material were the same Unit 4 soil, there were differences between the embankment and the borrow pit. The borrow pit was modeled as bare soil with no vegetation or gravel, with a much smaller top slope but a much larger catchment area. The embankment will be vegetated, and will have a surface layer with a gravel admixture but a steeper top slope. The catchment area of the embankment is smaller and the side slope is much less steep than the borrow pit face.

Although the borrow pit is an approximation to the embankment, the intent of this analysis was to provide insight into erosion projected out to 10,000 years. This analysis provides another line of evidence in addition to the sheet erosion modeling using USLE and the gully projection modeling using the permissible velocity method (NRC 2002) that demonstrate the stability of the proposed ET cover design. (See the response to UDEQ Interrogatories 71/1, 191/3, and 197/1.)

This interrogatory requests that quantitative uncertainty estimates be provided for the use of the borrow pit erosion model results as an analog to evaluate the influence of erosion on embankment performance at 10,000 years. While potentially interesting, such estimates are not necessary for demonstrating erosion resistance of the Federal Cell ET Cover. Furthermore, LEMs have been used as exploratory models providing insight into landscape–climate processes for many years, but they have not been developed to the level of other types of environmental modeling (Skinner et al. 2017). Typical methods used for calibration, sensitivity analysis, and uncertainty analysis are difficult to apply to LEMs since little data is available for calibration and verification (Skinner et al. 2017); (Temme et al. 2009). LEMs, however, even at this early stage, can be useful in providing insight into landscape-climate processes.

2.6 Interrogatory CR R313-25-25(4)-200/1: Use of RHEM to Develop Parameters for SIBERIA

Interrogatory Statement:

Please remodel erosion of the Federal Cell cover using the newer version of the RHEM model Al-Hamdan et al. 2015) applicable to disturbed soils and concentrated surface-water flow. The SIBERIA model results in the DU PA v.1.4 should be compared with those of SIBERIA modeling of erosion for the site based on the Grand Junction embankment modeling by Smith (2011). Modeling of the latter embankment indicates that significant gullying can occur over time on side

slopes even with vegetated soil on the embankment having considerable (i.e., 40%) added gravel (Smith 2011).

2.6.1 Interrogatory Response

UDEQ requests that modeling of erosion on the Federal Cell be redone using an updated version of the RHEM model. As described by Al-Hamdan et al. (2014), "RHEM was initially developed for functionally intact rangelands where concentrated flow erosion is minimal." Al-Hamdan goes on to describe the changes to RHEM as including accounting for changes in flow due to soil disturbance: "Disturbance such as fire or woody plant encroachment can amplify overland flow erosion by increasing the likelihood of concentrated flow formation." UDEQ states that the modeling for the Federal Cell should be redone because the previous version of RHEM used for the modeling "has limited application to describing erosion by concentrated flow on disturbed soils, as would be expected at Clive."

The response to UDEQ Interrogatory 71/1 describes the sequence of reclamation measures for quickly re-establishing natural conditions on the cover developed by SWCA (2013). Ecological and engineering measures described in the response to 171/1 will rapidly stabilize the cover in the short term and continue to provide long-stabilization. As SWCA (2013) states, "functioning native ecosystems comprised of the borrow soils at the Clive Site do not show erosion as the DRC suggests." The cover surface will not have the characteristics of disturbed rangeland soils, so the added features of RHEM for disturbed conditions are not relevant to modeling the Federal Cell. Thus, redoing the SIBERIA erosion model calibration with RHEM will not add to the information from the modeling results.

Erosion modeling of the Federal Cell and the Class A West Cell using methods in NRC- and EPA-approved guidance has demonstrated the stability of the proposed covers. Sheet and rill erosion modeling using USLE is described in the response to UDEQ Interrogatory 191/3. Evaluation of the potential for gully erosion on the Federal Cell using the permissible velocity method is performed as described in NUREG-1623 (NRC 2002) (response to UDEQ Interrogatory 71/1).

In addition, changes to the RHEM model have made it currently inapplicable to modeling scenarios at Clive. HAL (2018) note that slope length is no longer a functioning input variable to RHEM; all simulations have a set slope length of 50 meters (164 ft). See the response to UDEQ Interrogatory 191/3 for more information.

This interrogatory also requests a comparison of the borrow pit modeling results (DU PA v1.4 Appendix 10 (Neptune 2015c)) to the results of Smith and Benson (2016) for an embankment at Grand Junction. Smith and Benson (2016) describe a modeling study comparing cover stability for scenarios considering cover geometry, climate, rock fragment content of the surface layer, and vegetation. The conditions considered by these authors were: semi-arid and humid climate; surface layers of riprap, topsoil, and gravel admixture; and presence and absence of vegetation. These scenarios were simulated to 1,000 years by Smith and Benson (2016).

There are a number of reasons why the borrow pit simulations (DU PA v1.4 Appendix 10 (Neptune 2015c)) and Smith and Benson (2016) are not comparable. The characteristics of the topsoils used for the two covers are different. Smith and Benson described the properties of the

materials they used for the simulations in their Table 3.1. This table shows the particle size distribution of the topsoil as 40 percent sand, 40 percent silt, and 20 percent clay. In contrast, Unit 4 at the Clive Site is approximately 23 percent sand, 47 percent silt, and 30 percent clay (see also the response to Interrogatory 191 and Appendix A).

The Grand Junction site is not ecologically analogous to the Clive Site (SWCA 2013). Vegetation is an important factor in stabilizing covers. Smith and Benson (2016) assumed the dominant vegetation for the semi-arid case to be Mountain Big Sagebrush. In contrast, SWCA (2013) identifies the dominant vegetation community as Mountain Basins Mixed Salt Desert Scrub on analogs to the Clive Site. The soils at Clive are saline; different chemistry and fertility of soils at Grand Junction influence the characteristics of the native vegetation. SWCA (2013) describe biological soil crusts as a "dominant feature of the vegetation communities in the Great Salt Lake Basin." Biological soil crusts, important in stabilizing soils, are not considered by Smith and Benson (2016).

Clive borrow pit simulations projected to 10,000 years (DU PA v1.4 Appendix 10) considered unvegetated, Unit 4 soils with no added gravel. Smith and Benson (2016) show erosion model results for a cover in a semi-arid climate with a vegetated topsoil surface in Figure 4.1, and results for a cover in a semi-arid climate with an unvegetated gravel admixure surface in Figure 4.6. No directly comparable results to the Clive borrow pit simulation conditions (semi-arid, no vegetation, no gravel) were found in Smith and Benson (2016).

2.7 Interrogatory CR R313-25-25(4)-201/1: Estimating Rainfall Intensity

Interrogatory Statement

It is not clear that the Probable Maximum Precipitation (PMP) was determined using the procedures outlined in the National Oceanic and Atmospheric Administration and U.S. Army Corps of Engineers publication Hydrometeorological Report No. 49 (HMR 49) (1977).

According to Energy*Solutions*, these procedures resulted in a "*1-hour PMP rainfall intensity of 9.9 inches (Jones, 2012).*" However, DWMRC finds that a value of 9.8 or 9.9 inches is not the intensity, but rather the 1-hour PMP, or the maximum precipitation expected over 1 square mile when averaged over an hour.

Please re-calculate the PMP using NUREG/CR-4620, as outlined below.

2.7.1 Interrogatory Response

A detailed response to this interrogatory was developed by Hansen, Allen, and Luce (HAL 2017b). A summary of their final report is provided here. The complete report is provided in Appendix C.

Gully erosion potential was initially checked based on the calculation of permissible velocities according to the method presented in NUREG-1623, "Design of Erosion Protection for Long-Term Stabilization" (NRC 2002). As pointed out in the Interrogatory Statement, it is acknowledged that the methodology utilized previously failed to incorporate the proper rainfall intensity as outlined in NUREG/CR-4620 (Nelson et al. 1986).

In order to determine the probable maximum precipitation (PMP) intensity as outlined in the guidance in NUREG/CR-4620 (Nelson et al. 1986), it is necessary to first calculate the time of concentration for representative drainage areas for both the top and side slopes. The methodology outlined in Technical Release 55, "Urban Hydrology for Small Watersheds" (USDA 1986), was used to calculate the time of concentration for each representative slope.

TR-55 describes three types of drainage flow: sheet flow, shallow concentrated flow, and open channel flow. Sheet flow is defined as flow over planar surfaces at very shallow depths for up to 300 feet. After a maximum of 300 feet, the flow transitions to shallow concentrated flow. Open channels were not included in the calculations due to the absence of designed channels. The same Manning's roughness coefficient calculated to be 0.05 for use in the NUREG-1623 (NRC 2002) methodology using an empirical equation for channels with gravel beds with shallow flow depths of Bray (Coon 1998) was also used to represent the sheet flow roughness. It was decided to use the value calculated using the Bray method (0.05) instead of a higher value found in other publications for overland flow using sparse vegetative cover in order to be more protective. The above described methodology was applied to both the Class A West Cell and the Federal Cell to calculate the time of concentrations shown in Table 3 and

Table 4.

Table 3. Calculated Time of Concentration Using TR-55 Method for Class A West Cell.

Slope Description	Total Length (ft)	Slope (ft/ft)	Sheet Flow Length (ft)	Sheet Flow Manning's n	Shallow Concentrated Flow Length (ft)	Total Time of Concentration (min)
Top Slope (4%)	942	0.04	300	0.05	642	17.4
Side Slope (20%)	188	0.20	188	0.05	0	4.6

Table 4. Calculated Time of Concentration Using Tr-55 Method for Federal Cell.

Slope Description	Total Length (ft)	Slope (ft/ft)	Sheet Flow Length (ft)	Sheet Flow Manning's n	Shallow Concentrated Flow Length (ft)	Total Time of Concentration (min)
Top Slope (2.5%)	521	0.025	300	0.05	221	16.9
Side Slope (20%)	178.5	0.20	178.5	0.05	0	4.4

The rainfall depth is 9.9 inches, determined using the methods outlined in Table 6.3a of the US Army Corps of Engineers publication, Hydrometeorological Report No. 49 (HMR 49) (NOAA 1984), for determining an average 1-hour 1-square mile PMP. The steps were then followed from NUREG/CR-4620 (Nelson et al. 1986) to determine rainfall intensity from the PMP. The intensities for the Class A West and Federal Cells are shown in Table 5 and Table 6.

Table 5. PMP Rainfall Intensity for the Class A West Cell.

Slope Description	Rainfall Duration (T_c) (minutes)	% PMP (%)	Rainfall Intensity (i) (inches/hr)
Top Slope (4%)	17.4	53.8%	18.4
Side Slope (20%)	4.6	15.3%	19.8

Table 6. PMP Rainfall Intensity for the Federal Cell.

Slope Description	Rainfall Duration (T_c) (minutes)	% PMP (%)	Rainfall Intensity (i) (inches/hr)
Top Slope (2.5%)	16.9	52.1%	18.3
Side Slope (20%)	4.4	14.7%	19.8

Gully Erosion Potential

As opposed to the projection of the long-term effects of precipitation over time due to sheet erosion, the effects of gully erosion are determined by the consideration of a large single rainfall event. The procedure described in NUREG-1623 (NRC 2002) begins by calculating the peak runoff rate considering the PMP rainfall intensity, the slope length, and the multiplication factor of three recommended by NRC (2002). A flow depth is then calculated using the runoff rate, slope, and a roughness coefficient for channels with gravel beds and shallow depths. The flow rate and depth are then used to estimate a flow velocity.

The results for both the top slope and the side slope of the Class A West Cell using the vegetated slope condition are summarized in Table 7. Flow velocities on the top and side slopes of the Class A West Cell during the PMP event are predicted to be 2.37 and 2.07 ft/sec, respectively.

The permissible velocity method is commonly applied to determine channel stability. The slope is assumed stable if the calculated velocity (V, the velocity resulting from a PMP in this application) is less than the maximum permissible velocity (MPV). By contrast, if velocities exceed the MPV, it is assumed that the slope will experience excessive erosion that will lead to the formation of gullies. An MPV of 5.0 ft/s, appropriate for gravel channels, was selected from tables provided in NUREG/CR-4620 (Nelson et al. 1986). This methodology then directs that the estimates for the MPV be adjusted downward to account for the influences of flow depth. For the flow depths calculated for this cell the adjustment factor is 0.5, reducing the MPV to 2.5 ft/s. The side slope gully analysis was completed independently of the top slope.

Table 7. Gully Erosion Potential—Velocity Analysis for Class A West Cell.

Slope Description	Length (ft)	Slope (ft/ft)	i (in/hr)	c	Q (cfs/ft)	y (ft)	V (ft/sec)	Adjusted MPV (ft/sec)
Top Slope (4%)	942	0.04	18.4	0.5	0.60	0.25	2.37	2.5
Side Slope (20%)	188	0.20	19.8	0.5	0.13	0.06	2.07	2.5

Comparing calculated velocities to MPVs in Table 7 demonstrates that all slope scenarios using the ET cover system provide acceptable protection against gully erosion using these criteria by limiting the potential of gully formation from high velocity channelization.

2.8 Interrogatory CR R313-25-25(4)-202/1: Use of SIBERIA to Model Federal Cell Erosion

Interrogatory Statement:

The Division is concerned that the SIBERIA model referenced in DU PA v.1.4 discussions assumes a modeling-realm geometry inconsistent with that of the proposed Federal Cell. The Federal Cell embankment is approximately 30 feet high (height of waste under top slope and above grade) compared to the model analog height of 10 feet. Also, the SIBERIA model allows for several hundred meters of ground surface upslope from the sloping pit face, but that ground surface only has a 0.3% (0.003) grade in the model. By contrast, as described in Appendix 3 to the DU PA v.1.4, the waste under the top slope above and upslope from the side slopes of the embankment has a grade of up to 2.4%. This is about eight times greater. Energy*Solutions* needs to explain how these differences affect the results and how the Federal Cell modeling results can be reconciled against similar modeling studies conducted by Smith and Benson (2016) for the Grand Junction Uranium Mill Tailings Disposal Site.

2.8.1 Interrogatory Response

SIBERIA is employed in the DU PA model as a supplementary line of evidence for embankment stability. If SIBERIA results were the sole or primary basis for demonstrating embankment stability, the distinctions noted in the interrogatory could be relevant; however, LEMs such as SIBERIA are acknowledged to be subject to further development before their results should be considered conclusive in licensing situations. See also the response to UDEQ Interrogatory 199/1.

2.9 Interrogatory CR R313-25-25(4)-205/1: Erosion Analysis

Interrogatory Statement:

As discussed below, there appears to be an issue with the FractionGully 1.52 m depth data. Please explain why the 1.52 m depth percentages are smaller than the 1.97 m and 2.42 m depth results.

2.9.1 Interrogatory Response

The interrogatory creates Figure 205-2 to summarize the percentage of realizations within particular intervals/categories of "fraction of cover area" for six depth intervals. In general, Figure 205-2 and the associated Table 205-1 are used to conclude that the percentage of realizations with different fractions of cover area (below 0.03) are generally smaller for the depth interval they label at "1.52" than for deeper depth intervals. It was expected that deeper depths would consistently have a larger percentage of the realizations with smaller fractions. This behavior can be attributed both to how Figure 205-2 was created (how the summaries were calculated to create the curves), and also to the stochasticity incorporated in the creation of the fractions at each depth interval *within* a single realization.

First, while it is interesting to summarize over realizations within a depth category, it is important to keep in mind that, for one realization of the GoldSim model, a single realization is selected from 1000 and the fractions of cover for each depth category are used for that one realization. The fractions within each realization (one row of the GoldSim look up table) are created as described in Appendix 10 of the Clive DU PA Model v1.4 (Neptune 2015c); they come from the same distribution and sum to one. The fractions associated with the six or seven deepest depth intervals are all small (generally less than ~ 0.006) and are close together due to the relatively flat tail of the lognormal distribution used to generate them. Therefore, due to the stochasticity in generating the fractions from the lognormal distribution, there are realizations with a slightly higher fraction of cover in deeper intervals than in a shallower interval. For example, for one realization the fraction is 0 for depth interval (1.52, 2.03m], but then 0.0018 for the depth interval (2.03m, 2.53m], followed by 0 for the deepest two intervals. This stochasticity, along with different distributions used for each realization, contributes unexpected relative differences among depth intervals within the range of very small fractions and deep depth intervals.

The implications of this on the PA Model are expected to be negligible given how the realizations are used in the PA Model and the magnitude of the differences in fractions involved in the behavior pointed out in the interrogatory. The interrogatory provides an extreme case of erosion in Figure 205-4 and Table 205-2, created from summarizing over realizations within depth intervals. The resulting curves are presented as the minimum, mean, and maximum, but they do not represent particular realizations used in the GoldSim model and no longer meet the sum-to-one constraint within individual realizations. The summaries presented in Figures 205-4 and 205-2 are interesting if the results are not over-sold as representing actual erosion behavior of individual GoldSim realizations. For example, it would not be possible for a single realization to have the maximum fraction observed over all realizations for every depth interval, and statements regarding "mean erosion" using these summaries are only valid to the extent that behavior of individual realizations used in the GoldSim model reflects the averages per depth interval.

As described above, the general idea presented in Figure 205-2 and Table 205-1 may stem mainly from a concern that fractions within each realization are not non-increasing with depth at deeper depths. However, Figure 205-2 is not easy to replicate without additional information. In particular, it is not clear how the labels for the depth intervals were chosen or how many realizations were used to create it (just 250 to match the other plots, or all 1000 in the GoldSim

look up table?). The depth intervals (in mm) created for the look up table are (0,10], (10,152], (152,305], (305,457], (457,610], (610,762], (762,914] , (914,1.07e+03], (1.07e+03,1.22e+03], (1.22e+03,1.37e+03], (1.37e+03,1.52e+03], (1.52e+03,2.03e+03], (2.03e+03,2.53e+03], (2.53e+03,3.04e+03], and (3.04e+03,3.54e+03]. Two of the labels used in Figure 205-2 correspond to endpoints of these intervals (1.07m and 1.52m), but the additional depth labels (1.97m, 2.42m, 2.87m, and 3.32m) do not. They are also not midpoints. It is possible that interpolation was used to get these from Figure 205-1, but it is not clear why this would be done when the fractions provided specifically apply to the stated depth intervals. It is also not clear over what intervals of fraction the percentages of realizations were calculated. Figure 4 has been created to display the same information that Figure 205-2 is meant to represent, although using cumulative proportions as the interrogatory did for Figure 205-3 because this is a more natural and repeatable way to display the values in the look-up table. It uses all 1000 realizations and seven deepest depth intervals. The "trends" in the plot over depth intervals do not match those presented in Figure 205-1, but the general idea that curves are not "in order" by depth is the same.

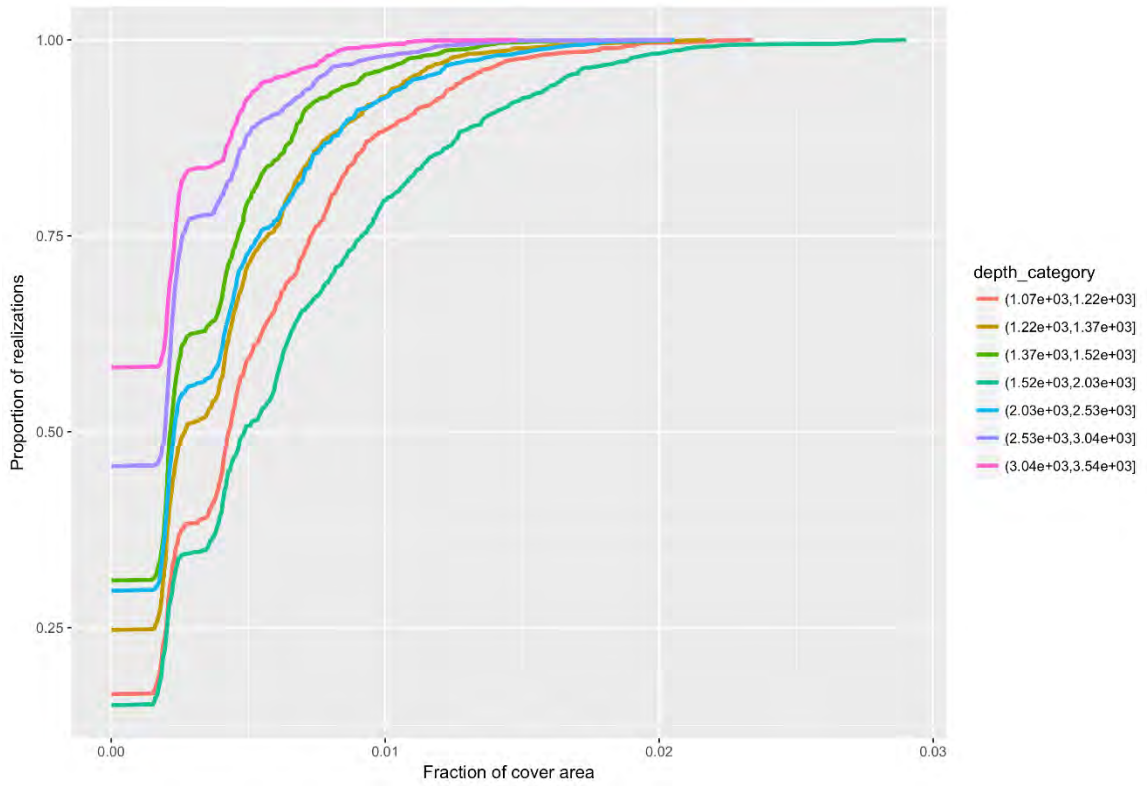

Figure 4. Empirical cumulative distribution functions (ecdf) of the values across realizations found in the GoldSim look-up table for the seven deepest depth intervals. Note that, in general, the deeper intervals have larger proportions of realizations with smaller fractions. The two green curves associated with depth intervals (1.37m, 1.52m] and (1.52m, 2.03m] do not follow the order with depth, which can be interpreted as consistent with the conclusion from Figure 205-1.

Using values of simulated cover area eroded by gullies from their Table 205-1, UDEQ states, "An eroded area of 1,087 m^2 means that the entire perimeter of the embankment has eroded back 0.6 m (1.9 feet), and a 5,433 m^2 eroded area means the perimeter has eroded 2.9 m (9.5 feet)." This statement is a gross misrepresentation of the modeled erosion processes. UDEQ is presenting a false equivalence between areally distributed erosion losses due to sheet flow and gullying on the embankment and losses due to cliff retreat, a mass wasting process.

Radon flux

UDEQ next presents comparisons between radon flux in the embankment predicted by the Clive DU PA Model v1.2 and several analytical solutions.

Direct comparison of late-time results from the Clive DU PA Model v1.4 with steady-state analytical solutions is made difficult by basic differences in the assumptions involved in the approaches. Analytical solutions typically are restricted by simplifying assumptions that allow for closed-form solutions. For example, a constant or uniform source concentration is a typical assumption. The PA Model, conversely, allows for movement as well as decay of radium-226, which amounts to a non-uniform source that analytical solutions do not account for.

The analytical solution procedure for multi-layered cover systems described in NRC's Regulatory Guide 3.64 (NRC 1989) and applied by UDEQ begins with calculating the flux from the waste zone assuming no cover exists (Equation 1 in SER Section 4.2.1 (SC&A 2015a)), and then repeating a similar calculation for each layer up the column. Reg. Guide 3.64 describes this iterative solution procedure as an "approximate method" due to the assumed boundary conditions at each step.

Typically, comparisons of analytical solutions to numerical solutions require that the numerical model be carefully prepared to match the assumptions of the analytical solutions. Differences in the assumed parameter values can also be important. For example, the SER states that since "the diffusion coefficient for the Rogers 2002 curve is simply a fixed value, UDEQ believes that the IAEA Equation radon flux is more representative of the conditions at the proposed Federal Cell." However, Table 205-3 of the interrogatory presents only values derived using the Rogers (2002) method.

Nevertheless, it is acknowledged that cross-comparison with different modeling methods can be valuable and instructive. The interrogatory states that radon flux, though at the ground surface, compares well to UDEQ's application of analytical solutions, but also mentions some discrepancies at depth. It is noted that the results from the IAEA Equation are generally within an order of magnitude of the DU PA Model v1.4 results at all depths despite possible differences in assumptions. UDEQ correctly states that the DU PA Model v1.4 is calibrated to focus on agreement with known analytical solutions of the flux at the ground surface rather than fluxes deep in the waste zone, which are generally not important to dose calculations.

Lack of evidence of significant erosional activity at the Site, planned ecological remediation of the soils used to construct the cover (response to Interrogatory 05/2), and erosion models that demonstrate the stability of the cover (response to Interrogatory 71/1) support the prediction that erosion of the embankment will be minimal and will not enhance radon fluxes. Given these site-

specific observations and modeling results, the differences in radon flux predictions between the DU PA Model v1.4 and UDEQ's application of analytical solutions at depths greater than 1 m are not meaningfully different.

The April 2015 SER (SC&A 2015a) also notes that the embankment's performance with respect to radon flux would be adequate even with complete removal of the cover system, as predicted doses are several orders of magnitude below regulatory limits. Thus, the comparison of the Clive DU PA Model v1.4 with other radon flux predictions, which show only modest differences at relevant depths, does not detract from the conclusion that radon fluxes are adequately attenuated by the embankment due to the depth of burial of radon-generating wastes and the prevailing site conditions.

3.0 Conclusion

UDEQ has raised many diverse issues in this set of interrogatories. The following points summarize this response:

- Predicted erosion performance of the Federal Cell is reasonable. Lack of evidence of significant erosional activity at the Site, planned ecological remediation of the soils used to construct the cover, and erosion models that demonstrate the stability of the cover support this position. Erosion of the embankment cover will be minimal and will not enhance radon fluxes or deep infiltration.
- Using uniform hydraulic properties to model the entire ET cover represents the only logical outcome of applying the Benson et al. (2011) method for assigning properties. Given their conceptual model that makes no distinction between the hydraulic properties of storage and barrier layers, the cover can no longer be represented by a layered system in the flow model.
- The proper rainfall intensities for the embankment surfaces have been calculated according to NUREG/CR-4620 (Nelson et al. 1986) and incorporated into the erosion models.
- The design for the amount of gravel to add to the soil in the top and side slopes was determined based on sheet erosion modeling using USLE and gully projection evaluation using the permissible velocity method of the NRC.
- The results of the SIBERIA modeling of the borrow pit provide another line of evidence, in addition to the more conventional modeling. This is useful in demonstrating the stability of the proposed ET cover design despite differences in the characteristics of the borrow pit and the embankment.
- The cover surface will not have the characteristics of disturbed rangeland soils, so the added features of RHEM for disturbed conditions are not relevant to modeling the Federal Cell. Thus, redoing the SIBERIA erosion model calibration with RHEM will not add to the information from the modeling results.

- The SIBERIA models of the borrow pit (DU PA v1.4 Appendix 10 (Neptune 2015c)) and a Grand Junction embankment (Smith and Benson 2016) are not comparable. No conditions directly comparable to the Clive borrow pit simulations (semi-arid, no vegetation, no gravel) were found in the Smith and Benson (2016) report.
- Radon fluxes are adequately attenuated by the embankment due to the depth of burial of radon-generating wastes and the prevailing site conditions.

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Appendix A. HAL 2018

DRC Interrogatory CR R313-25-7(2)-191/3

Selected Statements from DEQ Conclusion from April 2015 SER, Appendix C:
Interrogatory 191 requested EnergySolutions to provide additional information about the ability of steep side slopes to resist gully erosion. After reviewing…DEQ believes that the key analysis is….Appendix D uses both RUSLE and REHM to calculate rill or sheet erosion, with similar results. Both are well below the EPA's criteria for ……cover systems. One problem with the Appendix D analysis is that it does not describe how the values for the various RUSLE and REHM parameters were selected. For example, the RUSLE has R, K, L, S, and C parameters, but only L and S are functions of the embankment's design, so the basis for selecting the other parameters is not clear.
In conclusion, the analysis performed by HAL may or may not be correct, but before DEQ can accept it, each value selected and used in the analysis needs to be justified.

HAL Response: **February 12, 2018**

Universal Soil Loss Equation (USLE)

The USLE estimates average annual soil losses from erosion. In order to clarify the methodology used in the analysis, all references to RUSLE have been change to refer to USLE. While the equations are the same, the use of the acronym RUSLE could imply the use of the software program developed by the USDA for factor determination. The software package was not used because factors from a Utah-specific publication were relied on for the analysis as described below.

The review from DEQ indicated that the previous interrogatory response was lacking in the description of the selection of the parameters. Therefore, the summary of the methodology has been enhanced to provide additional background information. The USLE methodology is commonly used to determine the long-term stability of slopes and is an industry-standard means for design of erosion control. Guidance given by the EPA states that "The U.S. Department of Agriculture's (USDA's) Universal Soil Loss Equation is recommended as the tool to evaluate erosion potential" (US EPA Seminar Publication, 1991). The basis for this approach comes from the theory that "if adequate protection is provided to control sheet erosion, then rills and gullies will never form from rainfall" (Israelsen et al, 1984). Generally, the USLE equation is defined as:

A = R*K*LS*C*P

Where:

A = the average soil loss per unit area, expressed in tons/acre/year
R = the rainfall/runoff factor, which is the number of rainfall units for rainfall energy and runoff and snowmelt
K = soil erodibility factor in tons per acre per year per unit of R
LS = topographic factor (length and steepness of the slope)
C = the cover and management factor (equivalent to the VM factor), which is the ratio of soil loss from an area with a given cover and management relative to that from an identical area in continuous fallow
P = the supporting conservation practice factor, in this case assumed to be equal to 1

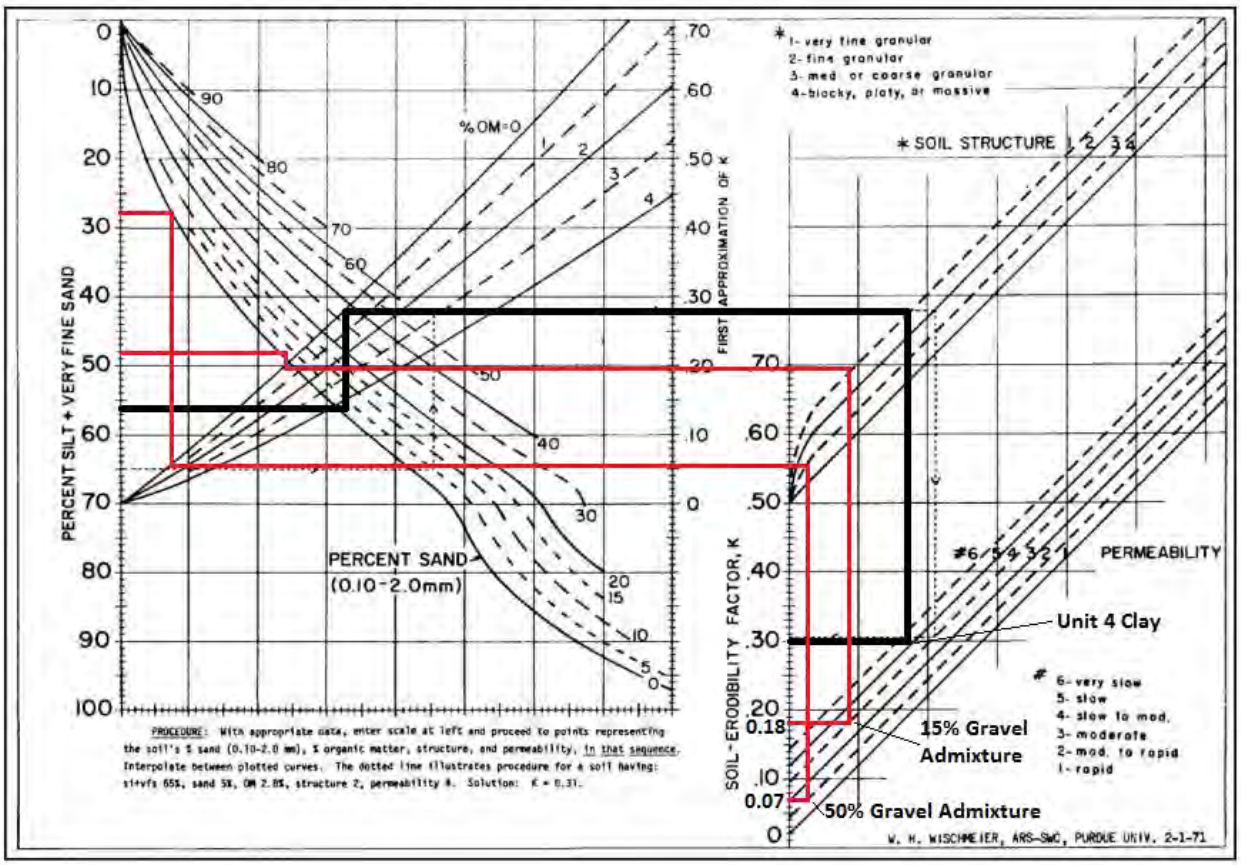
This procedure and site-specific factors are described in "Erosion and Sedimentation in Utah – A Guide for Control" (Israelsen, 1984) and "Design Hydrology and Sedimentation for Small Catchments" (C.T. Haan et al, 1994). The computed average sheet erosion soil loss is presented in Table 1.

R Factor

The R factor (6) is selected based on the Utah-specific Iso-Erodent (R) mapping provided in the Utah Water Research Laboratory report (Israelsen, 1984) which is also provided on the following page.

K Soil Erodibility Factor

The K values (0.18 and 0.07 for top slope and side slope, respectively) are based on the Unit 4-specific material characteristics with the top slope and side slope gravel admixtures together with the Wischmeier nomograph as described in the methodology presented in the Israelsen and Hann procedures and shown in the figure below. A particle size analysis using the hydrometer method was performed on the Unit 4 clay to determine the percent silt and very fine sand (see figure below) for use with the Wischmeier nomograph. The results of the hydrometer analysis are attached to this response.



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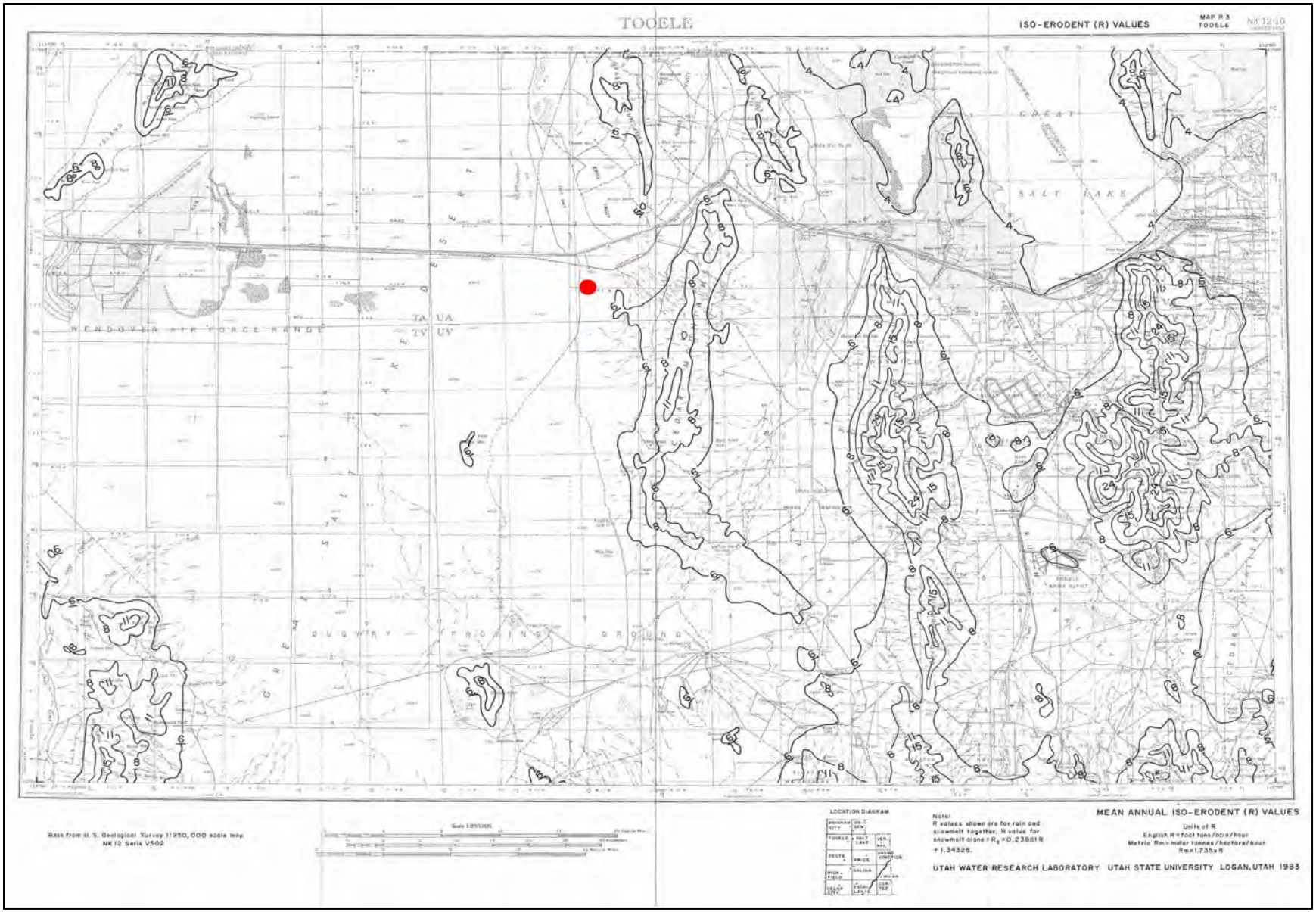
TOOELE
ISO-ERODENT (R) VALUES
MAP R 3
TOOELE
NK 12-10
GREAT
SALT LAKE
WENDOVER AIR FORCE RANGE
DUGWAY PROVING GROUND
LOCATION DIAGRAM
Note:
R values shown are for rain and snowmelt together. R value for snowmelt alone: $R_s = 0.23801R + 1.34326$.
MEAN ANNUAL ISO-ERODENT (R) VALUES
Units of R
English R = foot tons/acre/hour
Metric Rm = meter tonnes/hectare/hour
Rm = 1.735 x R
Base from U. S. Geological Survey 1:250,000 scale map
NK 12 Series V502
UTAH WATER RESEARCH LABORATORY UTAH STATE UNIVERSITY LOGAN, UTAH 1983

C Factor (VM Factor)

The C parameters used in the equation for both the 4% and 20% slopes were based on Table 9 and Table 10 of the US Department of Agriculture Handbook Number 537 "Predicting Rainfall Erosion Losses, A Guide to Conservation Planning" and are shown in the figures below. The C factor for the top slopes (0.2) is based on the sparse vegetative cover naturally found in the areas immediately surrounding the Clive facility (Table 10 of Handbook Number 537, No Appreciable Canopy, Type G with 20% ground cover) and the Unit 4 gravel admixture. The C factor for the side slope is based on the higher percentage of gravel in the side slope gravel admixture (50% gravel). The 50% gravel admixture on the side slopes results in a pseudo-gravel mulch once some of the fines have been removed. Therefore, a C factor of 0.02 was selected (Table 9 Handbook Number 537, Crushed Stone ¼ to 1 ½ in, Mulch Rate of 240 tons/acre, Land Slope of 21-33%, with a length limit of 200 feet).

TABLE 9.—*Mulch factors and length limits for construction slopes*[1]

Type of mulch	Mulch Rate	Land Slope	Factor C	Length limit[2]
	Tons per acre	*Percent*		*Feet*
None	0	all	1.0	—
Straw or hay,	1.0	1-5	0.20	200
tied down by	1.0	6-10	.20	100
anchoring and				
tacking	1.5	1-5	.12	300
equipment[3]	1.5	6-10	.12	150
Do.	2.0	1-5	.06	400
	2.0	6-10	.06	200
	2.0	11-15	.07	150
	2.0	16-20	.11	100
	2.0	21-25	.14	75
	2.0	26-33	.17	50
	2.0	34-50	.20	35
Crushed stone,	135	<16	.05	200
¼ to 1½ in	135	16-20	.05	150
	135	21-33	.05	100
	135	34-50	.05	75
Do.	240	<21	.02	300
	240	21-33	.02	200
	240	34-50	.02	150
Wood chips	7	<16	.08	75
	7	16-20	.08	50
Do.	12	<16	.05	150
	12	16-20	.05	100
	12	21-33	.05	75
Do.	25	<16	.02	200
	25	16-20	.02	150
	25	21-33	.02	100
	25	34-50	.02	75

TABLE 10.—*Factor* **C** *for permanent pasture, range, and idle land*[1]

Vegetative canopy			Cover that contacts the soil surface					
			Percent ground cover					
Type and height[2]	Percent cover[3]	Type[4]	0	20	40	60	80	95+
No appreciable		G	0.45	0.20	0.10	0.042	0.013	0.003
canopy		W	.45	.24	.15	.091	.043	.011
Tall weeds or	25	G	.36	.17	.09	.038	.013	.003
short brush		W	.36	.20	.13	.083	.041	.011
with average								
drop fall height	50	G	.26	.13	.07	.035	.012	.003
of 20 in		W	.26	.16	.11	.076	.039	.011
	75	G	.17	.10	.06	.032	.011	.003
		W	.17	.12	.09	.068	.038	.011
Appreciable brush	25	G	.40	.18	.09	.040	.013	.003
or bushes, with		W	.40	.22	.14	.087	.042	.011
average drop fall								
height of 6½ ft	50	G	.34	.16	.08	.038	.012	.003
		W	.34	.19	.13	.082	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.078	.040	.011
Trees, but no	25	G	.42	.19	.10	.041	.013	.003
appreciable low		W	.42	.23	.14	.089	.042	.011
brush. Average								
drop fall height	50	G	.39	.18	.09	.040	.013	.003
of 13 ft		W	.39	.21	.14	.087	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.084	.041	.011

TABLE 1
EFFECTS OF EROSION - AVERAGE SOIL LOSS ANALYSIS USING USLE (TOP SLOPE WITH UNIT 4 CLAY W/ 15% GRAVEL ADMIXTURE AND SIDE SLOPE WITH UNIT 4 CLAY AND 50% GRAVEL ADMIXTURE)

Slope Segment	R (ft tons/ac/hr)	K (tons/ac/EI)	L (ft)	S (%)	C	A (tons/ac/yr)		Total Soil Loss (mm/year)
Top Slope (4%)	6	0.18	942 (4%)	4%	0.2	0.25	0.24 overall	0.026
Side Slope (20%)	6	0.07	188 (20%)	20%	0.02	0.19		

The Rangeland Hydrology and Erosion Model (RHEM) Model Parameters

The RHEM model was used in HAL's interrogatory response entitled "DRC RFI Section 4.0 Erosion" completed in 2013 in order to corroborate the results of the USLE analysis. Since the completion of that effort, the RHEM on-line model has been updated. The latest version of the model (Version 2.3) lacks some of the functionality of the earlier model. More specifically, slope lengths are not able to be directly input as they were previously and therefore a direct comparison with the calculation completed using USLE is not possible. This appears to be an error within the program since the descriptions of the model available on the website include slope length as an input parameter option. Attempts to reach the contacts listed for the RHEM model in order to resolve the issue were unsuccessful. The model defaults to a slope length of 50 meters (164 feet). Additional parameter options for cover characteristics appear to have been added since 2013, including options for a distinction between foliar cover and basal plant cover as well as rock cover, litter cover and biological soil crust cover. Since the tool is a web-based model and not stand alone software, the version of the online tool used in the 2013 analysis is no longer available. The parameters described in the 2013 interrogatory for vegetative conditions, slope grades, climate station, soil texture class, and slope lengths are still valid for the analysis completed at the time but the results reported therein can no longer be validated.

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Appendix B. HAL 2017a

DRC Interrogatory CR R313-25-25(4)-198/1

DRC Interrogatory Statement:
Please provide the design bases and justification for the amount and sizing of the gravel in the top and side slopes of the Federal Cell. The proposal for the gravel admixture in the top slope (15%) appears too small. Also, please provide evidence for existing semi-arid or arid sites where only 15% gravel has been added to form a successful cover-system surface layer for a landfill. Please describe actual analog sites where 50% gravel for side slopes has been demonstrated to be effective against erosion.

HAL Response: **December 18, 2017**

The design basis for the amount of gravel to add to the soil in the top and side slopes were first determined based on the analysis of the long term sustainability of the slopes due to sheet erosion over time. The methods that were used are the Revised Universal Soil Loss Equation (RUSLE) and the Rangeland Hydrology and Erosion Model (RHEM). These methods produce an estimate of the average annual soil loss in terms of tons per acre per year. With the gravel admixed into the Unit 4 clay soil, average annual soil losses were calculated to be about 0.24 tons/acre/year using RUSLE which was also closely matched by the RHEM. This amount of loss is almost 10 times less than what has been recommended in EPA guidance for covers for hazardous waste facilities. A more detailed discussion of the methodologies and results is provided in the response to DRC Interrogatory CR R313-25-7(2)-191-3.

Once the slope was determined to be stable from an average soil loss perspective, checks on the gully erosion potential were completed based on the calculation of predicted velocities and comparing them to permissible velocity according to the method presented in NUREG-1623 "Design of Erosion Protection for Long-Term Stabilization". This second assessment based on an extreme intense rainfall event is recommended in NUREG-1623 because of the potential for significant damage to cover systems from such large events. In fact, this extreme intense rainfall event is known as the Probable Maximum Precipitation (PMP) and is so extreme that "the point precipitation data base, even if maximized for PMP moisture potential, shows no observed values even close to the 10-inch PMP estimate (the generalized, local storm PMP estimates in Utah)" (Jensen, 1995). Additionally, the methodology applies a flow concentration factor (F) which NUREG-1623 recommends to be 3. Therefore, the extreme event that is multiples of the highest ever recorded rainfall intensity in the area is compounded by an additional safety factor. The end result of this process is an analysis that is meant to produce a highly conservative value.

Flow velocities on the top and side slopes of the CAW embankment during the PMP event were predicted to be 2.37 and 2.07 ft/sec, respectively, as discussed in more detail in the response to DRC Interrogatory CR R313-25-7(2)-191-3. The acceptable Maximum Permissible Velocity (MPV) was selected from tables provided in NUREG/CR-4620. Under this method the slope is stable if the calculated velocity (V, the velocity resulting from a PMP in this application) is less than the MPV. By contrast, if velocities exceed the MPV, the slope will experience excessive erosion that will lead to the formation of gullies. HAL found that the calculated velocities resulting from the PMP did not exceed the prescribed permissible velocity.

Reference Review

The methods discussed above have been published and/or accepted by the US EPA and US Nuclear Regulatory Commission. Other methods referred to in the interrogatory, on the other hand, have not been adopted, published or referred to in guidance by federal agencies. While the works cited are part of productive ongoing academic research and study, they are not conclusive in their findings and should instead be the focus of additional research. A summary of each is provided below:

"Gravel Admixture for Erosion Protection in Semi-Arid Climates, Erosion of Soils and Scour of Foundations" (Anderson, C., and J. Stormont, 2005) – This paper was published as part of the proceedings of sessions of the GeoFrontiers 2005 Congress held in Austin, Texas. Along with some other conference proceedings articles, these early attempts to define a process for admixture design is very helpful in that it outlines practical steps to determine gravel size, gravel percentage and admixture thickness. This approach, however, has limitations that result from the lack of empirical evidence to back up the steps and applications of many of the equations presented in the paper. The paper states that "the design method for gravel admixtures presented here may serve as an outline for further erosion investigations and provide guidance for future designs of gravel-soil admixture layers". Therefore, the paper as written was not meant to be used as a proven method for admixture design but rather a starting point for further research and investigation.

"Design of Erosion Protection at Landfill Areas with Slopes Less than 10%" (Anderson, C., and Wall, S., 2010) – This paper is very similar to the aforementioned paper by Anderson and Stormont where it comes from the proceedings of a conference, in this case the International Conference on Scour and Erosion held in 2010. Much of the background language of this paper is the same as the 2005 article by Anderson and Stormont. Similarly, the methodology presented is very similar to the steps provided in 2005 with some changes. Again, the paper does not claim this to be a proven method but indicates it is taking steps to test its outcomes. It states that "the procedure described here is being applied to a landfill cover soon to be constructed in southern Nevada. The Nevada project will provide the first large scale application of the procedure." HAL was unable to find information regarding empirical data on a smaller scale nor was final information on the results of the large scale Nevada project able to be found. Without this information or additional discussion in the paper, the limits of the equation and how the parameters of success or failure are defined remain unknown. For example, assuming the Nevada project site is shown to be successful with the 40% gravel admixture there is nothing that would indicate if a lower percentage of gravel admixture, such as 25%, would also be adequate. Additionally, the suitability of the design and how success is defined is not sufficiently described in the paper to know whether the absence of observed gully erosion constitutes a successful design or if it is acceptable to have the formation of rills and gullies as long as the depth does not exceed the admixture layer thickness calculated using the method. This is an important distinction since the end result of the design process presented in the paper is the calculation of the thickness of the admixture layer which is presented as being dependent on the percentage of gravel in the admixture. This specific paper does not provide limits or conclusive guidance to the reliability of the method and therefore should serve as the starting point for further investigation and research.

"Erosion Protection at Landfill Slopes Greater than 10%" (Anderson, C. and Wall, S.) – This paper focuses on riprap on side slopes. The design proposed by Energy*Solutions* does not include riprap side slopes; therefore, this paper does not apply.

"Long-Term Cover Design for Low-Level Radioactive and Hazardous Waste Sites as Applied to the Rocky Flats Environmental Technology Site Solar Evaporation Ponds" (Stenseng, S.E. and Nixon, P.A., 1997) – The paper describing the design used at the Rocky Flats Environmental Technology Site was included as part of the proceedings from the 50th Industrial Waste Conference held in May 1997. The paper includes a brief description of the design basis for the 5% top slopes and 20% side slopes and the 40% gravel admixture. The admixture gravel content appears to have been selected instead of calculated as the result of a defined process. While instructive regarding the specific cover design discussed in the paper, no additional guidance is provided to guide application at other sites.

"Ecology, Design, and Long-Term Performance of Waste-Site Covers: Applications at a Uranium Mill Tailings Site" (Waugh, W.J. and Richardson, G.N., 1997) – This paper is similar to the Stenseng and Nixon paper discussed previously in that it contains a summary of the design parameters but does not provide a specific and applicable methodology for the design of a soil gravel admixture with regard to erosion protection.

Sites with Top Slopes Comprised of 15% Gravel Admixture

There are some examples of sites that have employed slopes with 15% admixture and give some measure of proof that a 15% admixture can be effective at controlling erosion. A test site was established at Hanford and is referred to as the Hanford Prototype Surface Barrier (PSB). The purpose of the PSB test site was to evaluate surface barrier constructability, construction costs, and physical and hydrologic performance at field scale (US Department of Energy, 2016). This field-scale test cover was installed in 1994 and is comprised of a top erosion protection layer made up of a silt loam admixed with 15% pea gravel. The top slope of 2% in this case is slightly less than the top slopes of 2.5% and 4% proposed by Energy*Solutions* but is an example of a cover system that relies on the same amount gravel admixture. A recent review completed by the US Department of Energy in 2016 of the data collected at the site through 2015 concluded that:

> *"The 19-year PHB record showed practically no evidence of wind or water erosion of the ETC barrier, despite 3 years of triple the mean annual precipitation; three simulated 1000-year-return, 24-hour precipitation events; and an intense, controlled fire that burned off all vegetation across half the barrier surface….Even in the absence of vegetation (e.g., following a fire), the pea gravel added to the silt loam protected the barrier surface from wind and water erosion….Overall, the monitoring results have confirmed that the PHB design is resistant to water and wind erosion and that resistance is expected throughout the barrier's 1000-year design life"*

Another test site using the same cover system was established at Hill Air Force Base in 1994 though little information has been published about that site to date.

Sites with Side Slopes Comprised of 50% Gravel Admixture

No sites were found that have used a gravel admixture on side slopes at or above 20%. Similarly, there were no methodologies found that specifically address the calculation of gravel admixtures for slopes greater than 10% other than the general methods found in NUREG-1623 and NUREG/CR-4620. For slopes over 9%, Simanton et al. found that the rate of water erosion diminishes exponentially with increasing cover of rock fragments. The effect of biological soil crust is also difficult to quantify but is expected to establish itself along the slopes as has been observed along natural slopes in the Clive area. The observation of natural analogs in the Clive vicinity could prove helpful in demonstrating the stability of steeper slopes although none would be available with such a high gravel content (50%) as the proposed side slope design. The required lengthy post-closure care period will perhaps provide the greatest opportunity for verification of the design methodology described previously.

The design process that was completed to determine the acceptability of the 50% gravel admixture on the 20% side slopes is in accordance with EPA and Nuclear Regulatory Commission guidance. There was no requirement found in the guidance procedures that existing sites be used as evidence to support proposed designs. While it is acknowledged that such evidence would be helpful, each site is different and contains unique design constraints based on physical layout, climate, material availability and project goals that make determinations based on sound methodologies necessary.

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Appendix C. HAL 2017b

DRC Interrogatory CR R313-25-25(4)-201/1

DRC Interrogatory Statement:
It is not clear that the Probable Maximum Precipitation (PMP) was determined using the procedures outlined in the National Oceanic and Atmospheric Administration and U.S. Army Corps of Engineers publication Hydrometeorological Report No. 49 (HMR 49) (1977). According to EnergySolutions, these procedures resulted in a "1-hour PMP rainfall intensity of 9.9 inches (Jones, 2012)." However, DWMRC finds that a value of 9.8 or 9.9 inches is not the intensity, but rather the 1-hour PMP, or the maximum precipitation expected over 1 square mile when averaged over an hour.
Please re-calculate the PMP using NUREG/CR-4620 as outlined below.

HAL Response: **December 19, 2017**

Gully erosion potential was initially checked based on the calculation of permissible velocities according to the method presented in NUREG-1623 "Design of Erosion Protection for Long-Term Stabilization". As pointed out in the Interrogatory Statement, it is acknowledged that the methodology utilized previously failed to incorporate the proper rainfall intensity as outlined in NUREG/CR-4620.

In order to determine the PMP intensity as outlined in the guidance in NUREG/CR-4620 it is necessary to first calculate the time of concentration for representative drainage areas for both the top and side slopes. The methodology outlined in Technical Release 55 "Urban Hydrology for Small Watersheds" was used to calculate the time of concentration for each representative slope.

TR-55 describes three types of drainage flow: sheet flow, shallow concentrated flow, and open channel flow. Sheet flow is defined as flow over planar surfaces at very shallow depths for up to 300 feet. After a maximum of 300 feet, the flow transitions to shallow concentrated flow. Open channels were not included in the calculations due to the absence of designed channels. The same Manning's roughness coefficient calculated to be 0.05 for use in the NUREG-1623 methodology using an empirical equation for channels with gravel beds with shallow flow depths (Bray, 1979) was also used to represent the sheet flow roughness. It was decided to use the value calculated using the Bray method (0.05) instead of a higher value found in other publications for overland flow using sparse vegetative cover in order to be more protective. The above described methodology was applied to both the Class A West Cell and the Federal Cell.

CALCULATED TIME OF CONCENTRATION USING TR-55 METHODOLOGY FOR CLASS A WEST CELL

Slope Description	Total Length (ft)	Slope (ft/ft)	Sheet Flow Length (ft)	Sheet Flow Manning's n	Shallow Concentrated Flow Length (ft)	Total Time of Concentration (min)
Top Slope (4%)	942	0.04	300	0.05	642	17.4
Side Slope (20%)	188	0.20	188	0.05	0	4.6

CALCULATED TIME OF CONCENTRATION USING TR-55 METHODOLOGY

FOR FEDERAL CELL

Slope Description	Total Length (ft)	Slope (ft/ft)	Sheet Flow Length (ft)	Sheet Flow Manning's n	Shallow Concentrated Flow Length (ft)	Total Time of Concentration (min)
Top Slope (2.5%)	521	0.025	300	0.05	221	16.9
Side Slope (20%)	178.5	0.20	178.5	0.05	0	4.4

The rainfall depth determined using the methods outlined in Table 6.3a of the US Army Corps of Engineers publication Hydrometeorological Report No. 49 (HMR 49) for determining an average 1-hour 1 square mile PMP is 9.9 inches. NUREG/CR-4620 gives the following steps for determining rainfall intensity from the PMP:

PMP rainfall depth = (% PMP) x (PMP)

Where:
PMP rainfall depth = rainfall depth after adjusting the PMP for the duration, inches
% PMP = the region-specific % PMP based on the duration, %
PMP = Probable Maximum Precipitation, inches (9.9 inches using Table 6.3a from HMR 49)

The % PMP was obtained from a report commissioned by the State of Utah Division of Water Resources and Division of Water Rights, State Engineer's Office entitled "Probable Maximum Precipitation Estimates for Short-Duration, Small-Area Storms in Utah" (Jensen, 1995). The report states that "because the depth-duration values published in HMR 57 were very much like those derived in this study, the published HMR 57 depth-duration values were accepted for operational use in Utah." Therefore, the % PMP was determined using the Utah-specific depth-duration found in Figure 8 (Jensen, 1995) and HMR 57 instead of the general depth-duration relationships described in HMR 49 and NUREG/CR-4620.

Rainfall intensity (i) for the purpose of use in the rational equation is then calculated as:

i = PMP rainfall depth x 60 / rainfall duration

Where:
i = rainfall intensity, inches/hour
rainfall duration = time of concentration calculated as described above, minutes

The results of the above calculation is summarized in the table below.

PMP RAINFALL INTENSITY
CLASS A WEST CELL

Slope Description	Rainfall Duration (T_c) (minutes)	% PMP (%)	Rainfall Intensity (i) (inches/hr)
Top Slope (4%)	17.4	53.8%	18.4
Side Slope (20%)	4.6	15.3%	19.8

PMP RAINFALL INTENSITY
FEDERAL CELL

Slope Description	Rainfall Duration (T_c) (minutes)	% PMP (%)	Rainfall Intensity (i) (inches/hr)
Top Slope (2.5%)	16.9	52.1%	18.3
Side Slope (20%)	4.4	14.7%	19.8

As opposed to the projection of the long-term effects of precipitation over time due to sheet erosion, the effects of gully erosion are determined by the consideration of a large single rainfall event. The equation given in NUREG-1623 for the procedure to determine the peak runoff flow rate is:

$$\mathbf{Q = Fci\ A}$$

Where:
Q = Runoff Rate, cfs/ft
F = Flow concentration factor (recommended to use a factor of 3 by NRC staff in NUREG-1623)
c = dimensionless runoff coefficient
i = rainfall intensity, in/hr
A = catchment area, acres (using a 1 foot wide strip along the length of the slope)

Using this flow rate, a flow depth is calculated by solving the Manning Equation for normal depth on a one foot wide strip along the slope length. The Manning's n value was calculated to be 0.05 using an empirical equation for channels with gravel beds with shallow flow depths (Bray, 1979). The derivation of the Manning Equation to solve for depth is given in NUREG-1623 as:

$$\mathbf{y^{5/3} = Qn / (1.486\ S^{1/2})}$$

and $\mathbf{V = Q/y}$ where V is the flow velocity in ft/sec

The results for both the top slope and the side slope of the Class A West Cell using the vegetated slope condition are summarized in the following table. Flow velocities on the top and side slopes of the Class A West Cell during the PMP event are predicted to be 2.37 and 2.07 ft/sec,

respectively. The acceptable Maximum Permissible Velocity (MPV) was selected from tables provided in NUREG/CR-4620. The permissible velocity method is a commonly applied method to determine channel stability. Under this method the slope is assumed stable if the calculated velocity (V, the velocity resulting from a PMP in this application) is less than the MPV. By contrast, if velocities exceed the MPV, it is assumed that the slope will experience excessive erosion that will lead to the formation of gullies. The methodology presented in NUREG-1623 then directs that the estimates for the MPV be adjusted downward to account for the influences of flow depth. The side slope gully analysis was completed independently of the top slope.

GULLY EROSION POTENTIAL – VELOCITY ANALYSIS
CLASS A WEST CELL

Slope Description	Length (ft)	Slope (ft/ft)	i (in/hr)	c	Q (cfs/ft)	y (ft)	V (ft/sec)	Adjusted MPV (ft/sec)
Top Slope (4%)	942	0.04	18.4	0.5	0.60	0.25	2.37	2.5
Side Slope (20%)	188	0.20	19.8	0.5	0.13	0.06	2.07	2.5

Therefore, all slope scenarios using the ET cover system are assumed to provide acceptable protection against gully erosion using these criteria by limiting the potential of gully formation from high velocity channelization.

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Deep Time Supplemental Analysis Responses for the Clive DU PA Model

23 February 2018

Prepared by

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6. Remarks		

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Figure A-4. (From Neptune (2015a).) Gully exposure of a lens of sandy conglomerate from the outcrop shown in Figure A-3. The conglomerate contains distinctive clasts of black volcanic rock derived from bedrock exposures in the Grayback Hills, northwest of the Clive Site. The dashed line is the base of the laminated marl of Lake Bonneville (deep lake). The gravel lens is here approximately 1 meter thick. It is correlative with the Lake Bonneville Transgressive unit (0.76 m thick) listed in Table 3 of Neptune (2015b). 18
Figure A-5. (From Neptune (2015a).) Intermediate lake deposits of the regressive phase of Lake Bonneville exposed in the north quarry wall of the Clive Site. The lake deposits are exposed in the interval extending from the top of the hammer head to the middle of the handle and are overlain by aeolian silt with local reddening from soil alteration. 19

TABLES

Table 1. Compilation of Lake Sedimentation Rates. 9

ACRONYMS AND ABBREVIATIONS

DU	depleted uranium
ka	kilo-annum (1,000 years)
UDEQ	Utah Department of Environmental Quality (also referred to in quoted interrogatory text as "DEQ/SC&A," reflecting authorship of DEQ's consultant, SC&A, Inc.)

1.0 Overview and Conceptual Model

1.1 Aeolian Deposition

During warm interglacial climates like the present, the predominant process of sedimentation at the Clive Site is aeolian. (Note: the terms “aeolian” and “eolian” are used interchangeably in the geological literature and refer to wind-generated sedimentary processes. The names are derived from Aeolus, the Greek god of wind.) Aeolian source materials are transported and deposited by prevailing winds sweeping across barren dry lake beds and the wetted fringes of playas where gypsum crystals are supplied continuously by evaporation above sites of shallow groundwater. Aeolian sedimentation occurs in two modes: saltation or bouncing of sand-sized particles forming dune landforms, and suspension fallout that produces a near-uniform blanket of fine-grained silt deposited at the ground surface.

The primary mode of aeolian deposition at the Clive Site is suspension fallout. The average thickness of these deposits is about 72 cm (Neptune 2015a). The age of the aeolian silt deposits at the Clive Site is estimated to be between 14,500 and 10,000 years before present, based primarily on the estimates of the timing of final retreat of Lake Bonneville below the elevation of the Clive Site (Neptune 2015a). Data for the thickness variations and ages of aeolian sediments at the Clive Site are used to develop a distribution of the range of past aeolian sedimentation rates (mean rate of 59 mm per 1,000 years with a standard error of the mean of 5 mm). This distribution is used in the Deep Time model to project thicknesses of aeolian sediments over time. The sediment thickness numbers are calculated in the model by multiplying the aeolian deposition rates by the time when a future lake rises to the elevation of the Clive Site. Using computer simulation, the Deep Time model samples a range of values of the depositional rate and the time to the first lake arrival. A longer time to the first lake arrival and a higher aeolian deposition rate result in a thicker blanket of aeolian deposits over the Clive Site, which in turn reduces the Deep Time model projections of the peak ground surface radon flux. The peak radon flux is the critical model output for assessing the Deep Time model results.

UDEQ agrees with the thickness estimates and time constraints for aeolian deposition in the Clive area (see Interrogatory CR R313-25-8(5)(A)-18/3: Sediment Accumulation). They did not comment on and presumably accept the model representation of the future time of the arrival of the first lake. They disagree with the approach used to estimate the statistical variation in the aeolian deposition rate (standard error of the mean; see Interrogatory CR R313-25-8(5)(A)-18/3: Sediment Accumulation).

1.2 Intermediate Lake Sedimentation

The Lake Bonneville basin of Utah and Nevada has been occupied by fresh to saline lakes ranging in size from the scale of Lake Bonneville during the Last Glacial Maximum to the present day Great Salt Lake. Future glacial cycles will lead to the rise of the Great Salt Lake above the elevation of the Clive Site. A glacial cycle refers to climate intervals associated with long-term reduction in global temperature, reduction in atmospheric CO_2, and growth of ice sheets and glaciers with falling sea levels. An interglacial cycle refers to warmer periods between glacial cycles with sea levels at or near current levels. The earth has been in an interglacial cycle

since the Holocene epoch, a subdivision of geologic time representing the last 12 ka years before the present (ka is kilo-annum or 1,000 years).

The Deep Time model (Neptune 2015b) uses a combination of past patterns of glacial and interglacial cycles over the last 2 million years, global ice core and oxygen isotopic data, and the history of past lake cycles in the Lake Bonneville basin to develop model projections of future lake cycles in the Clive region. These model projections are closely tied to a widely accepted 100 ka length of global glacial cycles during the last 1 million years (Crowe et al. 2017; Lisiecki and Raymo 2005). Field observations and drill core studies of lake deposits from two locations in the Lake Bonneville basin are used to correlate observed lake sediments to lake patterns during glacial cycles.

Three processes of sedimentation will affect the Clive Site during future glacial and interglacial cycles, and the integrated processes will result in progressive burial of the Site through time. These processes are aeolian deposition, deep lake sedimentation, and intermediate lake sedimentation.

Aeolian deposition: During warm interglacial cycles like present-day conditions, small lakes like the modern Great Salt Lake are maintained (lake elevation about 1280 meters). Under these conditions, the Clive Site (elevation about 1307 meters) is at the surface, and sedimentation at the Site consists of deposition of aeolian silt as suspension fall-out from surface winds.

Deep lake sedimentation: During past glacial conditions, the Clive Site has been covered by large/deep lakes with lake surface elevations ranging from about 1360 meters (Stansbury Shoreline) to about 1620 meters (Bonneville Shoreline). These elevations are 53 to more than 300 meters above the elevation of the Clive Site. Sedimentation at the Site under these deep lake conditions is primarily from slow precipitation of carbonate with secondary quantities of fine-grained silt. The silt content of deep lake sediments varies depending on lake currents, distance to shorelines or surface outcrops, and fluvial (stream) sources of sediment. The Deep Time model uses a distribution of deep lake sedimentation rates that range from about 0.075 to 0.20 mm/yr (Neptune 2015b). The Clive Site is adjacent to areas of higher topography that are likely to be local sources of clastic sediments during future deep lake cycles.

Intermediate lake sedimentation: Intermediate lakes are defined with respect to the elevation of the Clive Site. They include lakes that rise to and slightly above the elevation of the Site. Intermediate lakes transition to deep lakes when the water depth exceeds the depth of wave agitation (arbitrarily defined as approximately 10 meters above the elevation of the Clive Site). Thus defined, intermediate lakes form during periods of fluctuating lake levels and also during transitory phases of transgressive and regressive deep lakes. Intermediate lake sedimentation is affected by wave activity and sediment transport associated with wave activity (longshore drift). Wave-driven currents transport clastic sediments. (Note: clastic sediments are defined as material that is mechanically or chemically fragmented and transported/deposited by sedimentary processes.) Intermediate lake sedimentation includes carbonate precipitation, but carbonate deposits tend to be secondary in volume to clastic sediments in areas of significant clastic sediment supply and/or wave activity.

Sedimentation associated with intermediate lakes in the Deep Time model is represented as a sediment thickness per intermediate lake event. UDEQ argues that the basis for representation of intermediate lake events is inadequately documented and that the depositional rates for the intermediate lake events may be too high. Overestimation of depositional rates could lead to Deep Time model projections that overestimate the depth of burial of the Clive Site over time.

2.0 UDEQ Interrogatory Responses

This section responds to Interrogatories CR R313-25-8(5)(A)-18/3 and CR R313-25-8(4)(D)-132/2. As noted by UDEQ in Interrogatory 132/2, the issues raised therein "are similar to some of the Interrogatory 18 responses. To reduce redundancy, consideration should be given to closing this interrogatory." Accordingly, this response is focused on the two main issues raised in Interrogatory 18/3: aeolian deposition and intermediate lake sedimentation rate. The latter issue covers the concerns raised in Interrogatory 132/2.

2.1 Interrogatory CR R313-25-8(5)(A)-18/3: Sediment Accumulation Part One—Aeolian Deposition

After much exposition on the subject of aeolian deposition under the heading *DEQ Critique of DU PA v1.4, Appendix 13*, this interrogatory states:

> In conclusion, the above discussion presented four concerns that DEQ/SC&A has identified with the Energy*Solutions*/Neptune aeolian deposition model. In order of perceived importance, these are:
>
> 1) Deposition in the sub-areas of the embankment is likely correlated, rather than independent. A correlated model would produce results that are more conservative than the current Energy*Solutions*/Neptune model. However, the degree of correlation is presently unknown (and perhaps unknowable).
>
> 2) The sample results do not represent a "point in time," as Energy*Solutions*/Neptune indicated in their previous response. Rather, the samples are an accumulation over 13,000 to 15,000 years (Appendix 13, p. 38). Thus, the sample results can be thought of as being time averages.
>
> 3) Using the Energy*Solutions*/Neptune model results in a dose calculation means that the dose receptor spends an equal amount of time in each embankment sub-area. The more conservative assumption is that the dose receptor spends all of his time in the sub-area with the least amount of deposition. Alternatively, the sub-area in which the dose receptor spends his time could be randomly selected.
>
> 4) Dividing the embankment into 11 sub-areas based on the number of samples, as was done for the Energy*Solutions*/Neptune model, appears reasonable. However, Energy*Solutions*/Neptune should provide the rationale for selecting this approach.
>
> DEQ/SC&A continues to believe that for nuclear licensing purposes the mean and standard deviation aeolian deposition model should be used.

2.1.1 Interrogatory Response

2.1.1.1 Factual Accuracy and Technical Applicability of the UDEQ Review Comments

Each of the four concerns outlined by UDEQ is addressed individually below.

Concern 1: UDEQ has questioned the approach used to select sub-areas for the embankment and has suggested that the number of sub-areas should be established initially and used to identify collection sites for each sub-area. They argue that sub-areas of the embankment are correlated rather than independent, and that a correlated model would produce more conservative results than the current Deep Time model. (Note: we assume "conservative" means thinner aeolian deposits that would allow higher ground-surface radon flux in the Deep Time model results.)

Response to Concern 1

The Clive Site was not divided into sub-areas. UDEQ has incorrectly equated "sub-areas" with field measurement sites. Field measurement sites for aeolian sediments at the Clive Site met two selection criteria (Neptune (2015a), Section 2.1.4.1):

1. Contained exposures of the base of the aeolian sediments and the underlying sequence of Lake Bonneville lake deposits.
2. Preserved the top surface of aeolian deposits to ensure the deposits were not changed by post-deposition erosion or construction activities at the Site.

Additionally, the measurement data for the aeolian sediments were designed to be used in the Deep Time model. The model requires thickness data for the aeolian sediments at the scale of the DU disposal cell—the model does not calculate aeolian deposition rates for sub-areas. Field data that met the two selection requirements were collected throughout the Clive Site (see Figure 8 and Table 2 in Neptune (2015a)).

Concern 2: UDEQ has argued that the field measurements of the thickness of aeolian sediments across the Site do not represent a "point in time" as inferred in the Deep Time report. They suggest instead that the sample sites are time integrated averages of aeolian deposition over 13,000 to 15,000 years.

Response to Concern 2

We agree in principle with the review comment. However, the Deep Time report did not claim that the thickness of aeolian sediments was a "point in time." UDEQ's confusion may result from an incorrect interpretation of the last paragraph of Section 4.0 of the Deep Time supplemental model (Neptune (2015b), Section 7.1):

> Therefore, the thickness of residual embankment material and sediment overlying the disposed DU waste at the time when the first intermediate lake recedes will be effectively equivalent to the thickness of aeolian sediments deposited up until that **point in time**, represented by the rising elevation of the surrounding grade (*emphasis added*).

Here the "point in time" refers to the time of return of the first lake to the Clive elevation, not processes of aeolian sedimentation. Aeolian sediments at the Clive Site represent an integrated response of multiple processes (aeolian deposition and erosion, soil formation) occurring over time at the spatial scale of the Clive Site. This is described in Section 5.1 of Neptune (2015c):

> The preserved record of eolian deposition at the Clive site integrates variations in eolian parameters and processes of deposition and burial over thousands of years. This integrated record is assumed to provide the most consistent information for forecasting eolian depositional rates over tens of thousands of years.

The Deep Time model uses a probability distribution of aeolian depositional rates projected forward in time. The development of the probability distribution for the aeolian depositional rate is described in Neptune (2015a), and its application is analogous to the spatial averaging of aeolian sediment thickness across the Clive Site discussed in the response to Concern 1 above.

Concern 3: UDEQ argues that the aeolian deposition rate and Deep Time model results used multiple sub-areas and should have included implicit assumptions about the location and exposure time of a dose receptor in each sub-area.

Response to Concern 3

UDEQ's objection is an improper interpretation of the radon flux and the Deep Time model results. Sub-areas were not used in the Deep Time model. More importantly, the ground surface radon flux has dimensions of area and time (pico-Curies per square meter per second). This performance metric is not a dose and does not include or require a receptor or a receptor location.

Concern 4: UDEQ has requested that a rationale be provided for dividing the embankment into 11 sub-areas.

Response to Concern 4

The rationale for selection of measurement sites for aeolian sediments is described in Neptune (2015a) and is repeated in the response to Concern 1 above (availability of suitable outcrops and the scale of representation of the Clive Site in the Deep Time model). The probability distribution used for the aeolian depositional rate in the Deep Time model is based on field data from the Clive Site (11 field measurement sites and 21 clay resource test pits). These data provide a statistically representative sample of the population of thickness data for aeolian deposits across the Clive Site.

The Deep Time model requires upscaling of the field measurement data to the model scale, a technically appropriate and established practice in environmental modeling studies (for example, Blöschl and Sivapalan (1995); Neuman et al. (2003); Zhang et al. (2004)). The field measurement scale of aeolian sediment thickness is applicable for areas of several square meters (individual measurement site); the application of the aeolian rate calculation in the Deep Time model is the DU disposal unit, a scale of thousands of square meters. The technically established statistic for upscaling is the mean thickness of the field measurement and the standard error of the mean to represent the variance of the averaged measurement data. Using the standard deviation of the measurement data as suggested by UDEQ would incorrectly distort the variance structure (representation of the variation of the measurement sites) in the Deep Time model application.

2.1.1.2 The Effects of the Aeolian Deposition Rate on the Deep Time Model Results and Uncertainty in the Results

UDEQ/SC&A have noted that differences between the standard error of the mean versus the standard deviation of the measurements have a small impact on the average model results (Interrogatory CR R313-25-8(5)(A)-18/3: Sediment Accumulation, p. 13). We agree. The important Deep Time model result is the ground surface radon flux through time. This model result is sensitive to the following: (a) the sub-model used to estimate the ground surface radon flux, (b) the time to the return of the next lake at the elevation of the Clive Site, (c) the aeolian deposition rate, and (d) lake sedimentation rates during glacial cycles. UDEQ comments critique only the variance of the aeolian depositional rate, and we have demonstrated that their comments are not applicable to the data used for aeolian sedimentation in the Deep Time model.

2.2 Interrogatory CR R313-25-8(5)(A)-18/3: Sediment Accumulation Part Two—Intermediate Lake Sedimentation Rate

After discussing intermediate lake sedimentation rates under the heading *DEQ Critique of DU PA Appendix 21*, this interrogatory concludes:

> For all of these reasons, Energy*Solutions*/Neptune needs to either (1) provide independent documentation that a sedimentation rate of 1.2 mm/yr is plausible or (2) define a plausible, defensible intermediate lake sedimentation rate and redo the deep time analysis.

2.2.1 Interrogatory Response

This response addresses the following topics related to UDEQ concerns on the intermediate lake sedimentation rate:

1. The technical rationale for the representation of intermediate lake sedimentation in the Deep Time model.
2. New information is compiled from the scientific literature that expands documentation of overall lake sedimentation rates and their application in the Deep Time model.
3. Field observations are summarized on the processes of intermediate lake sedimentation at the Clive Site during the last transgressive (rising lake) and regressive (declining lake) stages of Lake Bonneville (Appendix A).
4. The effects of intermediate lake sedimentation rates on the Deep Time model results, and by extension the limited value of additional studies in this area.

2.2.1.1 Intermediate Lake Sedimentation

UDEQ has questioned the intermediate lake sedimentation "rate" used in the Deep Time model, including both a reference to a sedimentation "rate" that is 10 times greater than the large lake sedimentation rate (Version 1.4 of the Deep Time model; Neptune (2015b)) and a sedimentation "rate" that they estimate to be as high as 5.64 mm/yr. They suggest the intermediate lake sedimentation "rates" used in the model are unrealistic and cite literature from the Eastern Great Basin of Utah supporting lake sedimentation rates that range from 0.12 to 0.83 mm/yr. (Note:

these sedimentation rates apply to lake sedimentation in general and are not specific to intermediate lake sedimentation.*)* UDEQ also argues, citing input from Dr. Paul Jewell, University of Utah, that lake sedimentation patterns can be complicated depending on proximity to active faults and local sources of stream sediment. They have requested enhanced documentation of sedimentation rates of 1.2 mm/yr or greater and development of a more defensible "rate" of intermediate lake sedimentation. UDEQ also suggests that revision of the intermediate lake sedimentation "rates" could require revision of the Deep Time model.

Establishing sedimentation rates for intermediate lakes is problematic for two reasons. First, the lake sediments are reworked by wave activity that intermixes deep lake sediments (carbonate marl), aeolian sediments, and intermediate lake clastic sediments. It is often difficult or impossible to distinguish the different types of deposits in core studies. Second, intermediate lakes are transitory features of limited duration. It is very difficult and impractical to attempt to obtain the data necessary to constrain the ages of intermediate lake sediments and to estimate depositional rates.

Recognizing these difficulties, the Deep Time model uses a pragmatic approach that represents sedimentation by intermediate lakes as a depositional thickness per lake event. Estimates of sediment thickness of intermediate lakes in the Deep Time model are derived primarily from conceptual models of the processes of lake sedimentation, studies of sediment cores from drill holes in the Lake Bonneville basin (Knolls and Burmester lake cores), and interpretations of lake sediments in a Clive pit wall (Neptune 2015b). The latter interpretations are from a single quarry-wall exposure that was studied in 1985. This combined information base is used to establish a probability distribution of sediment thickness per intermediate lake event (see Figure 11; Neptune (2015b)).

UDEQ derives their cited intermediate lake sedimentation "rate" of 5.64 mm/yr by dividing the geometric mean of the distribution of intermediate lake sediment thickness used in the Deep Time model (2.82 m) by the estimated duration of an intermediate lake (500 years; Neptune (2015b)). However, the Deep Time model does ***not*** use a sedimentation rate for intermediate lakes and, in fact, the Deep Time model report specifically cautions (Neptune (2015b), Section 7.1):

> There is virtually no information for the duration of intermediate lakes, due to the high mixing rate of shallow lake sediments, which makes dating of times within a single stratigraphic layer of a shallow lake sediment core extremely difficult. Thus, a distribution was chosen to roughly calibrate with the heuristic model: lognormal with geometric mean of 500 y and geometric standard deviation of 1.5.

UDEQ, in their comment, incorrectly used information from the Deep Time probability distribution of sediment thickness per lake event to calculate a sedimentation "rate" that is non-applicable and was not used in the Deep Time model results. The technically correct approach that UDEQ should have evaluated is a comparison of Deep Time model results for sedimentation rates during 100-ka glacial cycles. Under this approach, the composite sediment thickness of intermediate lake events is combined with aeolian and deep lake sedimentation. This composite sediment thickness is constrained in the model by observed sediment thicknesses of 15 to 20 meters per glacial cycle based on core studies at the Knolls and Burmester sites (Neptune (2015b), Section 7.4). This model interpretation of sediment thickness per glacial cycle is

equivalent to sedimentation rates of 0.15 to 0.20 mm/yr, and these rates are consistent with lake sedimentation rates in new studies reported herein.

2.2.1.2 Expanded Documentation of Lake Sedimentation Rates

This section examines lake sedimentation rates in response to UDEQ's request for documentation of rates greater than 1.2 mm/yr. This new information does not apply directly to the Deep Time model representation of intermediate lake sediment thickness per lake event. As noted above, the data from Table 1 rates should be compared with sedimentation rates used in the Deep Time model for100 ka glacial cycles.

Table 1 is a compilation of lake sedimentation rates from literature publications and calculations derived from unpublished data and/or interpreted data. Sedimentation rates in Table 1 range from as low as < 0.01 mm/yr to over 6.0 mm/yr. This range of variation is caused by a combination of factors, including:

1. Rates of carbonate precipitation (fine-grained calcareous ($CaCO_3$) mud).
2. Local availability of clastic sediment sources (gravel, sand, silt, and clay-sized particles), primarily from proximity to areas of active faulting, higher topography near lake edges, and/or near areas of river or stream that discharge into the lake.
3. Processes of wave activity that may produce strong longshore currents and may locally transport and deposit clastic sediments.
4. Mass movement of lake bottom deposits.

Table 1. Compilation of Lake Sedimentation Rates.

Lake	Location	Min Rate (mm/yr)	Max Rate (mm/yr)	TimeSpan (years)	Long/Short (rate duration)	Reference
Great Salt Lake	U.S.	0.57	0.57	11,500	Long	Thompson et al. (2016)
Great Salt Lake	U.S.	1.1	4.1	< 100	Short	Naftz et al. (2000)
Great Salt Lake	U.S.	0.1	6.7	< 10,000	Short/Long	Oliver et al. (2009)
Lake Baikal	Asia	0.05	0.05	> 100,000	Long	Colman et al. (1995)
Lake Bonneville	U.S.	0.8	0.8	12,000	Long	Thompson et al. (2016)
Lake Bonneville	U.S.	0.04	0.94	12,000	Long	Oviatt (2018 [in press])[1]
Lake Bonneville	U.S.	0.04	> 3.0	12,000	Long	Oviatt (2018 [in press])[2]
Lake Michigan	U.S.	< 0.01	0.84	< 10,000	Long	Robbins and Edgington (1975)
Lake Michigan	U.S.	3.0	3.0	< 100	Short	Robbins and Callender (1975)
Lake Tanganyika	Zaire	0.07	1.84	> 100,000	Long	Cohen et al. (1993)
Owens Lake	U.S.	0.4	0.4	> 100,000	Long	Bischoff et al. (1997)
Red Lake	Romania	1.17	3.2	< 100	Short	Begy et al. (2009)
Taihu Lake	China	0.1	0.42	< 100 yr	Short	Wang et al. (2001)

[1] Open lake; only carbonate marl
[2] Including deltas

High clastic sediment flux can cause very high local lake sedimentation rates. Very low sedimentation rates generally occur in lake interiors that are distant from shorelines and sources of clastic sediment (Oviatt 2018 [in press]). Significant variations in lake sedimentation rates can occur over short horizontal distances depending on the local variations in processes of sediment transport. During intervals of high wave activity, when intermediate lakes are present at the elevation of the Clive Site, sedimentation rates can vary from negative (erosion) to very high (progradation of gravel spits by longshore drift). Additionally, the dynamics of wave activity will vary through time, with short-term variations in lake levels and changes in wind direction and wind velocity. Maximum sediment deposition for intermediate lakes will most likely occur during storm events (storm surge).

2.2.1.3 Evidence of Clastic Sedimentation at the Clive Site

Field studies of the lake sediments at the Clive Site provide important evidence of significant past clastic sedimentation at the Clive Site associated with formation of transitory intermediate lakes. These clastic sediments have been studied primarily for the transgressive (rising lake) and regressive (declining lake) phases of Lake Bonneville (Neptune 2015a). Supporting documentation for these observations, including photographs of the lake sediments and larger-scale sedimentary features of longshore drift, were provided previously to UDEQ (Neptune 2015) and are repeated in Appendix A of this report.

The Clive Site has been and is expected to be an area of highly variable sedimentation during future glacial cycles; this includes sedimentation associated with aeolian activity and formation of intermediate and deep lakes. The optimal approach for representing the multiple dynamic processes of lake sedimentation is through model simulations using a distribution of composite sediment thickness for 100 ka glacial cycles. The sedimentation "rate" derived by UDEQ for intermediate lakes is not applicable to the Deep Time model.

2.2.1.4 Impact of Intermediate Lake Sedimentation on the Deep Time Model Results

The Deep Time model output of significance for the supplemental analysis is the ground surface flux of radon (Figure 1 this paper; derived from Neptune (2015c)). Figure 1 shows that the peak flux of radon occurs at about 60 ka, the model-projected time of the first occurrence of an intermediate lake at the Clive Site.

The important Deep Time model assumptions and parameters that control the timing and magnitude of the peak surface radon flux are:

1. The model representation of radon diffusion through the embankment cover and overlying sediments.
2. The time of the first lake event at the Clive Site.
3. The aeolian deposition rate.
4. The intermediate lake sediment thickness for individual lake events.

Generally, the longer the time to the first event, the thicker the mantle of aeolian sediments on top of the Clive Site. An intermediate lake event adds sediments above the top of the Site; the added amount is determined by randomly sampling (computer simulation) the sediment thickness probability distribution (see Figure 11; Neptune (2015b)). Overall, the Deep Time model projections of combined processes of sedimentation (aeolian, intermediate, and deep lake processes) affect the thickness of sediments covering the Clive Site over time. Increased depth of burial will result in a systematic reduction in the radon flux (see the curve of the surface radon flux in Figure 1).

An additional consideration is that the intermediate lake sediment thickness is not an independent parameter in the Deep Time model results. It covaries with both the aeolian sedimentation rate and the deep lake sedimentation rate. The three model parameters are constrained in the Deep Time model by the composite thickness of sediments during the 100-ka glacial cycles (15 to 20 meters thickness; Neptune (2015c)).

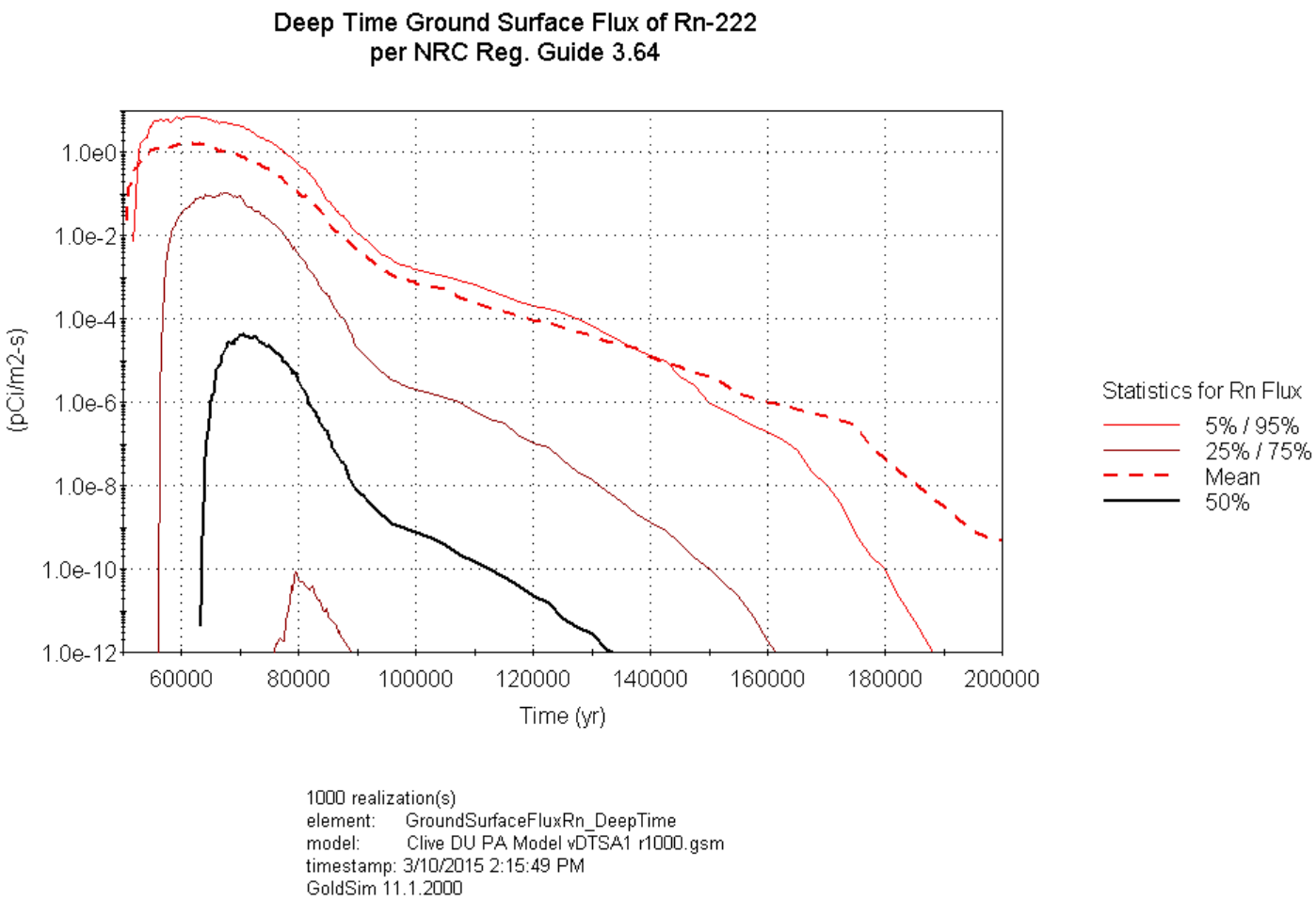

Figure 1. Deep Time ground surface flux of Rn-222 per NRC Reg. Guide 3.64.

3.0 Conclusion

UDEQ has raised several issues in the Deep Time interrogatories. The following points summarize this response:

- The aeolian sediment data reported in Neptune (2015a) were used to establish statistical parameters (sediment thickness and variations in sediment thickness) in the Deep Time model. These measurements are a statistically representative sample of the population of aeolian thickness data for the Clive Site and the DU disposal unit. UDEQ's assertions concerning sub-areas and sub-area correlations are not applicable to either the aeolian field studies or the aeolian sedimentation parameters used in the Deep Time model.
- UDEQ has incorrectly assumed that the embankment is divided into 11 sub-areas in the Deep Time model. The rationale for using the standard error of the mean in the probability distribution for the aeolian depositional rate in the Deep Time model was described in Neptune (2015a). The standard error of the mean is the correct statistical

parameter for representing the variance of the aeolian deposition rate for the scale of the Deep Time model application. The recommendations by UDEQ do not follow established modeling practices for environmental studies.

- The correct approach and statistical parameters are used for the aeolian depositional rate in the Deep Time model and the impact of the variation in this rate on model results is insignificant.
- Contrary to the interpretations in the review responses by UDEQ, the Deep Time model does not use an intermediate lake sedimentation "rate." Intermediate lakes are represented by a distribution of sediment thickness per lake event.
- The distribution of sediment thickness for intermediate lake events is integrated with the aeolian and deep lake sedimentation rates during 100-ka glacial cycles. The integrated sedimentation rates during the glacial cycles (0.15 to 0.20 mm/yr) are consistent with documented lake sedimentation rates, including rates cited in the review responses by the UDEQ and the newly developed data shown on Table 1 in this report.
- We agree with the UDEQ comment that lake sedimentation patterns can be complicated and are dependent on locations within lakes, interaction with wave-generated currents, proximity to active faults, and local sources of sediment. These issues are already addressed appropriately in the Deep Time model by integrating multiple sources of information on lake sedimentation, including observations of lake and aeolian sedimentary deposits at the Clive Site.
- Table 1 provides expanded documentation of lake sedimentation rates in response to the UDEQ review comments, but these rates do not apply to the representation of intermediate lakes in the Deep Time model. The data summarized in the table support wide ranges in lake sedimentation rates and include rates greater than 1.2 mm/yr.
- The model distribution used to represent intermediate lake sediment thickness is based on 1985 data at the Clive Site for primarily the Lake Bonneville sedimentation history, with limited local data for sedimentation associated with pre-Lake Bonneville glacial cycles. The integrated net sedimentation rates used in the model for the 100-ka glacial cycles are consistent with drill core data from the Clive region and published information on lake sedimentation rates (see Table 1).
- The range of sediment thicknesses for intermediate lake events and integrated lake sedimentation rates during glacial cycles used in the Deep Time model decreases the peak ground surface radon flux and the radon flux over time. The data used for the lake sedimentation rates are derived from and are consistent with core studies of deposits of Lake Bonneville for past glacial cycles, published studies of lake sedimentation rates, and field observations at the Clive Site.

On the basis of the concerns expressed by UDEQ as responded to herein, revision of the Deep Time model is not justified.

4.0 References

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Appendix A. Sedimentary Deposits of the Transgressive and Regressive Phases of Lake Bonneville Near and Within the Clive Site (Deposits of Intermediate Lakes)

Field studies of aeolian sediments and lake sediments in the Clive region (Neptune 2015a) have described local exposures of gravel, sandy conglomerate, and sand in the Clive region. These sediments were deposited primarily during the transgressive phase of Lake Bonneville, and patterns of clastic sedimentation associated with past intermediate lake events were documented. The cited studies were not focused on the lake events and thus detailed descriptions of the sediments, including facies variations and thickness variations within and near the Clive Site, have not been compiled.

The purpose of this brief summary is to document local characteristics of the deposits, including evidence of energetic longshore drift with formation of local spits during the last transgressive intermediate lake event near the Clive Site. The intermediate lake sediments contain distinctive clasts of black volcanic rocks derived from local bedrock exposed in the Grayback Hills northwest of the Clive Site. These relationships are consistent with southeast-directed wave activity driving longshore drift that transported coarse sandy conglomerate and sand southeastward from the Grayback Hills across the Clive Site.

Figure A-1 is a photograph of a roadcut exposure along Highway I-80 north of the Clive Site. The outcrops expose the upper part of spit deposits of sandy conglomerate of the transgressive phase of Lake Bonneville (deposited by longshore drift of an intermediate lake) overlain by Lake Bonneville marl (deep lake deposits). The marl is overlain by Holocene aeolian silt.

Figure A-2 shows the locations of the Grayback Hills, the Clive Site, and the roadcut exposure of Figure A-1. Buried ridges extend from the Grayback Hills toward the Clive Site and are upheld by spit deposits of sandy conglomerate formed by longshore drift associated with an intermediate lake. These ridges were interpreted originally as shorelines of the Gilbert phase of Lake Bonneville. Recent field work has shown instead that the topography is upheld by spits buried beneath the Lake Bonneville marl (Neptune 2015a).

Figure A-1. Roadcut exposures of the upper contact of the transgressive phase of Lake Bonneville.

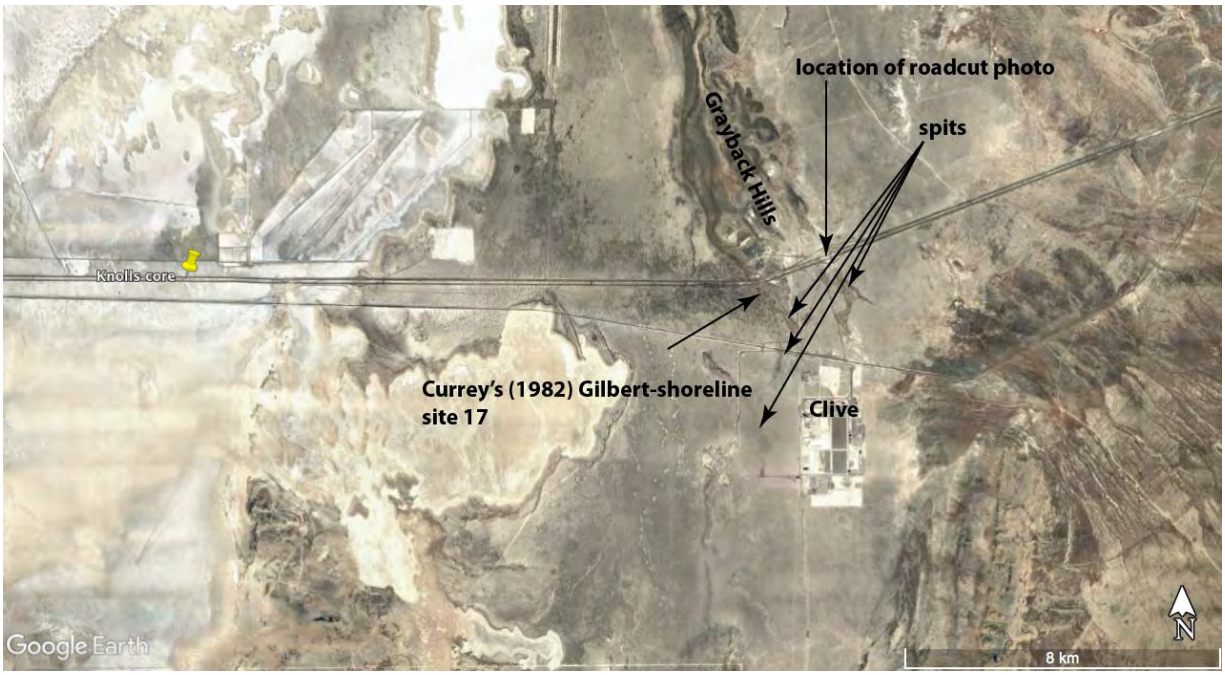

Figure A-2. Annotated Google Earth image showing the Clive area and buried spits developed on the southeast edges of the Grayback Hills. The spits prograded toward and across what is now the Clive Site.

Figure A-3 is from Neptune (2015a) and shows a quarry-wall exposure in the north part of the Clive Site that contains exposures of the upper contact of the transgressive deposits of Lake Bonneville.

Figure A-4 (also from Neptune (2015a) is a close-up view of the outcrop area shown in Figure A-3. The sandy conglomerate was deposited by longshore drift that prograded sediment from the northwest to southeast across the Clive Site. The thickness of this intermediate lake sediment is expected to thin across the Clive Site (north to south) away from the sediment sources at the Grayback Hills.

Figure A-3. (From Neptune (2015a).) View looking south from the north wall of Pit 29 at the Clive Site. The dashed line marks the contact between the laminated marl of Lake Bonneville (deep lake) and underlying transgressive sands with lenses of volcanic conglomerate (deposits of an intermediate lake).

Figure A-4. (From Neptune (2015a).) Gully exposure of a lens of sandy conglomerate from the outcrop shown in Figure A-3. The conglomerate contains distinctive clasts of black volcanic rock derived from bedrock exposures in the Grayback Hills, northwest of the Clive Site. The dashed line is the base of the laminated marl of Lake Bonneville (deep lake). The gravel lens is here approximately 1 meter thick. It is correlative with the Lake Bonneville Transgressive unit (0.76 m thick) listed in Table 3 of Neptune (2015b).

Figure A-5 is a photograph of the deposits of the regressive phase of Lake Bonneville exposed in the north wall of Pit 29 at the Clive Site. The sediments of this regressive intermediate lake are preserved as a gradational zone between overlying aeolian silt (Holocene) and underlying reworked marl of Lake Bonneville (light-colored sediments near the middle of the pick handle). These regressive intermediate lake deposits are approximately 30 centimeters thick and illustrate the variability of sedimentation patterns of intermediate lakes. The fine-grained silts of this regressive intermediate lake are attributed to a combination of draping of the underlying topography by fine-grained marl (the only available sediment source) and the probable rapid fall of lake levels during the regressive phase of Lake Bonneville at the elevation of the Clive Site.

Figure A-5. (From Neptune (2015a).) Intermediate lake deposits of the regressive phase of Lake Bonneville exposed in the north quarry wall of the Clive Site. The lake deposits are exposed in the interval extending from the top of the hammer head to the middle of the handle and are overlain by aeolian silt with local reddening from soil alteration.

NAC-0102_R0

Other Wastes Responses for the Clive DU PA Model

23 February 2018

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5. Reviewer	Mike Sully	13 Feb 2018
6. Remarks		

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ACRONYMS AND ABBREVIATIONS

CAW	Class A West embankment
CQA/QC	Construction Quality Assurance/Quality Control
DEQ	(Utah) Department of Environmental Quality
DOE	(United States) Department of Energy
DU	depleted uranium
DUO3	depleted uranium trioxide
ET	evapotranspiration
GDP	gaseous diffusion plant
LLRW	low-level radioactive waste
NRC	(United States) Nuclear Regulatory Commission
PA	performance assessment
SER	Safety Evaluation Report
SRS	Savannah River Site
UDEQ	Utah Department of Environmental Quality

1.0 Overview and Conceptual Model

The Clive DU PA is limited to the disposal of DU wastes of two general waste types: 1) depleted uranium trioxide (DUO3) waste from the Savannah River Site (SRS); and 2) anticipated DU waste as U3O8 from gaseous diffusion plants (GDPs) at Portsmouth, Ohio and Paducah, Kentucky. The quantity and characteristics of DU waste from other sources that has already been disposed of at the Clive Facility was not included. Similarly, other Class A LLRW anticipated for disposal within the Federal Cell was not included.

This choice was made for several reasons:

1. Probabilistic PAs, while a mature approach within the Nuclear Regulatory Commission (NRC) and the Department of Energy (DOE), are new to Utah LLRW regulators. This reality is reflected by Utah's need to utilize external contractor review support. A probabilistic PA is initially a more complex and expensive modeling approach than deterministic modeling; however, once the foundation is established it can easily be adapted for additional wastes and new data. Due to shorter half-lives, other Class A radionuclides have much shorter time periods for evaluation. Therefore, a relatively simplified approach was selected, with the intent that, once the basic model structure and approach was developed, additional Class A wastes could be more explicitly modeled as a follow-on activity. Given the commitment to place DU in the bottom of the Federal Cell, additional Class A wastes do not need to be modeled in order for embankment construction and initial DU placement to begin.
2. Class A LLRW had already been modeled multiple times for the Clive Site and basic cell design. These models demonstrated the Site's ability to achieve the performance objectives, albeit using deterministic rather than probabilistic performance assessments. Note that deterministic performance assessments for the Clive Site are consistently structured to demonstrate compliance even under extreme bounding conditions. These models also explicitly included DU at its specific activity (i.e., elemental DU), and existing disposals were placed in full compliance with a UDEQ-approved license. The Class A West (CAW) embankment differs from the Federal Cell in physical geometry and cover system design; however, the horizontal travel distances to compliance points are the same, the vertical vadose zone thicknesses are the same, and the precipitation falling on the cells is the same. Therefore, if the modeled infiltration is the same or less for the Federal Cell than for the Class A West embankment, then Federal Cell disposal of wastes already approved for disposal in the CAW can be expected to meet the performance criteria.
3. By definition (via the regulatory basis for 10 CFR Part 61), Class A LLRW decays to radiation levels that protect health and safety within the 100-year institutional control period. Therefore, the majority of Class A contaminants of concern have decayed away millennia before ingrowth concerns associated with DU would be exhibited.

In the final report for model version 1.4 (Neptune 2015a), Section 6.0 documents this scoping constraint: "The disposal volume above the DU waste is assumed to be backfilled with clean material for the purposes of this DU analysis." This constraint was established and has been

carried forward unchanged from the initial submittal of version 1.0 of the DU PA Model (Neptune 2011).

UDEQ acknowledged this approach in Section 1.0 of the 2015 SER (SC&A 2015):

> It should be noted that this SER apples only to approval/disapproval of the DU PA as required by UAC Rule R313-25-9(5)(a). That regulation does not consider "other wastes," which must be addressed in a separate performance assessment. If the DU PA performance assessment is approved, it is expected that the next step in the regulatory process would be submission of a proposed license amendment for review by DEQ.

Section 6.2.4 of the 2015 SER elaborates and provides Condition 4, which would apply to an amended License that would permit DU disposal:

> To meet the requirements of UAC R313-25-9(5)(a), Energy*Solutions* shall submit a revised performance assessment that meets the requirements of that provision and addresses the total quantities of concentrated DU and other radioactive wastes the facility now proposes to dispose in the Federal Cell. This revised performance assessment shall be subject to notice and comment and must be approved by the Director *prior to the land disposal of other radioactive waste* [emphasis added].

Energy*Solutions* did not object to this aspect of the 2015 SER, as this accurately reflects their intention and understanding of the regulatory process. Contrary to this agreed-upon regulatory process, Utah DEQ (2017) introduced two new interrogatories relating to other Class A waste. This is in spite of the basis for Interrogatory CR R313-25-9(5)(A)-196/1 correctly stating:

> Therefore, to address the R313-25-9(5)(a) "other waste" requirement, a revised PA, or a separate PA, must be prepared by Energy*Solutions*, and approved by DEQ, *before any "other waste" (understood to be DOE-generated Class A waste) is disposed of above the DU* [emphasis added].

Energy*Solutions* does not intend or request to dispose of other Class A LLRW above the DU until such time as a PA accounting for the combined effects of DU and other Class A LLRW is approved. This does not preclude approval to dispose of DU in the interim.

Current approved Clive deterministic PAs apply Unit 3 material properties to Class A waste. See Whetstone's *Revised Western LARW Cell Infiltration and Transport Modeling Report* (July 19, 2000) and their *Class A West Disposal Cell Infiltration and Transport Modeling Report* (Whetstone Associates 2011), which both include discussion of model insensitivity to waste thickness and other physical properties. This longstanding approach for the facility has been acceptable to UDEQ, dating to the earliest deterministic PAs. In raising an objection, UDEQ does not substantiate the change in approach from their prior approvals.

Modeling of waste layers as Unit 3 sandy soil has been accepted by the regulator precisely because Class A unstable waste is heterogeneous and may have a variety of physical forms. It would not be possible to model all possible waste form combinations; therefore, the model is simplified to represent waste layers as more permeable than the overlying cover and the underlying clay liner.

Furthermore, waste form can often contribute to delayed release of radionuclides for environmental transport; however, credit is not taken for this mechanism in current approved deterministic PAs nor in the DU PA v.1.4. For example, radionuclides present in waste as activated metal or within a grouted monolith would not be available for transport as early after disposal as radionuclides present as contamination on debris. By assuming that all activity is available for environmental transport immediately, Clive PAs bias environmental release to occur earlier than it may actually occur.

It is not necessary to model the potential for preferential pathways for radon or precipitation within or between actual waste placement layers in order to evaluate performance of the Federal Cell. For an evapotranspiration (ET) cover, infiltration is influenced by properties of the Unit 4 soil surface layer, while percolation is mainly controlled by Unit 4 Surface and Evaporative Zone layers and the Frost Protection layer, with some influence possible from the radon barrier. In other words, rates of infiltration, percolation, and exhalation are controlled by the cover system and the clay liner. Model performance will be essentially the same regardless of the modeled properties within the waste layers. See also *ET Cover Design Responses for the Clive DU PA Model* (Neptune 2018a).

Sandy soil properties were conservatively selected for modeling the waste layers in order to minimize potential effects of absorption/retardation that could occur if the waste layer were assumed to be clay. Note that, in practice, clay is often used as fill material within the embankment.

Appendix 2 to Neptune (2015a), *Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility, Clive DU PA Model v. 1.4* (Neptune 2015d), Section 8.1, remains consistent with Clive's prior approved PAs in this respect: "All wastes are assumed to have the characteristics of local Unit 3 sandy soil."

See also Appendix 16 to Neptune (2015a), *Model Parameters for the Clive DU PA Model, Clive DU PA Model v. 1.4* (Neptune 2015c), Section 4.16: "The current Clive DU PA Model has no generic waste inventory, but this material is defined as a placeholder. Any layers to be filled with generic LLW borrow material properties from Unit 3 (see Table 10)."

As noted in Interrogatory CR R313-25-9(5)(A)-196/1, Section 3.1 of Appendix 18 to Neptune (2015a), *Radon Diffusion Modeling for the Clive DU PA, Clive DU PA Model v. 1.4* (Neptune 2015b), states that other wastes are assigned Unit 4 properties. Appendix 18 has a typographical error and should state that other wastes are assigned Unit 3 properties, consistent with the Conceptual Site Model, Appendix 16, and the GoldSim model.

Note that the Federal Cell, as currently configured, isolates DU (and, ultimately, overlying Class A LLRW) from the adjacent 11e.(2) embankment. The Federal Cell has no existing waste placement of any type. Refer to *Federal Cell Design Responses for the Clive DU PA Model* (Neptune 2018b) for discussion of the designs and related issues in response to interrogatories under the category "Federal Cell Design."

While not prohibiting placement of DU upon approval of the Clive DU PA Model v.1.4, additional modeling is required by rule before Class A waste is disposed in the Federal Cell. There are two reasons that this is the case:

1. The performance of the ET cover included in the DU PA should be verified for Class A LLRW disposed in the same embankment as DU.
2. Incremental dose contributions from other Class A waste in the Federal Cell should be quantified for a complete probabilistic PA.

Considering that current approved PAs for the Class A West, LARW, and Mixed Waste cells include Class A LLRW in addition to DU, it is difficult to imagine a scenario where Class A LLRW would require any limitation below the Class A limits when disposed with DU under a probabilistic PA. Nonetheless, if demonstrated to be desirable under a combined probabilistic PA, Federal Cell waste acceptance criteria can be set to limit sensitive Class A radionuclide concentrations or placement location.

2.0 UDEQ Interrogatory Responses

This section contains responses for Interrogatories CR R313-25-9(5)(A)-196/1 and CR R313-25-9(5)(a)-203/1.

2.1 Interrogatory CR R313-25-9(5)(A)-196/1:

Please provide an analysis to demonstrate that the DU PA v1.4 assumed homogeneous Unit 4 silty clay material used to model the layer above the DU is representative of the various types of DOE-generated Class A waste Energy*Solutions* intends to dispose of in that layer. Density, among other factors, should be considered.

2.1.1 Interrogatory Response

As discussed above, the reference to Unit 4 material is in error. The use of Unit 3 material properties for Class A LLRW is reasonable and consistent with prior PAs for the facility.

2.2 Interrogatory CR R313-25-9(5)(a)-203/1:

Please describe how Energy*Solutions* proposes to address the requirements of R313-25-9(5)(a) to demonstrate that PA requires consideration of the “total quantities of concentrated depleted uranium and other wastes.”

2.2.1 Interrogatory Response

As provided in draft Condition 4 of the 2015 SER, prior to disposing of Class A LLRW other than DU in the Federal Cell, Energy*Solutions* will obtain approval of additional modeling. Energy*Solutions* does not intend or request to dispose of other Class A LLRW above the DU until such time as a PA accounting for the combined effects of DU and other Class A LLRW is approved. This does not preclude approval to dispose of DU in the interim.

3.0 References

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Neptune, 2018b. *Federal Cell Design Responses for the Clive DU PA Model,* NAC-0101_R0, Neptune and Company Inc., Lakewood CO, February 2018

SC&A, 2015. *Utah Division of Radiation Control, EnergySolutions Clive LLRW Disposal Facility, License No: UT2300249; RML #UT 2300249, Condition 35 Compliance Report; Appendix A: Final Report for the Clive DU PA Model, Safety Evaluation Report, Volume 1,* SC&A Inc., Vienna VA, April 2015

Utah DEQ, 2017. *Division of Waste Management and Radiation Control, EnergySolutions Clive LLRW Disposal Facility License No: UT2300249; RML #UT 2300249, Amended and New Interrogatories Related to Clive DU PA Modeling Report Version 1.4 Dated November 2015,* Utah Department of Environmental Quality (DEQ), Salt Lake City UT, May 2017

Whetstone Associates, 2011. *EnergySolutions: Class A West Disposal Cell Infiltration and Transport Modeling Report,* prepared for Energy*Solutions*, Whetstone Associates Inc., Gunnison CO, November 2011

NAC-0104_R0

Groundwater Exposure Responses for the Clive DU PA Model

23 February 2018

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	Name	Date
4. Originator	Gregg Occhiogrosso	12 Feb 2018
5. Reviewer	Mike Sully and Dan Levitt	12 Feb 2018
6. Remarks		

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FIGURES

Figure 1. Stratigraphic profile showing ET cover, waste zone, and stratigraphy below the Federal Cell. The deep aquifer is subdivided into the lower confined aquifer and the basal aquifer. 1
Figure 2. Conceptual model of Johnson et al. (2011). 5
Figure 3. Wells near York, NE. Generated using Nebraska Department of Natural Resources online mapping tools. The total area depicted is roughly 68 square miles. 6
Figure 4. Production wells within a 5-mile radius (~78 square miles) of the Clive Site. Generated using Utah Division of Water Rights online tools. Note that well 16-816 was drilled on January 9, 1996 and abandoned on January 30, 1996. This well was contemplated as a source of construction water for the Energy*Solutions* Clive facility, but not used. 7

ACRONYMS AND ABBREVIATIONS

DEQ	(Utah) Department of Environmental Quality
DU	depleted uranium
ECL	Effluent Concentration Limits
EPA	(United States) Environmental Protection Agency
ET	evapotranspiration
GWPL	groundwater protection limit
NRC	(United States) Nuclear Regulatory Commission
PA	performance assessment
PRA	probabilistic risk assessment
PWS	public water supply
RO	reverse osmosis
SER	Safety Evaluation Report
TDS	total dissolved solids
UDEQ	Utah Department of Environmental Quality

1.0 Overview and Conceptual Model

This document provides a summary of the important context for a discussion of potential risks associated with groundwater at the Clive Site. As discussed below, the hydrogeologic setting, geochemical conditions, and known usage history of the Site largely preclude traditional groundwater dose scenarios. The saline groundwater (discussed in Section 1.1.1) is of limited utility without extensive treatment. Low well yield in the shallow subsurface due to the soil texture necessitates that the withdrawal of any substantial quantity of water from beneath the Site involves extraction from lower aquifers, providing dilution of exposure concentrations (discussed in Section 1.2). Sections 2.0 considers the latest UDEQ interrogatories.

Figure 1 depicts the generalized stratigraphic profile of the Site subsurface; detailed discussion of the hydrogeologic system beneath the Site can be found in *ET Cover Design Responses for the Clive DU PA Model* (Neptune 2018). The water table aquifer which would be impacted by any migration from the waste cells is referred to as the shallow unconfined aquifer. Groundwater occurring at greater depths is referred to as the lower confined (~70–100 ft below ground surface) and basal (450–750 ft below ground surface) aquifers.

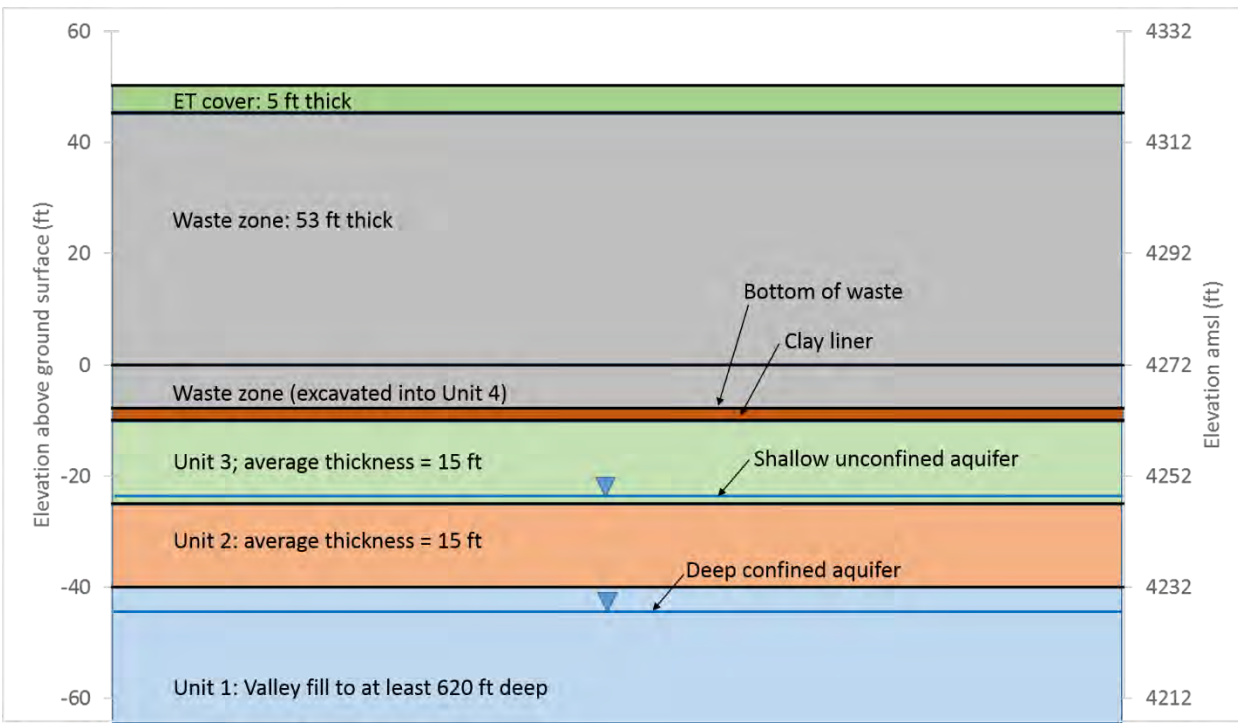

Figure 1. Stratigraphic profile showing ET cover, waste zone, and stratigraphy below the Federal Cell. The deep aquifer is subdivided into the lower confined aquifer and the basal aquifer.

Groundwater exposure as a dose pathway has been the subject of several past interrogatories. Certain exposure scenarios have been evaluated in past rounds of interrogatories with UDEQ. Round 2 Interrogatory Responses (Energy*Solutions* 2014) calculated doses for well drilling scenarios (reflecting practices commonly seen in the Clive area drainage basin) based on results from v1.2 of the Clive DU PA Model. The general characteristics of these aquifers that are relevant to potential groundwater dose scenarios are described below.

1.1 Considerations for a Groundwater Dose Pathway

1.1.1 Water Quality

The State of Utah classifies groundwater resources into four classes according to total dissolved solids (TDS) concentrations. Class I waters, referred to as "pristine," "irreplaceable," or "ecologically important," are most strongly protected and are subject to the most stringent protections regarding TDS and contaminant levels. Class II and Class III waters are referred to as "drinking water quality" and "limited use," respectively, and are similarly subjected to specific but less stringent standards. Class IV groundwater, defined by TDS concentrations greater than 10,000 mg/L, is referred to as "saline" and has no specific protection standards.

Typical TDS concentrations at the Clive Site range from about 10,000 mg/L to about 70,000 mg/L, and its water has been defined by UDEQ as Class IV (saline groundwater) (Utah 2014). For perspective, typical seawater TDS concentrations are about 35,000 mg/L, and the Environmental Protection Agency (EPA) Secondary Standard for the TDS level in drinking water is 500 mg/L. Poor water quality at all depths in the immediate vicinity of the Site limits the utility of the groundwater without treatment. An Energy*Solutions* analysis (Energy*Solutions* 2013) concluded that consumption of untreated, native groundwater would result in 100% mortality of the receptor due to salinity levels, making radiological risks irrelevant.

The lower confined aquifer exhibits lower, though still elevated, TDS levels and is also considered Class IV. While treatment of the groundwater to potable TDS levels is possible in principle by utilizing a desalination process such as reverse osmosis (RO), this practice is not found in the Clive facility basin. It has been acknowledged that RO treatment would also reduce contaminant concentrations, which is discussed in more detail below. Additionally, the probability of such a practice is low due to the lack of population and the availability of less costly and higher quality water sources throughout the west desert. Extraction wells in the area around the Site do exist, but these are generally installed in more productive gravel zones in the recharge areas of the surrounding foothills and they are generally used for industrial purposes. As such, a groundwater ingestion scenario in the immediate vicinity of the Site is highly unlikely, is outside of the known usage history of the Site, and has never been required in Energy*Solutions'* various other UDEQ-approved performance assessments (PA), nor is it supported by the promulgation of any new regulatory requirement since prior PA approvals.

1.2 Interaction of Shallow and Lower Aquifers

Groundwater level measurements and geochemical data suggest minimal flow from the shallow aquifer to the basal and lower aquifers. This is important to any discussion of a groundwater dose scenario because the shallow aquifer is not of sufficient yield to be a productive source and would not produce a reliable water supply for an inadvertent intruder using treated groundwater as a drinking water source. Therefore, a productive well in the vicinity of the Site would involve pumping from the basal or lower confined aquifers. Significant contamination of the lower aquifers would only occur with advective movement of radionuclides from the shallow aquifer (i.e., via downward water flow), which would be possible via movement through the naturally occurring material or some anthropogenic pathway like a multi-aquifer well. As discussed below, an anthropogenic pathway is very unlikely based on the Site conditions and usage history.

Based on simultaneous water level measurements in well clusters GW-19A/B, I-1-30/50/100, and I-3-30/50/100, Bingham Environmental (1996) reported an apparent upward hydraulic gradient, with freshwater equivalent head differentials of about 1–2 ft between deep (~100 ft depth) and shallower (~30–50 ft depth) well screens. Corresponding gradients (0.02 to 0.04) and upward velocities were calculated (0.05 ft/yr to 0.10 ft/yr). Bingham Environmental (1996) also noted that solute and isotopic data suggest "minimal or no vertical movement" from the shallow unconfined aquifer to the deeper confined aquifer, stating that, "Lower TDS concentrations for the few confined aquifer samples suggest the unconfined and confined aquifers may be chemically as well as hydraulically distinct systems." This evidence suggests that contamination of the lower aquifer due to the natural flow from the shallow aquifer is unlikely. UDEQ has acknowledged the upward gradient by including a performance standard in the Groundwater Quality Discharge Permit (Utah 2014) for the Site which states that a neutral or upward hydraulic gradient should be maintained in nested or paired monitoring wells.

2.0 UDEQ Interrogatory Responses

This section contains responses for Interrogatories CR R313-25-3 and R313-25-8-195/1 (a single interrogatory referencing two parts of the Utah Administrative Code) and CR R313-25-20-204/1.

2.1 Interrogatory CR R313-25-3 and R313-25-8-195/1: Aquifer Characterization and Interrogatory CR R313-25-20-204/1: Exposure to Groundwater

- **Interrogatory CR R313-25-3 and R313-25-8-195/1: Aquifer Characterization**
  - *Statement*: Please provide information assessing the aquifer hydraulic properties and groundwater quality for the lower confined aquifer (e.g., at 70–100 ft) and valley-fill or basal-aquifer-system aquifers (e.g., at 450–750 ft) at the Clive site. Specific types of information include, for example, groundwater flow velocities, aquifer transmissivities, water quality, sorption properties, and the degree of hydraulic interconnection between the upper and basal aquifers. Calculations should be shown for horizontal and vertical components of groundwater flow and contaminant migration velocities.

- **Interrogatory CR R313-25-20-204/1: Exposure to Groundwater**
  - *Statement*: Please revise your June 8, 2014, partial response to Interrogatory 182 by extending it to 10,000 years and including the groundwater consumption pathway, and include the results of the extended analysis in the next revision of the DU PA, including the Appendix 19 sensitivity analyses.
  - *Excerpt of Basis*: While preparing the April 2015 Safety Evaluation Report (SER), the Department of Environmental Quality (DEQ)/SC&A extended the Energy*Solutions* Interrogatory 182 partial response to 10,000 years and included the groundwater consumption pathway, as well as several postulated scenarios including a leaking well casing, a nearby failed or abandoned well that presents a direct path between the upper and lower aquifer, and fresh water in the lower aquifer. The results of this DEQ/SC&A analysis are given in the white paper, "Groundwater Pathway Doses, Part 2," Revision 2 (Marschke 2015).

2.1.1 Interrogatory Responses

These interrogatories share a common theme in their suggestion that various anthropogenic scenarios might cause cross-contamination of the lower aquifer, and therefore a perceived need for further development of the lower aquifer hydraulic properties. Because both stem from these postulated scenarios, they are addressed together rather than as separate responses.

2.1.2 Evaluation of Applicability of UDEQ Basal and Lower Aquifer Contamination Scenarios

Interrogatory R313-25-20-204/1 suggests the need to calculate groundwater consumption doses based on the exposure mechanisms conjectured in Marschke (2015)[1], which relied on two literature sources not specific to Clive area practices to support the idea of cross-contamination of a confined aquifer by the overlying unconfined aquifer (Johnson et al. 2011; Zinn and Konikow 2007). The applicability of the scenarios presented in the literature sources is largely unaddressed by Marschke (2015). Both sources, which consider mechanisms for contamination from an unconfined aquifer moving to a confined aquifer via wells screened through both aquifers, exclude justification of human groundwater consumption and are discussed below.

Johnson et al. (2011) conducted flow modeling for a synthetic domain meant to mimic the hydrogeologic setting near York, Nebraska, an area where irrigation wells are very common (and hydrogeologically different from the Clive drainage basin). The analysis attempted to quantify the impacts of nearby irrigation wells to a public water supply (PWS) well placed in the same vicinity. This analysis used hydraulic properties and hydrogeologic unit thicknesses specific to the Nebraska site, and included multiple multi-aquifer wells near the pumping well that provided hydraulic connection between the upper unconfined aquifer and the lower confined aquifer. Figure 2 from Johnson et al. (2011) is reproduced in Figure 2 below to provide some context regarding the conceptual model used in the study.

[1] Note that this paper is prominently watermarked "WORKING DRAFT—DO NOT CITE OR QUOTE" yet was cited by UDEQ.

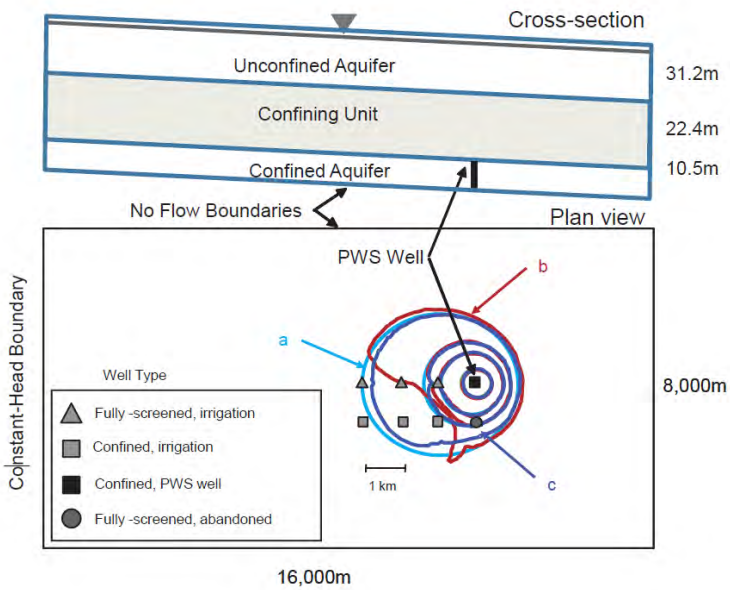

Figure 2. Conceptual model of Johnson et al. (2011).

The vicinity of the Clive Site does not have a similar hydrogeologic setting or a similar history of closely spaced irrigation wells when compared to the study site in Nebraska**Error! Reference source not found.**. Figure 3, generated from well installation records of the Nebraska Department of Natural Resources, shows hundreds of irrigation wells (purple). In the hydrogeologic setting of York, NE, cross-contamination of aquifers via the dense network of wells may indeed be a viable scenario warranting an analysis like that undertaken by Johnson et al. (2011). The scenario is not readily applicable to the Clive Site, as production wells installed in the Clive vicinity are comparatively rare and are primarily in upgradient gravel units within the recharge zone of the surrounding foothills, as shown in Figure 4. The well nearest the Clive Site, identified as 16-816 in Figure 4, was abandoned in 1996. The hydraulic gradient in the shallow aquifer is generally toward the northeast.

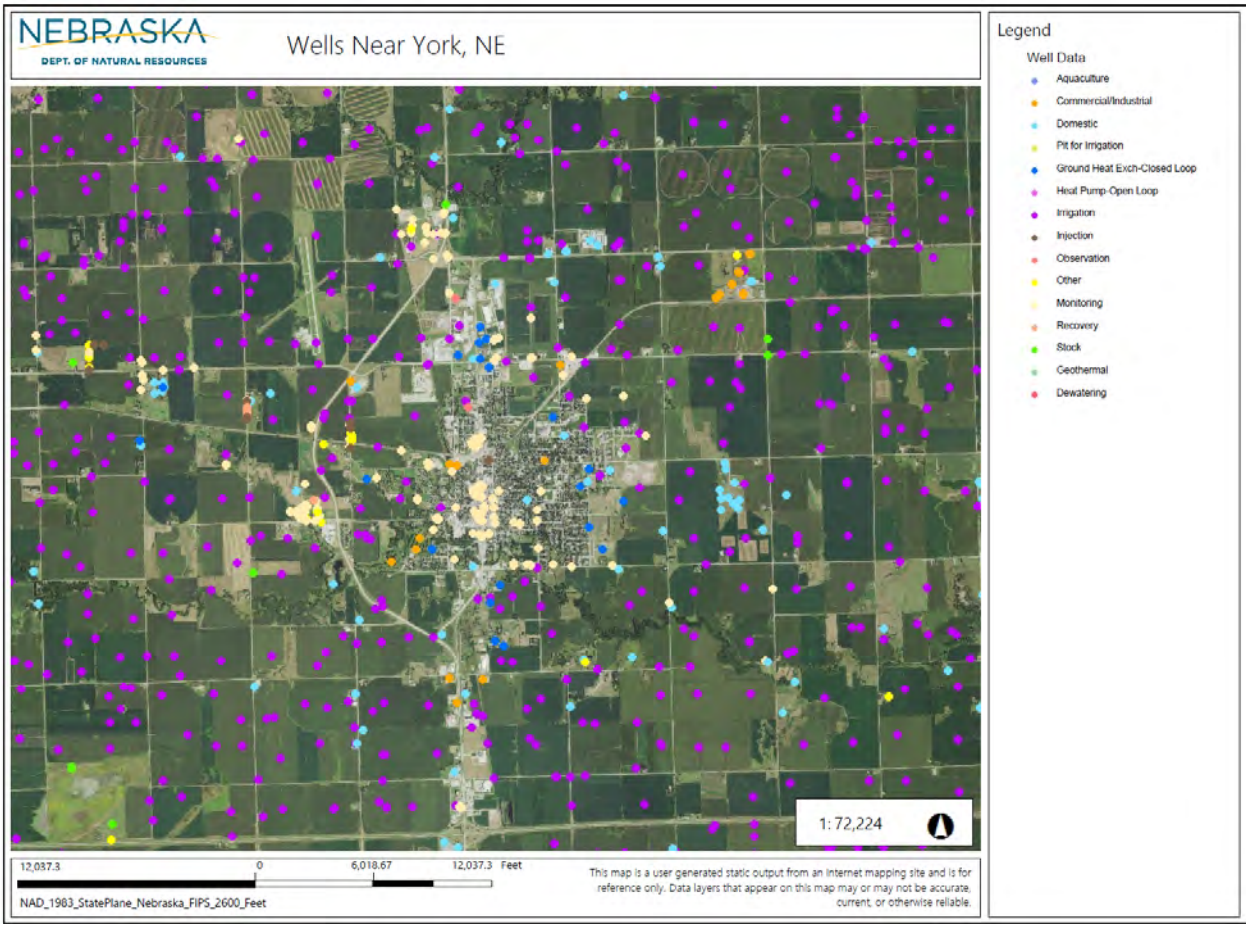

Figure 3. Wells near York, NE. Generated using Nebraska Department of Natural Resources online mapping tools. The total area depicted is roughly 68 square miles.

Figure 4. Production wells within a 5-mile radius (~78 square miles) of the Clive Site. Generated using Utah Division of Water Rights online tools. Note that well 16-816 was drilled on January 9, 1996 and abandoned on January 30, 1996. This well was contemplated as a source of construction water for the Energy*Solutions* Clive facility, but not used.

The postulated mechanism for contamination of the lower aquifer with radionuclides from the Clive Site would require not only a network of pre-existing multi-aquifer wells near a pumping well, but also that the wells be in a specific geometry relative to one another and the Site. Multi-aquifer wells might promote the flow of uncontaminated water to a pumping well for many possible configurations. Additionally, given the low yields of the upper aquifer, it is unlikely that

it could sustain prolonged elevated flows to the lower aquifer near the hypothesized multi-aquifer wellbore. In short, the list of suppositions necessary for this mechanism of contamination is long and specific. Johnson et al. (2011) also noted that:

> Predicting the impact of contaminants on a PWS well due to leaking multi-aquifer wells is, in general, not possible. However, the modeling steps described here can provide site-specific insight into the potential for multi-aquifer wells to affect a confined-aquifer PWS well.

Marschke (2015) made no attempt to apply the modeling steps laid out in Johnson et al. (2011) to the Clive Site. Nevertheless, Marschke (2015) stated that "Johnson et al. (2011) determined that a dilution factor of 10 would be appropriate" to calculate the relative flows from the upper and lower aquifer to a well screened in the lower aquifer. Considering that no attempt was made to apply the methodology on a site-specific basis, the dilution factor of 10 cited by Marschke (2015) is arbitrary at best.

The second study cited, Zinn and Konikow (2007), is similarly a hypothetical model domain meant to simulate the effects of existing, non-pumping wells on nearby pumping wells. The authors noted the relevance of the study to regions with agricultural history like Nebraska and Alberta, where numerous irrigation wells potentially affect local flow and transport. The model domain size and shape are described as "arbitrary," with the boundary conditions "conceptually similar to a river valley":

> These conditions led to a predevelopment steady state regional flow field that was conceptually similar to the side of a river valley or other simple groundwater basin—a groundwater divide with primarily downward infiltration of water at the upstream end of the system, predominantly horizontal flow near the middle part of the system, and predominantly upward flow near the constant-head boundary.

The hydrologic conditions considered are not similar to the Clive Site. The model domain is assigned homogenous properties, dissimilar to the Site (e.g., hydraulic conductivity of 76.2 m/day compared with Clive Site values on the order of 0.1 m/day). As noted above, the combination of hydraulic properties and boundary conditions produces vertical hydraulic gradients on either side of the domain. For certain configurations of pumping and non-pumping wells, vertical flows in the non-pumping wells were altered. Zinn and Konikow (2007) noted that "the effect of intraborehole flow is highly dependent on the location of the borehole within the system, particularly in relation to the head field of the system." This mechanism for contamination of the lower aquifer is thus extremely improbable at the Clive Site, as it requires an unlikely combination of pumping wells and non-pumping wells in a prescribed geometry. Furthermore, the expense to install such a well pumping network far exceeds the cost of transporting potable water from other sources outside of the Clive drainage basin. Moreover, as described above in the discussion of Johnson et al. (2011), UDEQ made no attempt to apply this scenario using site-specific hydrogeological unit structure or parameter values. As before, many conditions which are inconsistent with the current use of the Clive Site are necessary for this mechanism of contamination.

In summary, the applicability of these contamination scenarios to the Clive Site is not well supported upon closer examination of their bases. NRC's Regulatory Guide 1.174 expresses the need for site-specific information in probabilistic risk assessments (PRAs):

> One overriding requirement is that the PRA should realistically reflect the actual design, construction, operational practices, and operational experience of the plant and its owner.

Regulatory Guide 1.200 also states that a consensus PRA standard is that PRAs should use "plant-specific information versus generic information to represent the as-designed, as-built and as-operated plant."

Interrogatories CR R313-25-3 and R313-25-8-195/1 express the perceived need for further evaluation of aquifer properties and flow regimes for the aquifers below the shallow unconfined aquifer, based on scenarios developed for markedly different hydrogeologic conditions rather than on site-specific information. Given the improbability of any scenario at the Clive Site by which deeper aquifers would become contaminated and thus impact the Federal Cell's ability to satisfy the required performance objectives, further evaluation is completely unnecessary.

2.1.3 Updated Groundwater Ingestion Tc-99 Concentration Estimate

A simple bounding calculation based on v1.4 of the Clive DU PA Model results shows that even modest mixing with lower aquifer water and RO treatment process results in exposure concentrations of Tc-99 associated with basal and deep groundwater below 3,760 pCi/L.

One thousand realizations of the Model were run with groundwater concentrations calculated until 10,000 years, as requested in the interrogatory. The peak median concentration (i.e., the median value of Tc-99 concentrations across the realizations at each time step) was about 4,000 pCi/L at the hypothesized shallow aquifer groundwater well location. The 95th percentile values for all times were below 45,000 pCi/L. As such, a total dilution factor of ~12 would reduce Tc-99 concentrations to below the limit of 3,760 pCi/L, even for the peak 95th percentile concentration.

As discussed above, due to the high salinity of the groundwater, reverse osmosis or a similar process would be required prior to consumption. Marschke (2015) assumed a conservative dilution factor of 10 due to the RO treatment (i.e., 90% removal). RO Tc-99 removal rates as high as 99% (dilution factor of 100) have been documented (Williamson 1992). As such, removal of Tc-99 by RO is likely adequate to bring well water concentrations well below 3,760 pCi/L, even for the 95th percentile concentrations.

An additional dilution factor due to mixing with water from the lower aquifer was estimated in the Round 2 Interrogatory Responses and was also utilized for calculations by Marschke (2015). It was calculated using the Thiem-Dupuit equation for the most likely (though still highly improbable) scenario of a well drilled near the Clive Site and screened in the lower aquifer. The resulting dilution factor was about 300. Applying this factor along with the RO dilution factor reduces Tc-99 concentrations to negligible levels, on the order of 10 pCi/L, even for the 95th percentile case.

In summary, though highly unlikely given the history and usage of the Clive Site, use of the groundwater from the lower aquifer units would involve dilution of the contamination to an extent that the risks to human health in a groundwater ingestion scenario would be negligible.

3.0 Conclusion

The poor water quality (Class IV) of water at the Clive Site limits its utility without treatment, which would reduce radionuclide concentrations along with TDS concentrations. Substantial withdrawals from the shallow aquifer are difficult due to low well yields, and cross-contamination of the underlying aquifers is unlikely due to the natural hydrogeologic separation and observed upward hydraulic gradients. Scenarios proposed by UDEQ involving anthropogenic hydraulic connections are not applicable to the Clive Site, as these scenarios are based on literature studies of areas with starkly contrasting usage histories and hydrogeologic conditions.

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Recycled Uranium Responses for the Clive DU PA Model

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5. Reviewer	Mike Sully and Dan Levitt	
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ACRONYMS AND ABBREVIATIONS

CAW	Class A West embankment
DEQ	(Utah) Department of Environmental Quality
DU	depleted uranium
ET	evapotranspiration
GDP	gaseous diffusion plant
GWPL	groundwater protection limit
PA	performance assessment
PGDP	Paducah Gaseous Diffusion Plant
PORTS	Portsmouth Gaseous Diffusion Plant
SER	Safety Evaluation Report
UDEQ	Utah Department of Environmental Quality
WAC	waste acceptance criteria

1.0 Overview and Conceptual Model

This document discusses issues related to the disposal of depleted uranium (DU) containing recycled uranium in the Federal Cell. Recycled uranium waste contains fission products such as Tc-99 which are not necessarily present in other DU wastes. UDEQ issued interrogatories related to Tc-99's source term concentration and the groundwater concentration at compliance endpoints, but deemed the questions closed, stating that any license would be granted under the condition that no DU containing recycled uranium would be disposed at the Site. Precedent exists for disposal of Tc-99 at the Clive Site, as UDEQ has permitted Tc-99 disposal in the adjacent Class A West (CAW) Disposal Cell. Issues surrounding disposal of DU containing recycled uranium are discussed, including the mechanisms of exposure and responses to the interrogatories (Section 2.0).

In the performance assessment (PA) model, all radionuclides, including Tc-99 and other fission products, are transported via various transport processes which would cause contaminant migration through the waste zone and into the underlying geologic units. Exposures are evaluated at the hypothetical receptor locations (compliance points).

Contaminant transport includes transport media (water, air, soil), transport processes (advection-dispersion, diffusion, plant uptake, soil translocation), and partitioning between phases. Diffusion occurs in gas and water phases. Dilution occurs when mixing with less concentrated water. Hydrodynamic dispersion is associated with water advection. Dissolution in water is limited by aqueous solubility.

Infiltration of water through the cover, into wastes, and toward a hypothetical groundwater user is the transport pathway for Tc-99 cited in UDEQ's interrogatories related to recycled uranium. Tc-99 is unique in that it is regarded as relatively long half-lived and mobile in the environment because it does not generally sorb to the soil structure as readily as other radionuclides, meaning it can be transported for longer distances.

The Clive DU PA Model calculates potential exposure concentrations in a probabilistic fashion by incorporating uncertainty in each parameter value through Monte Carlo simulation, in which the model is run thousands of times using different combinations of parameter values in each realization. Details of the modeling processes can be found in the *Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility* (Neptune 2015b).

Tc-99 has been accepted for disposal of waste with a limiting Tc-99 concentration in the adjacent Class A West embankment, based on deterministic modeling using extreme bounding conditions. The cited basis for the prohibition of DU containing recycled uranium is that the PA Model does not adequately capture the range of possible waste concentrations. UDEQ goes on to claim that the evapotranspiration (ET) cover performance may not adequately limit infiltration to assure compliance with the groundwater protection limit (GWPL) at the hypothetical receptor location. ET cover performance is addressed in *ET Cover Design Responses for the Clive DU PA Model* (Neptune 2018a).

2.0 UDEQ Interrogatory Responses

This section contains responses for Interrogatories CR R313-25-8(4)(a)-08/1 and CR R313-25-7(9)-51/3. UDEQ's conclusions on the interrogatories regarding the disposal of wastes containing recycled uranium are reproduced below. A single response is provided since the interrogatories are essentially identical.

2.1 Interrogatories CR R313-25-8(4)(a)-08/1 and CR R313-25-7(9)-51/3

Interrogatory CR R313-25-8(4)(a)-08/1: Groundwater Concentration Endpoints
DEQ has stated that no depleted uranium (DU) waste containing recycled uranium will be allowed to be disposed at Clive, so this interrogatory is closed.

Interrogatory CR R313-25-7(9)-51/3: Nature of Contamination
This interrogatory is closed because any license amendment will contain a license condition that disposal of recycled uranium is not allowed in the DU waste. Furthermore, the license condition will indicate that DU-waste containers shall contain neither heels of enriched uranium at average concentrations greater than that allowed in the license nor heels of transuranic compounds at average concentrations greater than 10 pCi/g (the Class A limit).

2.1.1 Interrogatory Response

Interrogatories 08/1 and 51/3 were deemed closed under the unsubstantiated condition that no DU waste containing recycled uranium would be disposed at the Site, to be dictated by License condition. These interrogatories are linked by their concern with groundwater exposures to radionuclides, principally fission product radionuclides like Tc-99 which may be present in DU wastes containing recycled uranium. UDEQ cited uncertainty in Tc-99 concentrations in groundwater relative to the GWPL of 3790 pCi/L over the compliance period of 500 years to justify the prohibition of waste containing recycled uranium (April 2015 SER, Section 6.1.2):

> Because there is significant uncertainty regarding the Tc-99 concentration in the DU3O8 to be produced from the GDP tailings, and because Tc-99 and other mobile isotopes may exceed the GWPL at 500 years, DEQ approves this portion of the DU PA with the condition that no DU waste containing recycled uranium be accepted for disposal inside the Federal Cell at Clive. Based on this restriction, GWPLs for the 500-year compliance period can easily be met regardless of uncertainties in the infiltration rate through the ET cover.

The concerns expressed are thus related to the waste concentrations upon emplacement (as opposed to hypothetical ranges of concentrations in DU being stored at the Clive Facility) and the performance of the cover system and the associated infiltration rates, which impact potential exposure concentrations at hypothetical receptor locations.

From a risk perspective, this condition is arbitrary and unsupported, given that modeling results demonstrate that DU containing Tc-99 and other fission products can be safely disposed at the Federal Cell. Furthermore, Tc-99 in other Class A wastes is licensed for disposal in other comparable embankments at the Clive Site. The relevant modeling concepts are briefly summarized below, followed by responses to the concerns expressed in the SER which precipitated the closure of these interrogatories.

Comparison of v1.4 Model Results to GWPL

Refinements to the PA Model incorporated in v1.4 have resulted in predicted Tc-99 concentrations in the upper aquifer well below the GWPL (3,790 pCi/L) over the 500-year compliance period. As presented in the v1.4 *Final Report for the Clive DU PA Model* (Neptune 2015a), ten thousand realizations of the Model were run and the peak Tc-99 concentration at the hypothetical groundwater compliance well was recorded for each run. The mean and median peak values across the realizations were 26 pCi/L and 4.3E-2 pCi/L, respectively. The 95th percentile peak value was 150 pCi/L. These results are a small fraction of the GWPL of 3790 pCi/L.

Due to these updated estimates, the prohibition of DU wastes containing recycled uranium is not required to remain in compliance with the GWPL, as even the 95th percentile estimates of peak Tc-99 concentrations are more than an order of magnitude below the GWPL for the 500-year compliance period. Any refusal to remove a prohibition on disposal of recycled DU is arbitrary, unsupported by the Model, and contrary to site precedence.

Responses to UDEQ Concerns

1) ET Cover Performance

Issues pertaining to the ET cover performance and net infiltration into the waste zone are discussed in *ET Cover Design Responses for the Clive DU PA Model* (Neptune 2018a).

2) Tc-99 Waste Concentrations

Some uncertainty in the Tc-99 concentrations of wastes derived from gaseous diffusion plant (GDP) operations is acknowledged, as direct measurements of fission product concentrations are rare. However, a blanket prohibition of DU containing recycled uranium is not justifiable due to uncertainties in Tc-99 concentrations. Tc-99 disposals at the Site in the CAW cell undergo receipt and acceptance actions to confirm compliance with the waste acceptance criteria (WAC), with WAC values established using a transport modeling approach not unlike the Federal Cell PA Model. Federal Cell disposals would be subject to similar receipt and acceptance procedures, and a WAC could be established in a similar fashion.

UDEQ's contention that Tc-99 concentrations in the Model are not adequate is based on Section 4.1.2 of the April 2015 SER, which hypothesizes a possible Tc-99 concentration in cylinder heels as high as 5,700,000 ppb. This value is based on a mass balance approach summarized in Hightower et al. (2000); it should be interpreted as an extreme bounding value, and is described as such by Hightower et al. (2000). As noted in NUREG/CR-2300 (NRC 1983):

> The simplest quantitative measure of variability in a parameter or a measurable quantity is given by an assessed range of the values the parameter or quantity can take. This measure may be adequate for certain purposes (e.g., as input to a sensitivity analysis), but in general it is not a complete representation of the analyst's knowledge or state of confidence and generally will lead to an unrealistic range of results if such measures are propagated through an analysis.

As such, a bounding, hypothetical maximum value is of limited utility and should be discounted in favor of measured values from similar waste streams. A more realistic, measured value for an upper Tc-99 cylinder heel concentration is presented in Appendix C of Hightower et al. (2000), where measurements of heel concentrations were taken from a cylinder used multiple times at both Portsmouth and Paducah:

> Several empty feed cylinders have been identified that contain heels of feed and/or product from the periods when reactor returns were being fed to the cascades. Cylinder 003174 is such a cylinder with 13 lb of feed material heel remaining. This cylinder had been filled at the PGDP [Paducah Gaseous Diffusion Plant] UF6 feed plant with UF6 prepared from reactor returns material sometime after the cylinder's purchase date of June 1954. After the original charge in this cylinder had been fed to the cascades, the cylinder was filled with enriched product from Paducah and shipped to the PORTS [Portsmouth Gaseous Diffusion Plant], where the enriched material was fed to the Portsmouth cascade for further enrichment. This cylinder was similarly refilled with enriched product and emptied two more times without any washing, leaving its original heel of reactor returns feed material combined with the heels left from emptying enriched product three times into the cascades. (Hightower et al. (2000), Appendix C)

The highest, "first wash" Tc-99 concentration for this cylinder is reported as 270,000 ppb, a factor of 20 lower than UDEQ's hypothetical extreme bounding value derived from the mass balance approach. The April 2015 SER claimed that the PA Model concentrations were as much as 3.7 times too low when compared to the value of 5,700,000 ppb. When compared to the measurements from this heavily used cylinder, however, the uncertainty currently incorporated in the Model for Tc-99 concentrations is representative.

It is also worth noting that mobilization of the heel material for concentration measurement required dissolving the heel with an acidic wash solution. The Model conservatively takes no transportation rate credit for this solid waste form or waste packaging, and assumes all radionuclides are immediately available for transport in the liquid phase at the first model time step, a simple and conservative approach compared to more complicated release models that incorporate mass-transfer limitations due to, for example, solubility and/or sorption (NUREG/CR-5532, Kozak et al. (1990)). Additional discussion of the potential for doses via groundwater is discussed in the response to Interrogatory CR R313-25-20-204/1: Exposure to Groundwater in *Groundwater Exposure Responses for the Clive DU PA Model* (Neptune 2018b).

3.0 Conclusion

UDEQ's stated prohibition of disposal of DU containing recycled uranium is based on uncertainties in the performance of the cover system and in the concentration of fission products in the wastes. As shown above, the latter concern is based on an extreme theoretical value. Furthermore, the prohibition stands in contrast to site precedence, as disposals of Tc-99 have been permitted in the CAW Cell, subject to WAC limitations. A similar framework could be applicable to the Federal Cell, though DU PA Model v1.4 results suggest the risk associated due to disposal of DU containing recycled uranium is minimal, and that no such WAC limitation is warranted.

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Federal Cell Design Responses for the Clive DU PA Model

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ACRONYMS AND ABBREVIATIONS

CAW	Class A West embankment
CQA/QC	Construction Quality Assurance/Quality Control
DU	depleted uranium
ET	evapotranspiration
LLRW	low-level radioactive waste
PA	performance assessment
SER	Safety Evaluation Report
UDEQ	Utah Department of Environmental Quality

1.0 Overview and Conceptual Model

Version 1.4 of the Clive DU PA is based on a Federal Cell design that physically isolates DU and Class A LLRW from the adjacent 11e.(2) embankment. This is a change from the approach modeled in versions 1.0 and 1.2, which consisted of a single cell with a barrier wall intended to isolate the different waste types.

The choice to revise the Federal Cell design to a standalone embankment was made for several reasons:

1. The Federal Cell is proposed to have an evapotranspiration (ET) cover design, while the existing 11e.(2) cell has a rock armor cover design. Final cover has been constructed over a large portion of the currently open 11e.(2) cell footprint. Joining the two cover designs would be difficult to engineer and model.
2. Remediating the existing completed 11e.(2) cover to an ET design would be costly in terms of time, labor, and materials. The relatively small loss of overall site capacity, compared with a single-cell design, was not judged to warrant the activity.

Appendix 3 to Neptune (2015a), *Embankment Modeling for the Clive DU PA, Clive DU PA Model v. 1.4* (Neptune 2015b), explains that version 1.4 of the DU PA considers a single, standalone Federal Cell. This cell is located to the west of the existing 11e.(2) mill tailings cell and to the south of the existing Class A West (CAW) cell. Energy*Solutions* engineering drawing series 14004 was referenced and included in Appendix 3. Drawings 14004 V1A and 14004 V3A are reproduced from this report as Figure 1 and Figure 2, respectively, below.

The Federal Cell isolates DU (and, ultimately, overlying Class A LLRW) from the adjacent 11e.(2) embankment. The Federal Cell has no existing waste placement of any type. It appears that at least one of the interrogatories on this topic fails to recognize the design revision from version 1.2 to version 1.4 of the DU PA Model.

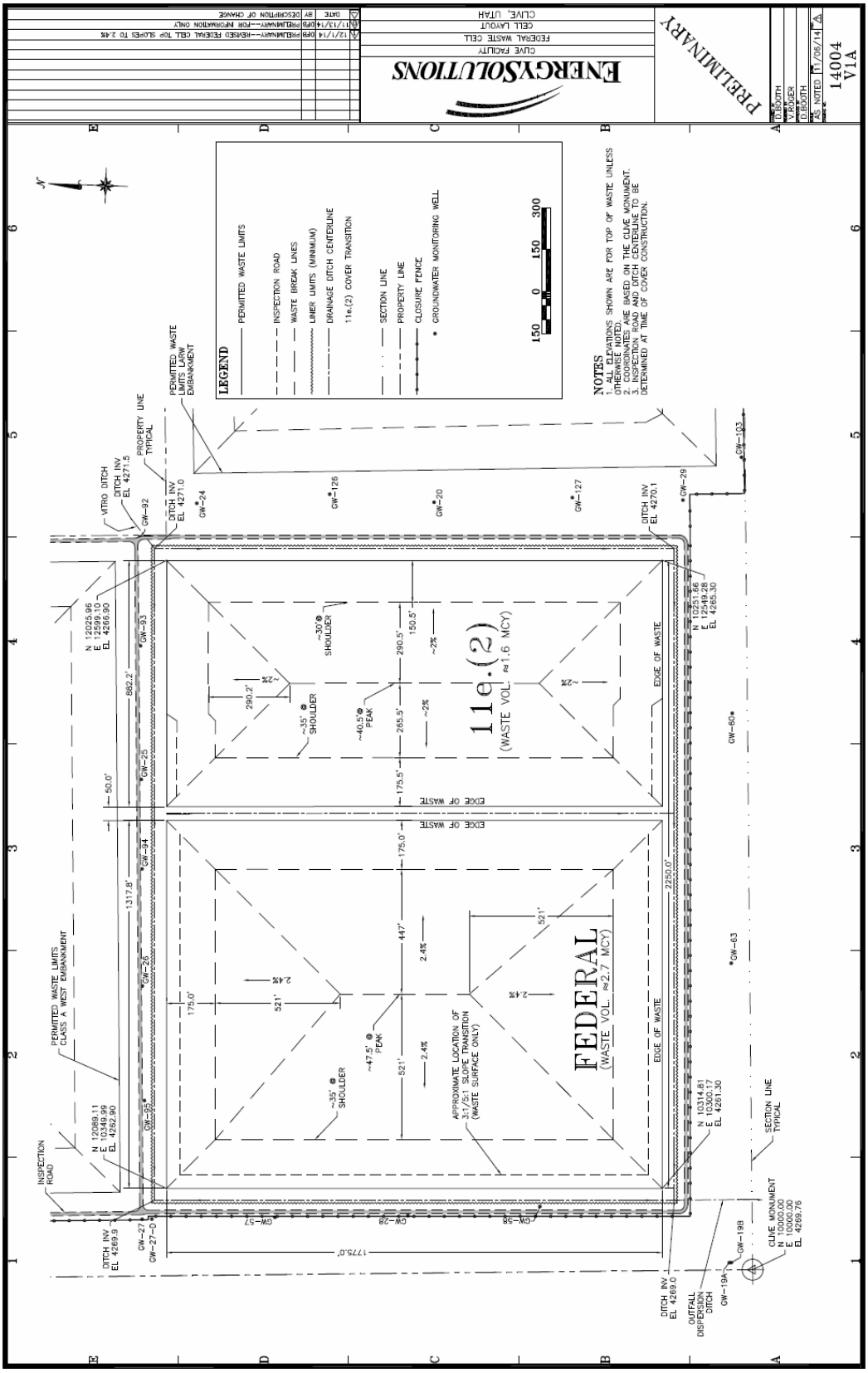

Figure 1. Federal Cell and 11e.(2) Cell engineering drawing 14004 V1A (Neptune 2015b).

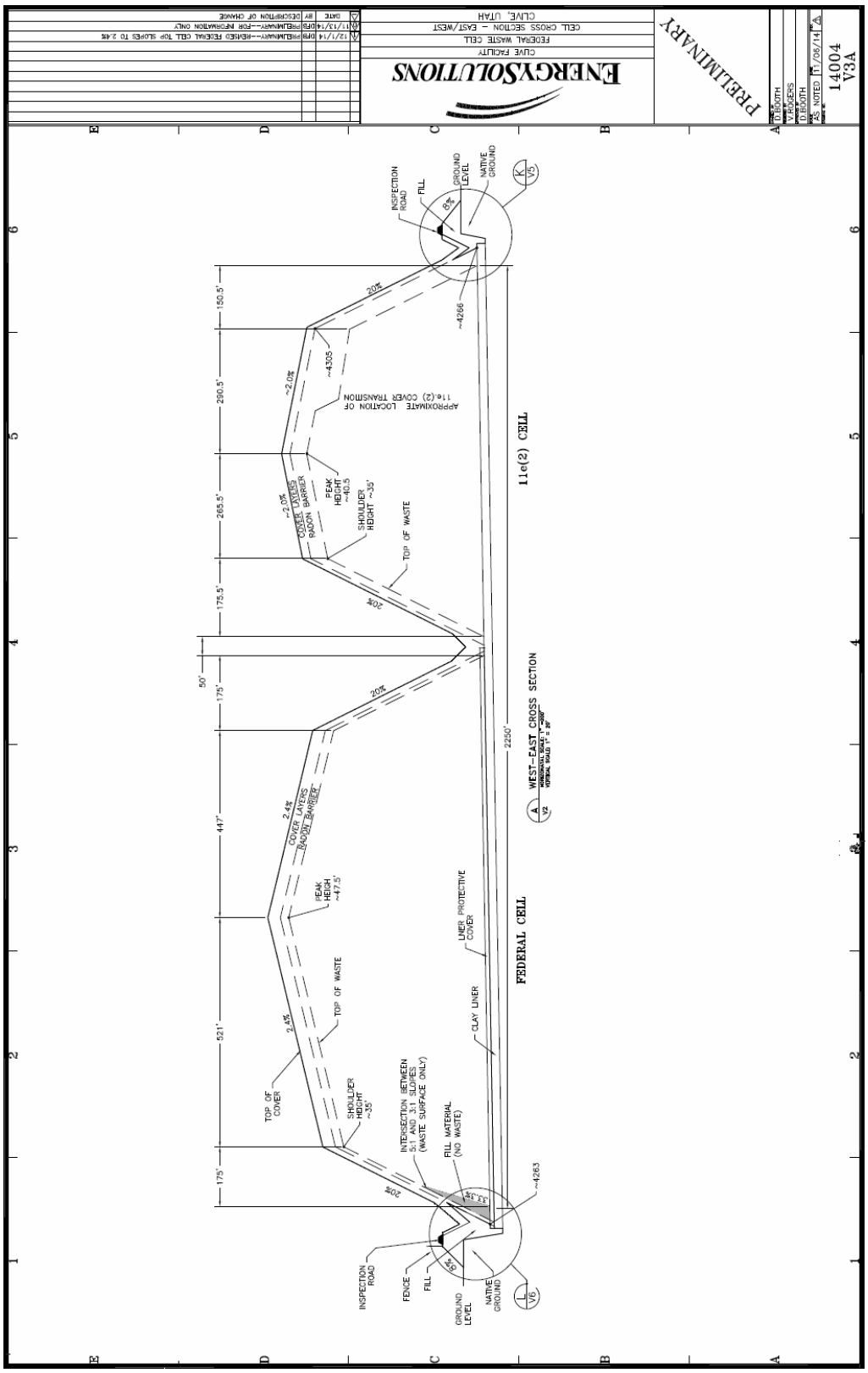

Figure 2. Federal Cell and 11e.(2) Cell engineering drawing 14004 V3A (west-east cross section) (Neptune 2015b).

2.0 UDEQ Interrogatory Responses

This section contains responses for Interrogatories CR R313-25-7(2), CR R313-25-7(6)-81/2, CR R313-25-7(6)-84/3, CR R313-25-7(2)-160/2, and CR R313-25-22-162/2.

2.1 Interrogatory CR R313-25-7(2) and 7(6)-81/2: Comparison of Disposal Cell Designs

> No further analysis has been performed on disposal cell designs since v1.2.

2.1.1 Interrogatory Response

This statement is incorrect. Version 1.2 of the DU PA proposed to dispose DU, Class A LLRW, and 11e.(2) waste within a single embankment, with DU and Class A LLRW separated from 11e.(2) waste by a clay barrier wall. As discussed above, version 1.4 of the DU PA models a distinct Federal Cell that is completely separate from the 11e.(2) cell.

The interrogatory basis furthermore states:

> …Energy*Solutions* has advised that the proposed Federal Cell will be physically separated from the 11e.(2) cell. Energy*Solutions* has provided only engineering drawings but no written description of the new cell (i.e., Appendices 3 and 16 to the DU PA have not been revised).

This statement is also incorrect. Appendices 3 and 16 of the DU PA, v1.4, correctly incorporate the Federal Cell design and dimensions as a single, standalone embankment separate from the 11e.(2) cell. There is no reason for this interrogatory to remain open.

2.2 Interrogatory CR R313-25-7(6)-84/3: Below-Grade Disposal of DU

> No further analysis was performed in Appendix 21 on the below-grade disposal of DU.

2.2.1 Interrogatory Response

The interrogatory basis discusses a discrepancy between the reported potential number of DU drums and cylinders in Appendices 3 and 4 to Neptune (2015a):

> Please explain the difference between v1.4 Appendices 3 and 4 regarding the maximum number of cylinders and drums, and demonstrate how the entire DU inventory can be disposed below grade.

This discrepancy traces back to the use of different Energy*Solutions* drawings as points of reference for the Neptune documents. Appendix 3 to Neptune (2015a) includes engineering drawing 14004 L1A as Figure 7 and as the basis for the potential number of DU drums and cylinders that could physically fit below grade in the Federal Cell. Appendix 4 to Neptune (2015a) references drawing 14004 SK1 as its data source. Clearly, the different drawings are intended to project different disposal scenarios.

While the difference between the scenarios is acknowledged, it is also irrelevant to the licensing decision. Section 6.2.4 of the 2015 SER provides Condition 2 that would apply to an amended

License approving DU disposal: "All DU waste must be disposed of below the original-grade level of the proposed Federal Cell (i.e., 4,272 ft-amsl)." This constraint will control waste placement operations to be consistent with the important model assumption that DU waste is placed below the original grade of the Federal Cell, regardless of the number or type of cylinders and/or drums disposed.

There is no Utah or Federal Rule whereby Energy*Solutions* must demonstrate that all DU in storage (or that will ever be created at any site within the United States) must completely fit within the permitted capacity of the Federal Cell. However, this interrogatory demands, without regulatory basis, that Energy*Solutions* "demonstrate how the entire DU inventory can be disposed below grade." By refusing to close interrogatories associated with DU capacity under various disposal configurations, UDEQ's reviewers imply a requirement that the Site be able to dispose of the full national inventory of DU available for disposal. This is without regulatory basis and is thus arbitrary and capricious on the part of UDEQ. Note also that, if approved, the Energy*Solutions* Clive facility would not be the only U.S. site licensed for DU disposal.

Energy*Solutions* will only place DU below grade within the approved top slope footprint of the Federal Cell, and in accordance with Construction Quality Assurance/Quality Control (CQA/QC) requirements applicable for the waste form and container. These controls, together with the type and timing of shipments for disposal, will drive actual cell utilization. Disposal operations will be performed to optimize cell utilization within License constraints, but will often result in under-utilized capacity due to material handling and spacing needs, use of clean fill for shielding and contamination control, and other inefficiencies.

For example, the figures used to estimate potential total cylinders and drums that could be disposed under various configurations assume regular, tight spacing for each container. It will not always be operationally practical to maintain tight spacing, perhaps due to rigging or equipment needs. Regardless of these realities and of the actual volume ultimately disposed, further disposal of DU in the Federal Cell will cease once the below grade capacity is exhausted.

2.3 Interrogatory CR R313-25-7(2)-160/2: Comparison of Class A West and Federal Cell Designs

See also Interrogatory CR R313-25-25(4)-202/1: Use of SIBERIA to Model Federal Cell Erosion.

2.3.1 Interrogatory Response

A response to Interrogatory 202/1 regarding use of SIBERIA to model erosion is provided in *Erosion Responses for the Clive DU PA Model* (Neptune 2018).

The basis for Interrogatory 160/2 goes on to discuss a prior request (SC&A 2015) to compare similar ET cover designs between the Class A West and Federal Cell:

> DRC is currently reviewing a license amendment request to use an ET cover of similar design to that proposed for the Federal Cell in the DU PA. Any recommendations and conclusions from that review must be applied to the proposed Federal Cell as well.

Since submitting the request for approval of an ET cover design on the CAW cell, Energy*Solutions* has begun construction of a rock armor cover on the CAW cell. More importantly, the DU PA models the Federal Cell's ET cover as designed. CAW cover licensing is separate and distinct from the Federal Cell. Since their geometry differs, any attempt to couple or join the reviews is unsupported and arbitrary. Therefore, this aspect of the question is moot.

2.4 Interrogatory CR R313-25-22-162/2: Disposal Cell Stability

This interrogatory can be closed because the same issues are raised in Interrogatory CR R313-25-7(2)-160/2: Comparison of Class A West and Federal Cell Designs, which remains open.

2.4.1 Interrogatory Response

We concur that this interrogatory should be closed. See above for discussion of Interrogatory CR R313-25-7(2)-160/2.

3.0 References

Neptune, 2015a. *Final Report for the Clive DU PA Model, Clive DU PA Model v1.4,* NAC-0024_R4, Neptune and Company Inc., Los Alamos NM, November 2015

Neptune, 2015b. *Embankment Modeling for the Clive DU PA, Clive DU PA Model v1.4,* NAC-0019_R4, Neptune and Company Inc., Los Alamos NM, October 2015

Neptune, 2018. *Erosion Responses for the Clive DU PA Model,* NAC-0108_R0, Neptune and Company Inc., Lakewood CO, February 2018

SC&A, 2015. *Utah Division of Radiation Control, EnergySolutions Clive LLRW Disposal Facility, License No: UT2300249; RML #UT 2300249, Condition 35 Compliance Report; Appendix A: Final Report for the Clive DU PA Model, Safety Evaluation Report, Volume 1,* SC&A Inc., Vienna VA, April 2015

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