Neptune and Company Inc.

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Clive DU PA Model, version 1

Appendix 2

Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility

Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility

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Prepared by

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Acronyms and Abbrev.

Ac	actinium
Am	americium
amsl	above mean sea level
bgs	below ground surface
BLM	Bureau of Land Management
Bq	becquerel (1 disintegration per second)
CAS	Class A South (embankment)
CEDE	committed effective dose equivalent
CFR	U.S. Code of Federal Regulations
Ci	curie (37 GBq)
CSF	cancer slope factor
CSM	conceptual site model
CWF	Containerized Waste Facility
DCF	dose conversion factor
DOE	U.S. Department of Energy
DU	depleted uranium
DUF_6	depleted uranium hexafluoride
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ETTP	East Tennessee Technology Park
FEIS	Final Environmental Impact Statement
FEP	features, events, and processes
FR	Federal Register
ft	foot/feet
g	gram
GDP	gaseous diffusion plant
GWPL	groundwater protection limit(s)
GTCC	greater than Class C waste
ha	hectare
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
IHI	inadvertent human intruder
ka	thousand years ago
K_d	soil/water partition coefficient
kg	kilogram
K_H	Henry's Law constant (air/water partition coefficient)
km	kilometer
ky	thousand years
L	liter

LARW	low-activity radioactive waste
LLW	low-level radioactive waste
MCL	maximum contaminant level(s)
m	meter
Ma	million years ago
mg	milligram
Mg	megagram (one metric ton)
MLLW	mixed [hazardous and] low-level radioactive waste
MOP	member of the public
MPa	megapascal
mrem	millirem
mSv	millisievert
My	million years
NRC	U.S. Nuclear Regulatory Commission
NTS	Nevada Test Site
NUREG	an NRC publication
OHV	off-highway vehicle
Pa	protactinium
PA	performance assessment
PAWG	Performance Assessment Working Group (DOE)
pCi	picocurie
Po	polonium
ppm	part per million
Pu	plutonium
QA	quality assurance
Ra	radium
RfD	reference dose
Rn	radon
SRS	Savannah River Site
Sv	Sievert
Tc	technetium
TDS	total dissolved solids
TEDE	total effective dose equivalent
TF	Treatment Facility
Th	thorium
U	uranium
UAC	Utah Administrative Code
UNF	used nuclear fuel
UWQB	Utah Water Quality Board
yr	year

1 Introduction

The safe storage and disposal of depleted uranium (DU) waste is essential for mitigating releases of radioactive materials and reducing exposures to humans and the environment. Currently, a radioactive waste facility located in Clive, Utah (the "Clive facility") operated by Energy*Solutions* is proposed to receive and store DU waste that has been declared surplus from radiological facilities across the nation. The Clive facility has been tasked with disposing of the DU waste in an economically feasible manner that protects humans from future radiological releases.

To assess whether the proposed Clive facility location and containment technologies are suitable for protection of human health, specific performance objectives for land disposal of radioactive waste set forth in Title 10 Code of Federal Regulations Part 61 (10 CFR 61) Subpart C, and promulgated by the Nuclear Regulatory Commission (NRC), must be met. In order to support the required radiological performance assessment (PA), a detailed computer model will be developed to evaluate the doses to human receptors that would result from the disposal of DU and its associated radioactive contaminants (collectively termed "DU waste"), and conversely to determine how much DU waste can be safely disposed at the Clive facility.

This conceptual site model (CSM) document describes the site conditions, chemical and radiological characteristics of the wastes, contaminant transport pathways, and potential exposure routes at the Clive facility that are used to structure the quantitative PA model. The PA model will be developed as a probabilistic model taking into account uncertainties inherent to model variables and site-specific conditions. The GoldSim systems analysis software (GTG, 2010) will be used to construct the probabilistic PA model. This PA model is intended to reflect the current state of knowledge with respect to the proposed DU disposal, and to support environmental decision making in light of inherent uncertainties.

The CSM report, and the associated features, events and processes report, are regarded as "living documents." That is, as further information is gathered during the course of model development, the CSM might evolve and, consequently, be updated. Changes to the CSM will be tracked so that the evolution is well documented. Nevertheless, this version of the CSM (revision 1) is expected to include most of the features, events and processes that need to be included in the evaluation of the Clive facility for disposal of DU waste.

2 Scope of the Conceptual Site Model

The overall scope of this PA is to evaluate the long term siting and performance integrity of the Class A Embankment at the Clive facility for the proposed disposal of DU waste. The need for the PA is driven by Federal and State of Utah regulations, which require an evaluation of the potential human radiation doses and consequences of disposal of radioactive waste. The regulations contain procedural requirements, performance objectives, and technical requirements for near-surface disposal, including disposal in engineered facilities with protective earthen/rock covers, which may be built fully or partially above-grade, such as the radioactive waste disposal cells at the Clive facility. The overall PA process is illustrated in Figure 1.

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

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

The quantitative probabilistic PA model will be used to evaluate the migration of radionuclides contained in the DU wastes, and the subsequent human doses resulting from potential exposure to radionuclides, based on projecting current societal conditions up to 10,000 years into the future. However, because the radioactivity from the DU wastes (including progeny) will increase for more than 2 million years, and will persist for at least a billion years, further modeling of potential long-term future scenarios will be performed beyond the 10,000 year compliance period. The longer term model will address mechanisms by which radionuclides might be dispersed in the environment, suggesting concentrations of radionuclides in various media.

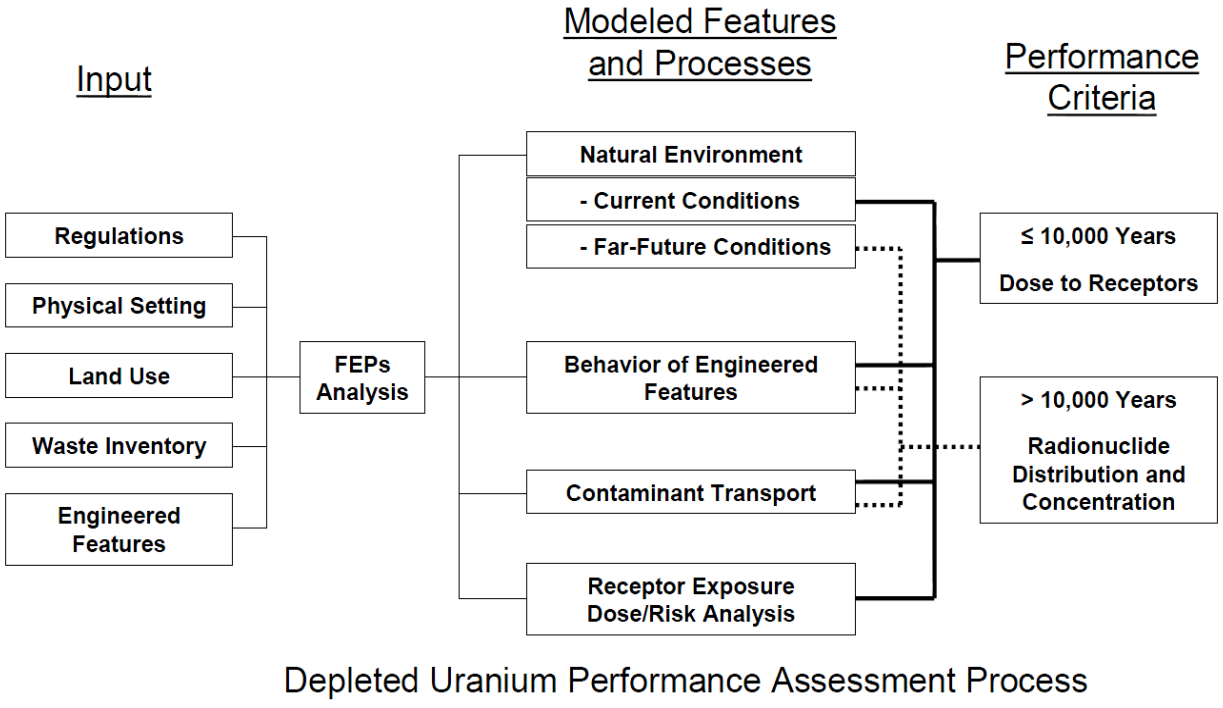

Figure 1. Conceptual diagram of the performance assessment process

However, the long term future model will not directly address human doses, because it is not clear what human exposure scenarios might be reasonable given events in the long term future that might dramatically alter human society and civilization. Therefore, the focus of the longer-term modeling will be scenarios developed to represent potential features, events and processes that affect contaminant fate and transport over these much longer periods.

The quantitative model will be used to evaluate potential human radiation doses from exposure to radionuclides contained in the DU wastes that may result from migration through the engineered and natural systems to the potentially exposed population. Note that regulations specify estimation of *dose*, rather than risk; however, there are risks implied in the regulatory dose limits (see Section 4). Risk-based decision-making is best supported with probabilistic modeling, and has been used to assess compliance and inform decision making at many challenging radioactive waste sites under various regulatory requirements. The U.S. Environmental Protection Agency (EPA) has published probabilistic risk assessment guidance for human exposure to chemicals (EPA, 2001) and promotes the use of probabilistic methods for performance assessments of radioactive disposal facilities in its *Environmental Radiation Protection Standards* (40 CFR 191). The U.S. Department of Energy (DOE) has implemented a probabilistic PA at the Waste Isolation Pilot Plant, at the Yucca Mountain Project, and for low-level radioactive waste (LLW) disposal facilities at the Nevada Test Site (NTS), and the Los Alamos National Laboratory, and has more recently initiated similar efforts at the Savannah River Site. The NRC has adopted this approach as well, as documented in its *Performance Assessment Methodology for LLW Disposal Facilities* (NRC, 2000). Further, the National Research Council has argued in favor of the risk-based approach in its recent book, *Risk and Decisions* (National Research Council, 2005). More generally, various agencies and professional organizations (e.g., EPA's Council for Regulatory Environmental Modeling, Society for Risk Analysis) have consistently moved in the direction of supporting risk-based decisions with probabilistic analysis so that the potential risks are modeled more realistically (as opposed to conservatively) and uncertainty is numerically characterized.

Thus, the quantitative PA model will be probabilistic; with uncertainties associated with the complex evolution from waste disposal to human exposure and dose captured through input parameter probability distributions. Attention will be paid to developing model input parameter distributions that reflect both the uncertain state of knowledge and the appropriate spatio-temporal scaling. The focus of the uncertainty analysis in the PA model will be parameter uncertainty. The PA model will also be developed with the capability of running the model under various FEP scenarios to allow for an assessment of scenario uncertainty. This will be important for the longer-term scenarios in particular.

As noted above, the probabilistic approach models future conditions by projecting current conditions as reasonably as possible while including uncertainty in the parameters or assumptions of the model. This is differentiated from "conservative" (i.e., biased toward safety) modeling that is sometimes performed, typically using point values for parameters (implying a great deal of confidence; i.e., no uncertainty). This type of conservative modeling is often termed "deterministic" modeling, and has often been 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, conservative dose results from PA models do not support the full capability of a disposal facility. Conservative, deterministic models may have utility at a "screening" level, but, they do not provide the full range of information that is necessary for important decisions such as compliance or rule-making (Bogen 1994, Cullen 1994).

Of further concern is the type of modeling environment that is needed to support the types of decisions that are made on the basis of PA models. The GoldSim modeling environment is focused on development of "systems-level" models. These models are intended to characterize the effects and consequences of system level dynamics. In this case, the system consists of the waste disposal facility and the interaction of the facility with the environment (e.g., weather, water, biota, etc.) in the 10,000-yr duration for which quantitative modeling will be performed with human dose as the endpoint of interest, as well as the longer duration for which media concentrations resulting from potential future scenarios involving, for example, climate change, re-occurrence of large lakes, will be evaluated. That is, the domain of the model is large both spatially and temporally. However, decisions need to be made in the face of uncertainty regarding the applicability of the Clive facility for disposal of DU, and, more generally, for the design of the disposal facility.

Systems-level models are aimed precisely at supporting decision making in this type of context. More detailed "process-level" models, which might model at a much more refined spatial scale (and perhaps temporal scale), can provide useful input to the systems-level model, but they do not as readily support decision-making at the more holistic scale of the systems-level response. For example, a systems-level model will evaluate the movement of radionuclides from the waste zone, through the unsaturated zone, to the saturated zone, by considering the average effects across those system components, as opposed to the effects at a more refined scale such as every cubic meter, which is more common for process-level modeling. Process-level models are often geared towards capturing variability at small spatial scales, whereas systems-level models are aimed at capturing uncertainty in the system as a whole. PA modeling is concerned with the latter, including demonstration of compliance followed by a decision analysis in the spirit of achieving ALARA (as low as reasonably achievable; see Section 4) releases and doses to optimize disposal and closure (e.g., engineered barriers, institutional controls).

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

A further statistical issue of concern is the challenge of capturing dependencies or correlation structures with this type of dynamic probabilistic system. Inputs for parameters (variables) are usually provided independently of each other. However, it is very important to capture correlations between variables in a multiplicative model. Otherwise, system uncertainty is not adequately constrained. GoldSim provides some limited capability to introduce correlation into a PA model, but steps will be taken to evaluate the correlation effects of some variables.

Processes that contribute to the fate and transport of these contaminants are also abstracted into mathematical models. That is, process-level models are sometimes important for providing input to PA models. Model abstraction is best performed by running process-level models for some cases or scenarios that correspond to a design over the inputs. The response can be modeled using a statistical response surface, which can then be carried or abstracted into the PA model. The systems-level PA model is then fully coupled across processes, meaning that inputs and outputs from each process affect the prior and posterior processes.

With a probabilistic dynamic PA model, a global sensitivity analysis can be performed to identify those parameters that are most important for predicting the model results. This type of sensitivity analysis is performed using statistical methods from data mining allowing all input parameters to be varied simultaneously. This allows the combined effect of changes in parameters to be evaluated. The sensitivity analysis tools can then be used to determine whether more information should be collected to reduce uncertainty. This is fully consistent with the concepts underlying the PA maintenance program that DOE uses under DOE M 435.1 to reduce uncertainty in LLW PAs (DOE, 1999).

3 Site Description

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

Currently, the Clive facility receives waste shipped via truck and rail. Pending the findings of the PA, DU waste will be stored in a permanent above-ground engineered disposal embankment that is clay-lined with a composite clay and rock cap. The disposal embankment is designed to perform for a minimum of 500 years based on requirements of 10 CFR 61.7, which provides a long-term disposal solution with minimal need for active maintenance after site closure. More detail relating to the properties of the disposal embankment is provided in Section 3.6.1 .

Figure 2. Location of the Clive site operated by Energy*Solutions* (from Google Earth)

The Energy*Solutions* Clive facility is divided into three main areas (Figure 3; Energy*Solutions*, 2008):

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

The subject of this CSM and associated modeling is DU waste disposed or to be disposed in the Class A South cell. The terms "cell" and "embankment" are here used interchangeably.

3.1 Land Management

The Bureau of Land Management (BLM) administers much of the land around the Clive facility; this land is public domain (NRC, 1993). The disposal site is located within a 260-ha (640-acre) section of land that was originally selected for the disposal of the Vitro Chemical Company uranium tailings (see "Vitro" in Figure 3). This section of land occupies approximately 40 ha (100 acres), while the remaining 220 ha (540 acres) is owned and operated by Energy*Solutions*. The Tooele County Commission zoned the Clive site as a "Hazardous Industrial District," which

falls within the West Desert Hazardous Industry Area, an area that prohibits future residential housing in the near vicinity of the Clive site (NRC, 1993).

NRC (1993) and the BLM (BLM staff, personal communication, 2010) indicates that the area surrounding the Clive facility is used for cattle and sheep grazing purposes and recreation. While the site is zoned for hazardous waste disposal by Tooele County, the lack of potable water at this site makes the surrounding area an unlikely location for any residential, commercial, or industrial developments (Baird et al., 1990).

Figure 3. Disposal and Treatment Facilities operated by Energy*Solutions*

3.2 Climate

3.2.1 Temperature

Regional climate is regulated by the surrounding mountain ranges, which restrict movement of weather systems in the vicinity of the Clive facility. The most influential feature affecting regional climate is the presence of the Great Salt Lake, which can moderate downwind temperatures since it never freezes (NRC, 1993). The climatic conditions at the Clive facility are characterized by hot and dry summers, cool springs and falls, and moderately cold winters (NRC, 1993). Frequent invasions of cold air are restricted by the mountain ranges in the area. Data from the Clive facility from 1992 through 2009 indicate that monthly temperatures range from about -2°C (29°F) in December to 26°C (78°F) in July (Whetstone, 2006).

3.2.2 Precipitation

The Clive facility is characterized as being an arid to semi-arid environment where evaporation greatly exceeds annual precipitation (Adrian Brown, 1997a). Data collected at the Clive facility from 1992 through 2004 indicate that average annual rainfall is on the order of 22 cm (8.6 in) per year (Whetstone, 2006). Precipitation generally reaches a maximum in the spring (1992-2004 monthly average of 3.2 cm [1.25 in] in April), when storms from the Pacific Ocean are strong enough to move over the mountains (NRC, 1993; Whetstone, 2006). Precipitation is generally lighter during the summer and fall months (1992-2004 monthly average of 0.8 cm [0.32 in] in August) with snowfall occurring during the winter months (Whetstone, 2006; NRC, 1993; Baird et al., 1990).

3.2.3 Evaporation

Because of warm temperatures and low relative humidity, the Clive facility is located in an area of high evaporation rates. NRC (1993) indicates that average annual pond evaporation rate at the Clive facility is 150 cm/yr (59 in/yr), with the highest evaporation rates between the months of May and October. Previous modeling studies indicate that the Dugway climatological station nearby is comparable to the Clive site with respect to evaporation and have reported pan-evaporation estimates of 183 cm/yr (72 in/yr), which is considerably greater than average annual rainfall (Adrian Brown, 1997a). Because of the high evaporation rate, the amount of groundwater recharge due to precipitation is likely very small, except during high intensity precipitation events (Adrian Brown, 1997a).

3.3 Geology

3.3.1 Site Geology

The Clive facility rests on lacustrine deposits from the ancestral Lake Bonneville, which was a pluvial lake that existed during the late Pleistocene. The geology is characterized by north-south trending mountain ranges surrounded by sediment filled basins. The site is bounded by the Cedar Mountains to the east and the Great Salt Lake Desert to the west. Surficial drainage is generally in a westward direction away from the nearest mountain range.

NRC (1993) indicates that based on subsurface borehole logs, lacustrine deposits extend to at least 75 m (250 ft) underneath the site, however these estimates are limited to the depths of boreholes drilled from previous hydrogeologic investigations (e.g., Envirocare [2004]). Oviatt et

al. (1999) examined the upper 110 m (361 ft) of the Burmester core, a sediment core that was collected to a depth of 307 m (1007 ft) in the 1970s to characterize major pluvial lake cycles in the Bonneville Basin. Brodeur (2006) also indicates that sediments can be up to a thousand meters thick in some regions of the basin and greater than 200 m (700 ft) thick in the basin at the Clive site.

The sediments underlying the Clive site are described as four separate stratigraphic units based on grain size and sediment characteristics. These units are described in NRC (1993), Adrian Brown (1997a), and Envirocare (2004) and are introduced from the ground surface down:

- Unit 4 (surface) is composed primarily of silt and clay between 1.8 and 5 m (6 and 16.5 ft) thick, with an average thickness of 3 m (10 ft). Minor amounts of sand within the silt and clay can be found along with some evaporite mineral content. This layer is rather impermeable due to the silt and clay composition and therefore makes it difficult for water to readily pass through it.
- Unit 3 lies beneath Unit 4 and is composed of a silty sand between 2.1 and 7.6 m (7 and 25 ft thick, with an average thickness of 3 m (10 ft). The water table of a shallow, unconfined aquifer occurs near the bottom of this Unit on the western side of the site. This shallow aquifer is saline.
- Unit 2 lies beneath Unit 3 and is composed of clay with occasional lenses or interbeds of silty sand. This unit is between 0.76 and 7.6 m (2.5 and 25 ft) thick and is saturated with saline groundwater.
- Unit 1 underlies Unit 2 and is composed of silty sand with interbedded layers of clay and silt. The Envirocare investigation indicates that the total thickness of Unit 1 is at least 75 m (250 ft) (Envirocare, 2004). The deepest borehole at the time of this investigation was drilled to 250 ft below ground surface (bgs) without encountering bedrock. Unit 1 is saturated beneath the facility and contains a locally confined aquifer. Envirocare (2004) also indicated that a borehole drilled at an area north of the facility did not encounter bedrock at a depth of 200 m (700 ft) bgs.

3.3.2 Site Seismotectonics

The Clive site does not have any known active faults in its vicinity. NRC (1993) indicates that the nearest faulting is located 29 km (18 miles) to the north, having occurred between 1 million to 25 million years ago (1 to 25 Ma). Although the site is not located near any active faults, isostatic rebound is suspected to be the cause of any recent seismic activity in the Lake Bonneville area.

NRC (1993) cites two seismic investigations that were conducted for the Vitro tailings disposal facility and a proposed site for a supercollider that was to encompass a 24-km (15-mile) elliptical ring around the Clive site. Based on these studies, NRC (1993) indicated that nearby structures and seismogenic areas that could pose a hazard include the fault zones within a 72-km (45-mile) radius of the site. These include the eastern flank of the Cedar Mountains, western flank of the Lakeside Mountains, Northwest Puddle Valley, eastern flank of the Newfoundland mountains, and the western flank of the Stansbury Mountains. However, NRC (1993) concluded that no

active fault zones lie beneath the Clive site, and there is no macroseismic evidence of a capable fault in the vicinity of the site.

3.4 Hydrology

3.4.1 Surface Water

The Clive site is located within a hydrologically closed basin west of the Cedar Mountains. As there is no outlet from the basin, any water that would flow by the site would pond several miles to the west in a playa (NRC, 1993).

No surface water bodies are present on the Clive site and any stream flows from higher elevations usually evaporate and/or infiltrate before reaching flatter land (NRC, 1993). Indicators of channelized flow are not present on the Clive site (Baird et al., 1990). The nearest stream channel ends about 3.2 km (2mi) east of the site, and the nearest water body that is utilized is approximately 45 km (28 mi) to the east. The only significant water body in the region is Great Salt Lake. NRC (1993) indicates that no historical (chronic) flooding has occurred in the vicinity of the site. Given the 1300-m elevation of the Clive facility, it is not subject to flooding from the Great Salt Lake, which is not expected to exceed 1285 m (4217 ft) amsl (NRC, 1993).

3.4.2 Groundwater

The NRC recognizes "groundwater" to include all subsurface water, in both unsaturated and saturated zones. This convention is used in the following descriptions.

3.4.2.1 Groundwater Flow Regime

Local groundwater recharge from meteoric sources is generally limited, since pan-evaporation greatly exceeds precipitation (NRC, 1993). Recharge is more likely to occur in areas adjoining the surrounding mountain ranges, moving as subsurface flow to the center of the basin.

Given the strong evaporation potential at the site, it may be expected that some unsaturated zone (vadose zone) groundwater may actually move upward. An upward gradient is not only due to evaporation of water at the ground surface, it is also driven by the transpiration of plants, which pull water from the ground and release it to the dry atmosphere. The coupled effect of these two processes, or evapotranspiration, serves to keep near-surface soils dry enough that precipitation often does not penetrate to lower soils.

Groundwater at the Clive site is found within a low-permeability saline aquifer starting near the bottom of the Unit 3 stratigraphic unit, and saturating the Unit 2 stratigraphic unit. The depth to groundwater is between approximately 6 and 9 m (20 and 30 ft) bgs at an approximate elevation of 1295 m (4250 ft) amsl (Brodeur, 2006).

The regional (saturated) groundwater system flows primarily to the east-northeast toward the Great Salt Lake (Envirocare 2004) and the local shallow groundwater follows a slight horizontal gradient to the north-northeast (Brodeur, 2006).

3.4.2.2 Groundwater Quality

The underlying groundwater in the vicinity of the Clive site is of naturally poor quality because of its high salinity and, as a consequence, is not suitable for most human uses (NRC, 1993).

Brodeur (2006) reports that groundwater beneath the Clive site had a total dissolved solid (TDS) content of 40,500 mg/L (40.5 ‰). The majority of the cations and anions are sodium and chloride, respectively. This is not potable for humans. For comparison purposes, sea water typically has a TDS content of 35,000 mg/L (35 ‰), thus the salinity content at the site is much higher than average sea water.

3.5 Ecology

NRC (1993) and Envirocare (2000) characterized the Clive facility as a homogeneous, semi-desert low shrubland, primarily composed of shadscale (*Atriplex confertifolia*). The shrubland is part of the Northern Great Basin Desert Shrub Biome and has been described as a saltbrush-greasewood shrub complex. The development of modeling of biotic processes is detailed in the Biological Modeling white paper.

3.5.1 Local Vegetation

Several plant communities identified include shadscale-gray molly (*Kochia americana* var. *vestita*), shadscale-gray molly-black greasewood (*Sarcobatus vermiculatus*), and black greasewood-gardner saltbrush (*Atriplex nuttallii*). Envirocare (2000) and SWCA (2011) confirmed that the predominant vegetation over most of the site is shadscale. Shrubs are widely spaced, totaling between 1.5% and 20% ground cover, depending upon vegetation association. The shadscale-gray molly community covers most of the South Clive site, with black greasewood becoming prominent only on the eastern quarter of the site. SWCA (2011) found very little transition between the shadscale-gray molly and black greasewood vegetation associations, and that shadscale and gray molly totaled less than 0.5% cover in the geasewood association, suggesting that the shadscale-gray molly-black greasewood community identified by Envirocare (2000) is perhaps better classified as a pure greasewood community. Envirocare reported that the black greasewood-gardner saltbush community only occurs in the far northeast corner of the Clive site. Seepweed (*Suaeda torreyana*), perfoliate pepperweed (*Lepidium perfoliatum*), and halogeton (*Halogeton glomeratus*) are the most common understory plants. Sage (A*rtemisia* spp.) and rabbitbrush (*Chrysothamnus* spp.) which are characteristic of much of the Great Basin shrubland, do not occur on the valley floors around Clive due to their low salt tolerance, but may occur on bajadas and well-drained slopes. No threatened or endangered plant species are known to occur in the near vicinity of the Clive site (NRC, 1993).

3.5.2 Local Wildlife

The Clive site consists of two main habitat types, shadscale flats and greasewood. Comprehensive faunal surveys have not been conducted around the Clive site, but NRC (1993) indicates that species diversity is low. Species typical of these shrubland habitats include black-tailed jackrabbit (*Lepus californicus*), Townsend's ground-squirrel (*Spermophilus townsendii*), Ord's kangaroo rat (*Dipodomys ordii*), deer mouse (*Peromyscus maniculatus*), horned lark (*Eremophila alpestris*), and the desert horned lizard (*Phrynosoma platyrhinos*). Jackrabbits, deer mice, and grasshopper mice (*Onychomys leucogaster*) were the only mammals trapped during surveys conducted for the 1993 Environmental Impact Statement (EIS) (NRC 1993). Additional trapping conducted in October 2010 collected only deer mice at the Clive site, and deer mice, grasshopper mice, Ord's kangaroo rat, and chisel-toothed kangaroo rat in neighboring areas with steeper slopes and greater density of grasses (SWCA 2011). Pronghorn antelope can also be

found near the facility, but the area is considered to be poor habitat (NRC, 1993). The bald eagle and the peregrine falcon are two federally-listed species that could occur in the project area. However, NRC (1993) indicates that the U.S. Fish and Wildlife Service concurs with the conclusion that the project site would not affect either species due to the distance to the nearest nesting site.

A variety of invertebrates is expected to occur at the Clive site. Invertebrates, particularly ants, play a key role in maintenance of desert shrub communities. Harvester ants of the genus *Pogonomyrmex* create large, easily recognizable nests, and play an important role in the development of desert soils and the dispersal of plant seeds. Surveys conducted in 2010 found that the Western harvester ant (*Pogonomyrmex occidentalis*) was by far the dominant ant species at the site, independent of vegetative association (SWCA 2011).

3.6 Engineered Features

3.6.1 Class A South Disposal Cell Design

Depleted uranium waste is proposed for disposal in the Class A South disposal cell. The Class A South Cell, which is part of the Federal Cell, is about 541 × 436 m (1,775 × 1,430 ft), with an area of approximately 24 ha (58 acres), and an estimated total waste volume of about 2.7 million m^3 (96 million ft^3). A drainage ditch surrounds the disposal cell on three sides, with 11e.(2) waste on the fourth side. The cell is constructed on top of a compacted clay liner covered by a protective cover. Waste will be placed above the liner and will be covered with a layered engineered cover constructed of natural materials. The top slopes will be finished at a 4% grade while the side slopes will be no steeper than 5:1 (20% grade).

The design of the Class A South Cell cover has been engineered to prevent the effects of erosion, reduce the effects of infiltration, and to protect workers and the public from radionuclide exposure. The cell cover is a layered composite of a clay radon barrier, filter material, sacrificial soil, and rip rap. The clay radon barrier is designed to minimize infiltration of precipitation and runoff and reduce the migration of radon from the waste cell. The filter material is intended to confine dew and condensates in order to reduce the likelihood of the radon barrier clay from drying out. The purpose of the rip rap cover is to ensure the integrity of the underlying layers and overall waste cell by providing protection from physical weathering sources such as erosion by water and wind. The detailed properties of each cell layer may be found in engineering drawings (Energy*Solutions*, 2009a) and in the white paper on Embankment Modeling.

3.6.2 Degradation of Engineered Features

While the engineered liner and cap are expected to be constructed as designed, and to perform well over the coming decades, they will likely degrade with time. Sheet erosion by wind and water is expected to be minor while the rip rap is intact, and is likely to be counteracted by aeolian deposition of loess (wind-blown sediment) filling the interstices of the gravel, cobbles and boulders. It is possible, however, that the rip rap may be displaced or degraded by processes such as unusual weather events (e.g., tornadoes), animal activity, or human activities after the loss of institutional control. These events may result in damage to the rip rap and cap, though the damage is likely to be localized. This could result in gully erosion, and possibly the exposure of

deeper parts of the cap or the waste itself. Details are provided in the Erosion Modeling white paper.

4 Regulatory Context

Energy*Solutions* is permitted by the State of Utah to receive Class A Low Level and Mixed Low-Level Radioactive Waste (LLW and MLLW) under Utah Administrative Code (UAC) R313-25, *License Requirements for Land Disposal of Radioactive Waste.* The wastes that are received must be classified in accordance with the UAC R313-15-1008, *Classification and Characteristics of Low-Level Radioactive Waste.* The classification requirements in UAC R313-15-1008 reflect those outlined in NRC's 10 CFR 61 Section 55, but include additional references to radium-226 (Ra-226). Further, groundwater protection levels (GWPLs) must be adhered to, as outlined in the site's *Ground Water Quality Discharge Permit* (UWQB, 2010). The regulatory context within the Federal and State regulations is discussed in the following sections.

4.1 Nuclear Regulatory Commission Regulations

Title 10 CFR 61 (Code of Federal Regulations, 2007) is the Federal regulation for the disposal of certain radioactive wastes, including land disposal at privately-operated facilities such as that managed and operated by Energy*Solutions* at Clive, Utah. It contains procedural requirements, performance objectives, and technical requirements for near-surface disposal, including disposal in engineered facilities with protective earthen covers, which may be built fully or partially above-grade. Near-surface disposal is defined as disposal in or within the upper 30 meters of the earth's surface (10 CFR 61.2).

The promulgation of 10 CFR 61 required a Final Environmental Impact Statement (FEIS) which was issued in 1982 (NRC, 1982). The FEIS focused on the waste streams typically disposed by NRC licensees at the time, and did not take into account facilities that generated high concentrations and large quantities of DU, which was not then considered to be waste. As a result, the NRC did not establish a concentration limit for uranium isotopes in the waste classification tables presented in 10 CFR 61.55.

4.1.1 Section 61.55: Waste Classification

Section 61.55 defines three classes of radioactive waste for near surface disposal—Class A, Class B, Class C—and discusses the fourth, commonly called "greater than Class C" (GTCC) waste, which, "in the absence of specific requirements in this part […] must be disposed of in a geologic repository […] unless proposals for disposal of such waste in a disposal site licensed pursuant to this part are approved by the Commission" (§61.55[2][iv]). The Class A, B, and C wastes are defined based on concentrations of specific long-lived radionuclides (defined in Table 1 of §61.55), or, in the absence of long-lived ones, on specific short-lived radionuclides (defined in Table 2 of §61.55). These tables are reproduced in Figure 4 for convenience.

Wastes containing radionuclides listed on both tables are classified using a combination approach as specified in §61.55(5):

> §61.55(5) Classification determined by both long- and short-lived radionuclides. If radioactive waste contains a mixture of radionuclides, some of which are listed in Table 1, and some of which are listed in Table 2, classification shall be determined as follows:

> (i) If the concentration of a nuclide listed in Table 1 does not exceed 0.1 times the value listed in Table 1, the class shall be that determined by the concentration of nuclides listed in Table 2.
> (ii) If the concentration of a nuclide listed in Table 1 exceeds 0.1 times the value listed in Table 1 but does not exceed the value in Table 1, the waste shall be Class C, provided the concentration of nuclides listed in Table 2 does not exceed the value shown in Column 3 of Table 2.

The scope of this PA includes the disposal of DU, which by default falls into the category of Class A waste:

> §61.55(6) Classification of wastes with radionuclides other than those listed in Tables 1 and 2. If radioactive waste does not contain any nuclides listed in either Table 1 or 2, it is Class A.

Nevertheless, DU presents an interesting case, as the uranium it contains is fundamentally different from the Class A wastes that NRC had in mind when it devised the classifications. Uranium does not appear in Table 1 of 10 CFR 61.55 (Figure 4) because, at the time of the development of the regulation, uranium waste did not, and was not expected to, exist in significant quantities. The nature of the radiological hazards associated with DU presents challenges to the estimation of long-term effects from its disposal. As DU evolves toward secular equilibrium with its progeny, a process that will take over 2 million years, it becomes a greater radiological hazard due to the in-growth of its decay products. Recognition of this special behavior of DU has prompted the NRC to revisit the regulation in a rule-making. This is discussed in Section 4.1.5 , below. Until that rule-making is complete, however, 10 CFR 61 stands as the controlling regulation.

TABLE 1

Radionuclide	Concentration curies per cubic meter
C–14	8
C–14 in activated metal	80
Ni–59 in activated metal	220
Nb–94 in activated metal	0.2
Tc–99	3
I–129	0.08
Alpha emitting transuranic nuclides with half-life greater than 5 years	[1] 100
Pu–241	[1] 3,500
Cm–242	[1] 20,000

[1] Units are nanocuries per gram.

TABLE 2

Radionuclide	Concentration, curies per cubic meter		
	Col. 1	Col. 2	Col. 3
Total of all nuclides with less than 5 year half-life	700	([1])	([1])
H–3	40	([1])	([1])
Co–60	700	([1])	([1])
Ni–63	3.5	70	700
Ni–63 in activated metal	35	700	7000
Sr–90	0.04	150	7000
Cs–137	1	44	4600

[1] There are no limits established for these radionuclides in Class B or C wastes. Practical considerations such as the effects of external radiation and internal heat generation on transportation, handling, and disposal will limit the concentrations for these wastes. These wastes shall be Class B unless the concentrations of other nuclides in Table 2 determine the waste to be Class C independent of these nuclides.

Figure 4: Waste classification Tables 1 and 2 from 10 CFR 61.55

4.1.2 Section 61.41: Protection of the Public

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

> **§ 61.41 Protection of the general population from releases of radioactivity.**
> Concentrations of radioactive material which may be released to the general environment in ground water, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 millirems [0.25 mSv] to the whole body, 75 millirems [0.75 mSv] to the thyroid, and 25 millirems [0.25 mSv] to any other organ of any member of the public. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable.

However, the approach to dose assessment suggested by §61.41 is now dated, and NRC recommends the current International Commission on Radiological Protection 30 (ICRP 1984) methodology in their Performance Assessment Methodology, NUREG-1573 (NRC 2000):

> **3.3.7.1.2 Internal Dosimetry**
> The NRC performance objective set forth in Section 61.41, is based on the ICRP 2 dose 3-79 methodology (ICRP, 1979), but current health physics practices follow the dose methodology used in Part 20, which is currently based on ICRP 30 methodology (ICRP, 1979). The license application will contain many other assessments of potential exposures (e.g., worker exposure, accident exposures, and operational releases) that will need to use ICRP 30 dose methodology. For internal consistency in the application, it is recommended that the performance assessment be consistent with the methodology approved by the NRC in Part 20 for comparison with the performance objective. Therefore, PAWG [the performance assessment working group] believes that calculation of a TEDE [total effective dose equivalent] for the LLW performance assessment—a summation of the annual external dose and the CEDE [committed effective dose equivalent]—is acceptable for comparison with the performance objective.
> As a matter of policy, the Commission considers 0.25 mSv/year (25 mrem/year) TEDE as the appropriate dose limit to compare with the range of potential doses represented by the older limits that had whole-body dose limits of 0.25 mSv/year (25 mrem/year) (NRC, 1999, 64 FR 8644; see Footnote 1). Applicants do not need to consider organ doses individually because the low value of the TEDE should ensure that no organ dose will exceed 0.50 mSv/year (50 mrem/year).

The estimation of dose to a MOP in the PA model therefore uses the ICRP 30 TEDE approach.

There are a number of implicit assumptions in using dose as a performance metric, in that it is being used as a proxy for risk. Risk involves a biological effect. The biological effect of greatest interest at the doses evaluated here is cancer. The risk of cancer to an exposed individual depends upon a large number of assumptions, the most influential being 1) that the major source of data for radiological risk assessment; i.e., the Hiroshima/Nagasaki atomic bomb survivors, is relevant for the doses evaluated, and 2) that risks can be extrapolated from large doses to small doses in a linear fashion, with no threshold of effect (i.e., no dose is without some risk of cancer). Both of these assumptions are controversial, yet provide the basis for most radiation regulation. The implications of these assumptions are discussed in the Dose Assessment white paper.

4.1.3 Section 61.42: ALARA and Collective Dose

A second potential decision rule pertains to populations. There is no clear decision rule as far as collective (cumulative population) doses are concerned. However, the regulations state that "reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable" (ALARA). There are, however, other competing objectives, and the resource implications are large to achieving ALARA on a collective level. Additionally, the words "reasonably" and "achievable" are not precise. The two words perhaps imply some degree of consideration of trade-offs, but no clear definition is published. Assuming that there are trade-offs, then this implies that an analysis that explicitly evaluates the trade-offs, and how different disposal options, designs, or sites may differentially satisfy the objectives and resource constraints (e.g., a decision or economic analysis) should be performed. Yet, at present, this has yet to be conducted in the context of the PA process, and there are no current specific regulations. However, the ICRP (1984) provides guidance regarding potential approaches.

4.1.4 Section 61.42: Protection of the Inadvertent Intruder

In addition to protecting any member of the public, 10 CFR 61 requires additional assurance of protecting individuals from the consequences of inadvertent intrusion. An inadvertent intruder is someone who is exposed to waste without meaning to, and without realizing it is there (after loss of institutional control). This is distinct from the intentional intruder, who might be interested in deliberately disturbing the site, or extracting materials from it, or who might be driven by curiosity or scientific interest.

> **§ 61.42 Protection of individuals from inadvertent intrusion.**
> Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste at any time after active institutional controls over the disposal site are removed.

Because the definition of inadvertent intruders encompasses exposure of individuals who engage in normal activities without knowing that they are receiving radiation exposure, there is no practical distinction made here between a member of the public (MOP) and inadvertent intruders with regard to exposure/dose assessment.

4.1.5 Proposed Rule-Making Regarding 10 CFR 61

In 2005, the NRC proposed to consider whether or not the quantities of DU from uranium enrichment facilities warrant an amendment of the waste classification tables currently defined in 10 CFR 61 (NRC, 2005). In 2008, NRC staff responded to the October 2005 order which evaluated a generic case to determine if Part 61 standards could be met for near-surface disposal of DU (NRC, 2008). The results of this evaluation indicated that it may be possible, given certain conditions, to meet the standards for near-surface disposal of DU. Furthermore the NRC staff prepared several regulatory options. NRC staff also recommended that no classification change be made for DU, retaining its status as Class A waste, but that additional language be included requiring a site-specific PA prior to the acceptance of DU for disposal. In March 2009, the NRC agreed with the course of action recommended by the NRC staff in SECY-08-0147 and decided to keep DU classified as a Class A waste (NRC, 2009a). They also decided to initiate rule-making that would propose enhanced PA requirements for those facilities that plan to dispose of large quantities of DU (NRC, 2009b).

Most of the proposed changes to 10 CFR 61 involve the concept that no matter what classification DU is given, any disposal of the material should involve an analysis that will inform decision makers about the doses associated with such a disposal to individuals who might be exposed at some time after site closure. This position is substantially in concordance with that put forth by the National Research Council (2005), and with the approach that will be used in this PA.

4.2 State of Utah Regulations

Utah is an NRC agreement state, meaning that it is granted authority to enforce NRC regulation, or regulations of its own drafting that are substantially compatible with the NRC regulation, 10 CFR 61. The State of Utah has done so, in two Rules of the Utah Administrative Code (UAC): UAC Rule R313-25 *License Requirements for Land Disposal of Radioactive Waste*, and Rule R313-15 *Standards for Protection Against Radiation* (Utah, 2010). Each of these is discussed below.

4.2.1 Section R313-25: Licensing Requirements

Section R313-25-8 *Technical Analyses*. Parts (1)(a) and (b) of this Section are patterned closely after 10 CFR 61.41 and 42:

> (1) The specific technical information shall also include the following analyses needed to demonstrate that the performance objectives of R313-25 will be met:
> (a) Analyses demonstrating that the general population will be protected from releases of radioactivity shall consider the pathways of air, soil, ground water, surface water, plant uptake, and exhumation by burrowing animals. The analyses shall clearly identify and differentiate between the roles performed by the natural disposal site characteristics and design features in isolating and segregating the wastes. The analyses shall clearly demonstrate a reasonable assurance that the exposures to humans from the release of radioactivity will not exceed the limits set forth in R313-25-19.
> (b) Analyses of the protection of inadvertent intruders shall demonstrate a reasonable assurance that the waste classification and segregation requirements will be met and that adequate barriers to inadvertent intrusion will be provided.

In addition, a new section for R313-25-8 has recently been adopted, and is reproduced here:

> (2)(a) Any facility that proposes to land dispose of significant quantities of depleted uranium, more than one metric ton in total accumulation, after June 1, 2010, shall submit for the Executive Secretary's review and approval a performance assessment that demonstrates that the performance standards specified in 10 CFR Part 61 and corresponding provisions of Utah rules will be met for the total quantities of depleted uranium and other wastes, including wastes already disposed of and the quantities of concentrated depleted uranium the facility now proposes to dispose. Any such performance assessment shall be revised as needed to reflect ongoing guidance and rulemaking from NRC. For purposes of this performance assessment, the compliance period will be a minimum of 10,000 years. Additional simulations will be performed for an analysis for the period where peak dose occurs and the results shall be analyzed qualitatively.

4.2.2 Section R313-15-1008: Waste Classification

Rule R313-15 contains section R313-15-1008 *Classification and Characteristics of Low-Level Radioactive Waste*. The definitions in this section are essentially identical to those in 10 CFR 61.55, with one exception: Utah adds Ra-226 to the list of long-lived radionuclides in the regulations' Table I (see Figure 5), with a concentration limit of 100 nCi/g (Utah, 2010). Since Ra-226 is a decay product of uranium-238 (U-238), the principal component of DU, it is of direct interest to the disposal of DU waste.

The Energy*Solutions* Clive facility is licensed by the State of Utah for disposal of Class A waste, and has disposed of DU waste under that license. The wastes under consideration for disposal in the present PA, however, contain more than simply isotopes of uranium, potentially including some radionuclides listed in the tables shown in Figure 7 in addition to the Ra-226 added by Utah (Figure 5). In particular, the DU from certain sources contains some amount of technetium-99 (Tc-99). Therefore, for now at least, the determination of classification is driven not by the presence of uranium, but by the presence of radionuclides in the tables, as discussed in the quotation from §61.55(5) above.

TABLE I

Radionuclide	Concentration curie/cubic meter(1)	Concentration nanocurie/gram(2)
C-14	8	
C-14 in activated metal	80	
Ni-59 in activated metal	220	
Nb-94 in activated metal	0.2	
Tc-99	3	
I-129	0.08	
Alpha emitting transuranic radionuclides with half-life greater than five years		100
Pu-241		3,500
Cm-242		20,000
Ra-226		100

NOTE: (1) To convert the Ci/m^3 values to gigabecquerel (GBq)/cubic meter, multiply the Ci/m^3 value by 37.
(2) To convert the nCi/g values to becquerel (Bq)/gram, multiply the nCi/g value by 37.

Figure 5. Waste classification Table I from R313-15-1008

4.2.3 Groundwater Protection Limits

In addition to these radiological criteria, the State of Utah imposes limits on groundwater contamination, as stated in the Ground Water Quality Discharge Permit (UWQB, 2010). Part I.C.1 of the Permit specifies that GWPLs in Table 1A of the Permit shall be used for the Class A

LLW Cell. Table 1A in the Permit specifies general mass and radioactivity concentrations for several constituents of interest to DU waste disposal. These GWPLs are derived from Ground Water Quality Standards listed in UAC R317-6-2 *Ground Water Quality Standards*. Exceptions to values in that table are provided for specific constituents in specific wells, tabulated in Table 1B of the Permit. This includes values for mass concentration of total uranium, radium, and gross alpha and beta radioactivity concentrations for specific wells where background values were found to be in exceedence of the Table 1A limits. Note that according to the Permit, groundwater at Clive is classified as Class IV, saline ground water, according to UAC R317-6-3 *Ground Water Classes,* and is highly unlikely to serve as a future water source. As noted in Section 3.4.2.2 , the underlying groundwater in the vicinity of the Clive site is of naturally poor quality because of its high salinity and, as a consequence, is not suitable for most human uses, and is not potable for humans.

The DU waste PA will calculate estimates of groundwater concentrations at a virtual well near the Class A South Cell for comparison with these GWPLs.

5 Summary of Features, Events, and Processes (FEPs)

A requirement for the PA scenario development process is the preliminary identification of possible future states of the disposal system as it is subjected to external changes and factors (e.g., climate, weathering, demographic changes) over time. The identification of features, events, and processes (FEPs) is a key activity in developing scenarios for the Clive facility PA model. The identification, compilation, and screening of FEPs form the basis for scenarios and quantitative analyses used to evaluate site performance.

The list of FEPs pertaining to the efficacy of disposal and storage of DU waste at the Clive Facility was compiled from several PA-related FEPs documents published for other radiological waste disposal facilities (e.g., NEA, 1992; NEA, 2000; Guzowski, 1990; Guzowski and Newman, 1993). In addition to existing PA literature sources for FEPs, site-specific understanding of the environmental and engineered attributes of the Clive facility, geographical region, and population were also addressed in the compilation of FEPs for this assessment.

All FEPs identified in the literature and developed internally were compiled into an exhaustive initial list. This list was iteratively reviewed to reduce duplication among sources and to more broadly (or more precisely) group related FEPs for incorporation in the CSM. For each group of related FEPs, the rationale for its inclusion in or dismissal from the model was documented.

This section of the CSM identifies the FEPs and conditions pertaining to the conceptual model that are retained for use in developing the PA model. Details related to the identification and screening processes are discussed in the accompanying document *FEP Analysis for Disposal of Depleted Uranium at the Clive Facility*. Features, events, and processes were grouped into several categories based on groupings listed in the original source documents, and include some overlap and redundancy. Nevertheless, the groupings are not significant with respect to the CSM. What is important is that the FEPs are considered in the appropriate parts of the model. Only those FEPs retained for further consideration are discussed here. Once identified, these FEPs are qualitatively evaluated for inclusion in the CSM based on considerations of their likelihood and consequence.

Meteorology

Frost weathering and other meteorological events (e.g., precipitation, atmospheric dispersion, resuspension) are included in the CSM. Weathering may occur from frost cycles. Resuspension of particulates from surface soils allows them to be redistributed by atmospheric dispersion, which is a meteorological phenomenon. Dust devils are also possible at the site and a tornado occurred in Salt Lake City in 1999, which was the first tornado in Utah in over 100 years.

Climate change

Features, events, and processes of climate change considered in the conceptual model include effects on hydrology (including lake effects), hydrogeology, biota, and human behaviors. Lake effects include appearance/disappearance of large lakes and associated phenomena (sedimentation, wave action, erosion/inundation). Wave action, including seiches, is included in the CSM.

Hydrology

Several hydrogeological FEPs were identified for consideration in the conceptual model. Groundwater transport, in both the unsaturated and saturated zones, is potentially a significant transport pathway. For some model endpoints, such as groundwater concentrations that are compared to groundwater protection levels (GWPLs), it is the only pathway of concern.

Groundwater flow and transport processes include advection-dispersion, diffusion, changes in the flow system, recharge, and brine interactions. Inundation of the site may occur due to changes in lakes or reservoirs, which is included in lake effects of climate change.

Geochemical

Geochemical effects include chemical sorption and partitioning between phases, aqueous solubility, precipitation, chemical stability, complexation, changes in water chemistry (redox potential, pH, Eh), speciation, and leaching of radionuclides from the waste form. These processes are addressed in the model.

Other Natural Processes

The broad category of other natural processes considered for the conceptual model include ecological changes and pedogenesis (soil formation). Ecological changes are associated with catastrophic events (e.g., inundation), evolution, or climate change. Pedogenesis is expected on the cap, giving rise to vegetation growth or habitation by wildlife.

Denudation (cap erosion) may be sufficient to expose waste. Erosion of the repository resulting from pluvial, fluvial or aeolian processes can result from extreme precipitation, changes in surface water channels, and weathering. Sediment transport is an inherent aspect of erosion. Sedimentation/deposition onto the cell may also affect cell performance.

Note that seismic activity is unlikely to impact the Clive facility. Faults are not present within the vicinity of Clive, although effects of isostatic rebound are still possible in the Lake Bonneville area.

Engineered Features

Engineered features are intended to promote containment and inhibit migration of contaminants. Conditions potentially affecting site performance include failure of engineered features, cell design, material properties, and subsidence of the cell.

Containerization

Two key components of containerization were identified as FEPs: containment degradation and corrosion. Canister degradation, including fractures, fissures, and corrosion (pitting, rusting) could result in containment failure. These processes are evaluated in the conceptual model.

Waste

Attributes of waste that could influence the performance of the Clive facility include the inventory of radionuclides, physical and chemical waste forms, container performance, matrix performance, leaching, radon emanation, and other waste release mechanisms.

Source Release

Source release can result from many mechanisms, including containment failure, leaching, radon emanation, plant uptake, and translocation by burrowing animals. FEPs that fit in the category of source release include gas generation, radioactive decay and in-growth, and radon emanation.

Contaminant Migration

Contaminant migration for the CSM includes the mechanisms and processes by which radionuclides may come to be located outside of the containment unit. The following contaminant migration processes were identified for consideration in the CSM: resuspension, atmospheric dispersion, biotically-induced transport, contaminant transport, diffusion, dilution, advection-dispersion, dissolution, dust devils, tornadoes, infiltration, and preferential pathways.

Human exposure pathways could include animal ingestion, both as ingestion of fodder and feed by livestock, and ingestion of livestock by humans. Transport by atmospheric dispersion could be associated with limited resuspension, dust devils, and tornadoes. Modeling of biotic (plant- and animal-mediated) processes leading to contaminant transport, and the evolution of these processes in response to climate change and other influences, including bioturbation, burrowing, root development, and contaminant uptake and translocation are considered.

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. Transport in the gas phase includes gas generation in the waste, partitioning between air and water phases, diffusion in air and water, and radioactive decay and ingrowth. Infiltration of water through the cap, into wastes, and potentially to the groundwater is another contaminant migration concern. Preferential pathways for contaminant transport are also addressed.

Human Processes

The FEPs identified as human processes encompass human behaviors and activities, resource use, and unintentional intrusion into the repository. Human process FEPs identified for assessment are related to the human exposure model and include anthropogenic climate change, human behavior, human-induced processes related to engineered features at the site, human-induced transport, inadvertent human intrusion, institutional control, land use, post-closure subsurface activities, waste recovery, water resource management, and military activities.

Exposure

Exposure is an integral part of the conceptual model, and may result from reduced site performance. Exposure-relevant FEPs identified for evaluation include those related to dosimetry, exposure media, human exposure, ingestion pathways, and inhalation pathways. Dosimetry as a science is not a FEP *per se* but physiological dose response is accounted for in the PA model.

Transport pathways (e.g. food chains) that lead to foodstuff contamination, and human exposures due to inhalation of gaseous radionuclides and particulates are included. Exposure media include soil/dust and food. Exposure pathways (ingestion, inhalation, etc.) and physiological effects from radionuclides and toxic contaminants (e.g. uranium) are also assessed.

6 Waste Forms

The scope of this CSM is limited to the disposal of DU wastes of two general waste types: 1) depleted uranium trioxide (DUO_3) waste from the Savannah River Site (SRS) 2)anticipated DU waste as U_3O_8 from gaseous diffusion plants (GDPs) at Portsmouth, Ohio and Paducah, Kentucky. The quantity and characteristics of DU waste from other sources that has that already been disposed of at the Clive Facility was not included.

The quantity and characteristics of DU waste will constitute source terms in the PA model. This section provides background on the uranium cycle and origins and nature of DU waste in particular.

Depleted uranium consists of three isotopes of uranium (U-238, U-235, and U-234) and progeny from radioactive decay. The wastes proposed for disposal contain these isotopes of uranium, but some also include other "contaminants" in varying amounts (ORNL 2000, Energy*Solutions*, 2009b). These associated radionuclides are the result of introduction of used nuclear fuel (UNF) into the uranium enrichment process. In order to clarify that these wastes contain more than just DU (uranium isotopes), they are termed "DU waste." When this term is used, it refers to wastes, such as those from SRS, that contain DU and a small amount of contamination from actinides and fission products. If uranium hexafluoride derived from irradiated reactor returns is introduced to the cascade, the associated fission products and actinides migrate to the depleted end of the cascade, with the U-238.

6.1 Depleted Uranium Background

The uranium fuel cycle begins by extracting and milling natural uranium ore to produce "yellow cake," a mixture of various uranium oxides. Low-grade natural ores contain about 0.05 to 0.3%

by weight of uranium oxide while high-grade natural ores can contain up to 70% by weight of uranium oxide (NRC, 2010). Naturally occurring uranium contains the isotopes U-238, U-235, and U-234, and radioactive decay products in secular equilibrium with these primordial parents. Each uranium isotope has the same chemical properties, but differs in terms of radiological properties. Naturally occurring uranium has a typical isotopic composition of about 99.283% U-238, 0.711% U-235, and 0.006% U-234 by mass, although there are varying assays and estimates.

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

Three large GDPs were constructed in order to produce enriched uranium. The first of these diffusion cascades was built in Oak Ridge, Tennessee, at what was originally called K-Site (later called the K-25 Site, after its largest GDP cascade), and is now known as the East Tennessee Technology Park (ETTP). Two others of similar design were constructed in Paducah, Kentucky, and Portsmouth, Ohio (DOE 2004a and 2004b). The ETTP halted operations in 1985, the Portsmouth plant ceased in 2001, and the Paducah GDP continues to operate. The two more recent GDPs are host to a large inventory of depleted uranium hexafluoride (DUF_6), since the ETTP material was moved to Portsmouth.

The official definition of DU given by the NRC is uranium in which the percentage fraction by weight of uranium-235 is less than 0.711%. (its natural abundance) According to the International Atomic Energy Agency (IAEA), typical DU percentage concentration by weight of the uranium isotopes used for military purposes is 99.8% U-238, 0.2% U-235, and 0.001% U-234. Depleted uranium isotopic ratio values from gaseous diffusion plants, which processed material for both military and commercial purposes, are reported to be 99.75% U-238, 0.25% U-235, and 0.0005% U-234 (Rich et al. 1988). Because processing of uranium has only been practiced for roughly 60 years, there has not been sufficient time for noticeable in-growth of the daughter radionuclides in this by-product. Depleted refined uranium is therefore considerably less radioactive than natural uranium because it has less U-234, U-235, and progeny, per unit mass.

6.2 Savannah River Site Uranium Trioxide

The SRS produced DU as a byproduct of the nuclear material production programs, where irradiated nuclear fuels were reprocessed to separate out the fissionable plutonium-239 (Pu-239) (Fussell and McWhorter, 2002). Uranium billets were produced at the DOE Fernald, Ohio site, fabricated into targets at SRS, then irradiated in one of the SRS production reactors to produce Pu-239. The irradiated targets were processed in F-Canyon, where in acid solution, the fission products were separated from the plutonium and uranium, which were then separated from each other. After additional purification, the DU-bearing waste stream was transferred to the FA-Line Facility where it was processed into uranium trioxide which is now a focus of this PA. This DUO_3 contains small quantities of waste fission products and transuranic elements (Energy*Solutions*, 2009b), which will also be included in the PA model.

The DU waste was produced at the SRS from the 1950s to the late 1980s as a by-product in the manufacture of nuclear materials, as described above. The DUO_3 was produced from DUF_6 using a classic chemical separation process to separate and recover plutonium and uranium product. The DU was purified through multiple processing steps, and then transferred to a final production plant for conversion to uranium trioxide. Some of this material was sent off-site for commercial or military use, and the rest was stored on site, and is now slated for disposal.

The chemical separation process was performed in two separate processing cycles. The more highly radioactive processing, such as dissolution of irradiated target material from the SRS reactors, and removal of the vast majority of the highly radioactive fission products and actinides, was performed in the first processing cycle. The final purification of the uranium product stream to remove the remaining fission product and actinide "contaminants" was performed in a second processing cycle. A small fraction of these contaminants was carried forward with the uranium product. This process ceased operations in the late 1980s.

The SRS produced approximately 36,000 200-L (55-gal) steel drums of DUO_3 during the production campaigns (Fussell and McWhorter, 2002). This DUO_3, a solid powder at room temperature and pressure, is considered to be relatively homogeneous, based on known process controls and operations. The drums have an average mass of 680 kg (weight of 1,500 lb) apiece (Fussell and McWhorter, 2002). The condition of the drums varies from good to poor with a high percentage of the drums having some degree of outer surface corrosion. A significant number of drums in two facilities (221-21F and 221-22F) have been placed into overpacks as a mitigating action for corrosion control and to prevent spills. The estimated mass of DU from SRS proposed for disposal at Clive is 24,500 Mg (megagrams, or metric tons), assuming disposal of all 36,000 drums.

This material was characterized by SRS for uranium isotopes, fission products, and transuranics, as well as some metals and organic compounds (pesticides, herbicides, semi-volatile and volatile organic compounds) as recorded in the Waste Profile Record (Energy*Solutions*, 2009b). No organic compounds were detected, though low levels (0 to 2 mg/kg) of lead, arsenic, cadmium, chromium, selenium, silver, zinc and copper were found. These low levels of metal make up less than 5 parts per million (ppm) mass of the DU waste. Based on the physical properties description in the Waste Profile Record, the DU is stoichiometrically 83.22% uranium (100% UO_3) with over 99% U-238. Beals et al., (2002) provide additional information on trace radionuclides in the SRS DU waste.

6.3 Depleted Uranium Oxide from the Gaseous Diffusion Plants

Three large GDPs were constructed to produce enriched uranium. The first diffusion cascades were built in Oak Ridge, Tennessee, at what was the K-25 Site, but is now known as the East Tennessee Technology Park (ETTP). Two others of similar design were constructed in Paducah, Kentucky (PGDP), and Portsmouth, Ohio (PORTS) (DOE 2004a and 2004b). The cascades at the K-25 Site ceased operations in 1985, the Portsmouth plant ceased in 2001, the Paducah GDP continues to operate. The two more recent GDPs are host to a large inventory of stored DUF_6, including the ETTP material that was moved to Portsmouth.

The DOE is currently managing approximately 60,000 cylinders at both PGDP and PORTS (DOE 2004a, 2004b). For many years, interest has been expressed in converting the DUF_6 in these cylinders to an oxide form to support their long-term disposal. In May, 1995 an independent DOE oversight board recommended a study to determine a suitable chemical form for long-term storage of DU. Two Environmental Impact Statements (EIS) were prepared as part of the plan, one for Paducah, DOE/EIS-0359, (DOE 2004a) and one for Portsmouth, EIS-0360, DOE 2004b). These EISs describe the background and alternatives for DUF_6 conversion. With the completions of the EISs, "deconversion" plants were built at both the PORTS and PGDP locations. In 2002, DOE awarded a contract to Uranium Disposition Service, LLC (UDS) to design, construct, and operate two DUF_6 deconversion facilities at these locations. As of this writing, both plants have been built by UDS and have begun test processing DUF_6 into oxide form.

Of the DUF_6 cylinders that will be reused for disposal of the DU oxide, a fraction are contaminated with fission and activation products from introduction of reactor returns into the diffusion cascades. The contamination is similar in nature to that found in the SRS DU, and is modeled as such until more information is gained from the generation of DU oxide at Portsmouth and Paducah. Since the contaminated cylinders are a low priority for conversion, this information is unlikely to be available for several years.

6.4 Depleted Uranium Already Disposed at the Clive Facility

The DU PA Model does not account for DU that is already disposed at the Clive site, some of which is from the same SRS DU population (Fussell and McWhorter, 2002).

6.5 Modeled Radionuclides

A full list of radionuclides has been established for the CSM and the contaminant transport modeling effort:

fission products:
Sr-90, Tc-99, I-129, Cs-137

progeny of uranium and transuranics:
Pb-210, Rn-222, Ra-226, -228, Ac-227, Th-228, -229, -230, -232, Pa-231

uranium isotopes:
U-232, -233, -234, -235, -236, -238

transuranic radionuclides:
Np-237, Pu-239, -239, -240, -241, -242, Am-241

This radionuclide species list is based upon process knowledge, radionuclides analyzed for (though not necessarily detected) in the DU waste material, and decay products with half-lives over five years. A diagram showing each decay species is shown in the Radionuclide Transport section (Section 9). The decay chains are informative as they provide an understanding of how each species derived from a parent radionuclide. Many more short-lived progeny are accounted for in dose assessment calculations. Note that in several instances where the inventory has been

set to zero, these species may be daughters of a known parent with inventory of a potential future inventory species.

6.6 Chemical Characteristics of DU Wastes

Both forms of uranium oxide have some limited solubility in water, thus hydrologic transport is expected to occur to some extent. The solubilities of the two waste forms are dependent upon the geochemistry and their own inherent solubility. Other specific waste forms will be modeled as information becomes available if needed. This transport will start with release from the containment (e.g., drums, cylinders), followed by leaching of the radionuclides from the DU waste which is primarily a function of solubility. The solubility of the radionuclide species, including uranium, will depend upon two main geochemical processes: dissolution/precipitation and adsorption/desorption. These processes are largely controlled by the redox condition, pH, carbonate chemistry, and ionic strength of the local environments. The parameters used to model the transport of the uranium oxides and associated radionuclides are described in Section 9 . Retarded transport will be modeled using a solid/water partition (or distribution) coefficient (K_d) for each radionuclide species. The values (represented as statistical distributions) used for each radionuclide will depend upon the expected geochemical conditions within the various wastes and natural media.

The release of radon-222 (Rn-222) from its Ra-226 parent in the U-238/U-234 decay chain is also described in Section 9 . The transport of radon in both the saturated and unsaturated zones will be included in the PA model. Radon transport is controlled by the emanation factor, diffusion, advection, and partitioning parameters that will be incorporated into the transport modeling.

7 Modeling of the Natural Environment

The natural environment consists of those materials that surround the engineered facility, and make up its environs. This includes the lacustrine sediments of the Great Salt Lake Desert underlying the site, the groundwater within those sediments, the air above, and the biota living on and near the ground surface. Each of these environments is introduced below, along with their conceptual models for the PA.

7.1 Current Conditions

The basic conceptual model of the present day site is that the facility is located on a desert flat, with a biotic community established on the ground surface, and with unsaturated and saturated zones of groundwater below. This scenario is assumed to apply for the 10,000-yr duration of the quantitative model for this base case.

In general, natural processes in the environs will tend to make the site and its engineered features more like the natural environment. Wind and water will modify the cap, and biota will populate it. Throughout this evolving and mixing system, radionuclides that have been disposed within the facility will tend to migrate out to the natural system. A fundamental function of the PA is to estimate the rate and extent of that migration.

7.1.1 Groundwater Flow and Transport

Groundwater is considered in two parts: unsaturated zone (UZ) and the saturated zone (SZ). The UZ, often called the vadose zone, extends from the ground surface down to the water table, and is characterized by having both water and air in the porous spaces in the sediment. The SZ lies below the water table, and extends deep into the earth's crust. For the purposes of modeling, however, contaminants are assumed to penetrate only so far into the saturated sediments, which include natural horizontal barriers confining the vertical flow, as discussed in Section 3.3.1 .

7.1.1.1 The Unsaturated Zone

The engineered features of the landfill, including cap, waste, and liner, are all in the UZ, at least within the 10,000-yr duration of the quantitative model. The part of the UZ that extends from the bottom of the landfill liner to the water table consists of naturally-occurring lake sediments from the ancestral Lake Bonneville. Since the cap is intentionally designed to restrict permeability, interstitial water in the UZ below the facility is not expected to migrate upwards through the cap to surface soils, as it might do naturally given the strong evaporation potential at the surface. Rather, it is expected to migrate slowly down to the water table, at a rate equal to the rate at which the engineered liner leaks.

The natural UZ below the facility will be modeled as a column of discrete elements, called Cell Pathway elements in the GoldSim modeling framework. Each of these is connected in series to model the one-dimensional advective flow path to the water table. Diffusion in the water phase may also play a role in the transport of waterborne contaminants in the UZ, since the advective flux is expected to be small. The concentration gradients in the UZ are also expected to be predominantly vertical, so diffusion will also occur in the vertical direction, oriented with the column of cells.

Diffusion in the air phase within the UZ below the facility will not be modeled, since the only diffusive species would be radon, which is of greater concern at the ground surface. Upward radon diffusion to the ground surface will be dominated by radon parents in the waste zone, and is modeled within the engineered cap.

7.1.1.2 The Saturated Zone

Contaminant transport in the water phase in the SZ is fed by contaminants entering the water table beneath the disposal facility as recharge. The rate of recharge is the same as the Darcy flux (the rate of volume flow of water per unit area) through the overlying UZ, and is expected to be small enough that vertical transport within the SZ would be small. Most SZ waterborne contaminant transport will be in the horizontal direction, following the local pressure gradients which are reflected in water table elevations in an unconfined aquifer such as this. A point of compliance in the groundwater has been established to be 27 m (90 ft) from the toe of the waste embankment, so transport will be modeled to that point.

Saturated zone groundwater transport generally involves the processes of advection-dispersion and diffusion. Mean pore water velocity in the saturated zone is assumed to be determined by the Darcy flux and the porosity of the sediment. A range of values will allow the sensitivity analysis (SA) to determine if this is a sensitive parameter in the determination of concentrations at the

compliance well and resultant potential doses. Modeling of fate and transport for the saturated zone pathway will include advection, linear sorption, mechanical dispersion, and molecular diffusion.

The modeling of the SZ is similar to the modeling of the UZ, except that the "column" of GoldSim Cell Pathway elements is arranged horizontally. This will be modeled as a row of cells between the region below the disposal unit and the compliance well. These cells are saturated with water that flows along the row, in order to represent the aquifer.

7.1.2 Surface Water

The Clive facility is sited in an area of extremely low topographic relief, and surface water features such as stream channels are rare. The ancestral lake bed is quite flat, so there is little in the way of land surface gradients which might drive surface water flow. Most if not all meteoric water that lands on the ground is assumed to be returned to the atmosphere by evapotranspiration, and essentially none is abstracted by runoff.

The embankment cells on the waste disposal site have significant relief, and surface water runoff should be expected from these structures. The runoff and associated sediment transport will be local, and is likely to remain in the vicinity of the site. The principal effect of surface water flow is expected to be contribution to the formation of gullies, as discussed in Section 8.3 .

7.1.3 Air and Atmosphere

Contaminant transport in the air phase takes on two distinct forms: diffusion in the interstitial air in porous media below ground, and dispersion by the atmosphere above. Diffusion in interstitial air of porous media is a means by which contaminants reach the atmosphere at the ground surface. Dispersion of contaminants in the atmosphere can occur through direct diffusion of gaseous contaminants into ambient air, and through resuspension and movement of wind borne contaminated soil particles.

Airborne transport is a secondary contaminant transport mechanism at the Clive Facility. As containment features such as the cap become contaminated from the result of natural processes (e.g. radon diffusion, burrow excavation, plant senescence), radionuclides will migrate to surface soils, serving as a source for atmospheric transport. As these contaminants accumulate on the ground surface, either in a gaseous form (e.g. radon) or attached to solid particles, they undergo resuspension or volatilization into the atmosphere, leading to airborne transport. Airborne contaminants will be carried into ambient air by the wind and either inhaled directly by receptor populations or deposited onto exposure media such as vegetation or soils in the vicinity.

7.1.3.1 Diffusion Through Air in Porous Media

Contaminants released from the waste (or generated by decay of parents in any location) may be transported via the air pathway by migration of gaseous species through soil pore space. Over time, cracks, fissures, animal burrows, and plant roots can also provide preferential diffusion pathways that reduce the effectiveness of the engineered barrier.

Factors that influence the diffusion of contaminants through porous media include the volatility of the chemical species, its molecular weight, physical properties of the soil matrix (e.g.,

porosity, grain size distribution, and moisture content, which determine phasic tortuosity – that is, tortuosity in either the air or water phase), and temperature gradients. Diffusion in porous media and along preferential pathways is also driven by concentration gradients and mediated by effective diffusion coefficients through the tortuous diffusion path.

Diffusion rates are determined from the defined values for effective diffusivities, diffusive areas, diffusive lengths, and the calculated concentration gradients between adjacent cells, which varies as time progresses. Diffusion can take place in both air and water. In coordination with diffusion is radioactive decay and ingrowth, advection of water, partitioning of contaminants between water and air and between water and soils, and biotic processes. All these differential equations and transfer functions are solved at each time step by the PA model.

An important consideration related to the disposal of DU is the production of radon. Since Rn-222 is a descendent of U-238 and U-234, through Th-230 and Ra-226, it will be generated wherever Ra-226 occurs. As the radium, or any parent in the chain, migrates into the cap, either by diffusion in the water phase or translocation by biotic processes (see Section 7.1.4), it provides a source for Rn-222 in more locations beyond the disposed waste. Furthermore, not all of the radon that is produced enters the environment for transport. Some of it is retained within the solid material that held its parent, and decays to polonium-218 (Po-218) without moving. This phenomenon is called radon emanation, and is discussed in the radionuclide transport section (Section 9).

Radon that does enter the environment readily partitions between air and water, with a strong preference for the latter. Soil moisture therefore retards the migration of radon as it partitions into the soil, making it less available to diffusion in air under wetter soil conditions.

7.1.3.2 Atmospheric Dispersion

Atmospheric dispersion of airborne gaseous and particulate contaminants found in surface soils is expected. To the extent that contaminated subsurface soils are exposed or exhumed and plant litter is deposited on the surface, they become surface soils and as such will also be subject to atmospheric dispersion.

Atmospheric dispersion of contaminants is regulated by several factors. Contaminant chemistry, contaminant mobility, soil texture, effects of vegetation on the atmospheric boundary layer, topography, and meteorological conditions (predominant wind direction and speed, precipitation, temperature, and humidity) may influence dispersion of airborne contaminants as well as soil erosion and contaminant resuspension rates.

The Clive facility is sited in an exposed area, with little around it to protect from the winds. Wind dispersion is a likely mechanism of airborne transport. Contaminants deposited over or adsorbed onto soil may migrate from this area source as airborne particulates. Depending on the particle-size distribution and associated settling rates, these particulates may be deposited downwind or remain suspended, resulting in contamination of surface soils and/or exposure of regional receptors through inhalation, immersion, or external irradiation pathways.

Ancestral lake sediments prevalent at the Clive facility are fine-grained, and are susceptible to resuspension and entrainment in the wind, and to subsequent atmospheric dispersion. This

resuspension of naturally-occurring sediments, however, is moderated by local plant growth, which tends to create a boundary layer of lower-velocity air at the ground surface, and by the formation of desert crust, making the cemented particles of sediment in effect much larger.

The embankment cells on the site have significant relief in relation to the surrounding environment. A cover of gravel- and boulder-sized rip rap on the embankment cells would curtail atmospheric re-suspension relative to flat and more uniform areas. Eventually, however the rip rap may trap enough wind-driven (aeolian) sediment that the disposal site will approach the surrounding natural lake bed in appearance and behavior. Although these aeolian deposits will consist of uncontaminated material at first, they may become contaminated by the process of radon diffusion upward from the waste (with radon progeny left behind in the soils) and through the biotic processes discussed in the following section. Once radon gas and resuspended particles have entered the atmosphere directly above the cells, they can be dispersed over a wide area by the wind. Given these possible transport pathways, atmospheric dispersion of gases (e.g. radon and other volatile constituents) and of fine particles of sediment must be taken into consideration in the model.

Entrainment of contaminants into the atmosphere will contribute to the air inhalation exposure pathways for receptors that are present on the site itself. As particulates eroding from the embankment are deposited on surrounding land, this surrounding area may become a secondary source of radionuclide exposure. Atmospheric dispersion calculations in the PA model will support estimation of of gas and particulate air concentrations above the embankment, and off-site particulate deposition rates that can be used to estimate radionuclide soil concentrations in the area surrounding the embankment.

7.1.4 Biota

Biota of primary importance for movement of buried waste and subsurface soils are burrowing animals (both vertebrates and invertebrates, which provide constant mixing of the soil column) and plants, which can move buried wastes through root-uptake and translocation of contaminants to various parts of the plant.

7.1.4.1 Native Plants

Plants represent an important potential pathway for waste transport by way of rooting and conditioning of soil aggregates and particulates, nutrient exchange with soil surfaces, transport of nutrients from soil through plant tissues, deposition of organic materials and non-nutritive waste products at or near the soil surface, and physical mixing of soils through the addition of organic materials to soil due to root collapse and surface deposition. In particular, nutrient exchanges between the subsurface and surface also create the potential for the exchange of non-nutritive chemicals, such as with anthropogenic wastes.

Plant-induced transport of contaminants is assumed to occur primarily through absorption of contaminants into the roots, after which the contaminants are redistributed throughout all the tissues of the plant, both above-ground and below-ground. Upon senescence, the above-ground plant parts are incorporated into surface soils, and the roots are incorporated into soils at their respective depths. This process is illustrated in Figure 6, which shows the conceptual model for plant uptake, redistribution, and senescence. Note that relatively clean surface soils become more

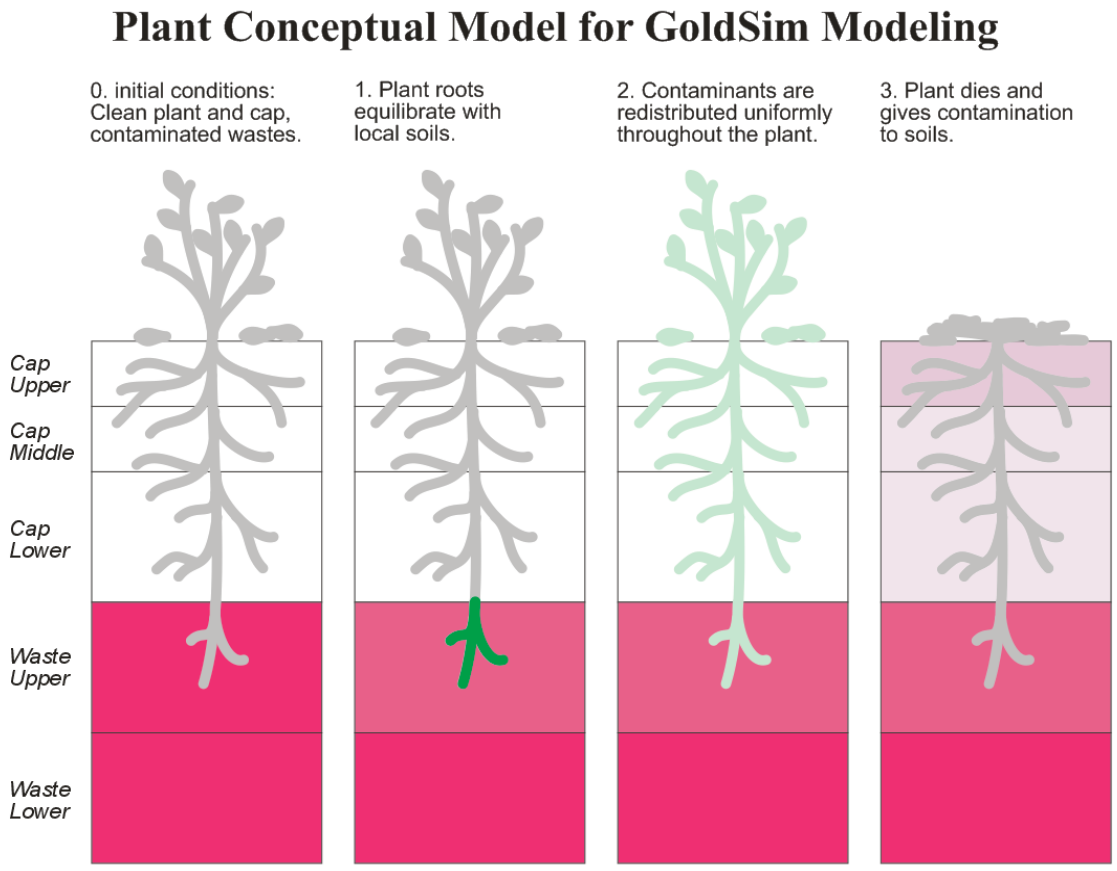

Figure 6. Conceptual model for plant transport

contaminated over time as subsurface contaminants are translocated to above ground portions of the plant, and ultimately to the surface soil as the plant senesces.

The degree to which plants can move contaminants from the subsurface, and the rate at which that transport can occur are dependent upon a number of factors such as plant rooting depth, total above ground plant biomass, total below ground plant biomass, relative abundance of plants, and density of plants roots by depth.

Plant rooting depths are influenced by a number of physical and physiological factors, but the ultimate limiting factor is the availability of water. Roots of desert plants generally do not exceed the depth to which water from precipitation infiltrates on a consistent basis. The maximum rooting depth of any desert plant is physically limited to the maximum depth from which the plant can obtain water. Of the plants that dominate the Clive site, black greasewood (*Sarcobatus vermiculatus*) is likely the most deeply rooted. Black greasewood is phreatophytic, meaning that it can utilize shallow groundwater, or derive supplementary water from the overlying capillary fringe and deplete soil water potential to values less than 4.0 megapascals (MPa). However, in areas where precipitation does not infiltrate to groundwater, black greasewood will not form taproots and will maintain a more shallowly rooted growth form. Excavations of several greasewood plants at the Clive site by SWCA (2011) found roots that did not exceed one meter

in depth. Several investigators have documented the types and metrics of plant species in bajadas, desert valleys, and saline mounds (Robinson 1958, Meinzer 1927, Groenveld 1990, Blank et al. 1998, Hansen and Ostler 2003, Rundel and Nobel 1991, and Holmgren and Brewster 1972).

The plant species currently inhabiting the Clive site are generally halophytic, meaning that they are adapted to saline environments. Dominant plant species in the saline environments around Clive include the halophytic shrubs black greasewood, shadscale, and the non-native forb halogeton. Soil chemistry of the alkali flat environment is a limiting factor that regulates the local plant community assemblages. It could be anticipated that the soil chemistry of constructed mounds such as the disposal cells may change over time as precipitation leaches salts from the mound soils, which are elevated above the surrounding terrain and decoupled from the saline groundwater. This change in soil chemistry could allow for the establishment of less salt-tolerant species, such as sage (*Artemesia spp)* and rabbit brush (*Chrysothamnus spp.),* which are common in less saline cool desert habitats. It is expected that plants will be the first colonizers of the Clive cap, though that is not expected to occur until the uppermost riprap layer has silted in sufficiently to allow for germination and root establishment.

7.1.5 Native Animals

Only limited biotic surveys of the Clive site have conducted, so site-specific information about the utilization of the site by specific animal species is likewise limited. However, based on the limited Clive studies and more comprehensive studies at other sites, burrowing animals, including invertebrates and mammals, are of importance when evaluating the mixing of soils and the potential for transporting buried wastes from the subsurface to the surface.

Ants

Ants fill a broad ecological niche as predators, scavengers, trophobionts and granivores, but it is their role as burrowers that is of main concern for evaluating transport of buried materials from the subsurface to the surface. Ants burrow for a variety of reasons but mostly for the procurement of shelter, the rearing of young and the storage of foodstuffs.

In arid areas of the Great Basin and southwestern U.S., harvester ants of the genera *Pogonomyrmex* and *Messor* are widespread, form large colonies, and often construct elaborate nests. A preliminary survey of the Clive site and surrounding areas in October 2010 found that the Western harvester ant (*Pogonomrymex occidentalis*) is by far the most common ant at the site, with nest densities ranging from two nests per hectare in mixed sage/juniper community, to 33 nests per hectare in areas with abundant grasses (SWCA 2011). Only a single other ant species (*Lasius* sp.) was identified at the Clive site during the preliminary surveys, and it occurred only in the mixed grass vegetative association.

Several investigations have focused on ants as a taxonomic group of importance for the potential to move buried waste at locations such as the Idaho National Laboratory (INL), and the Hanford Site in southeastern Washington (Blom 1990, Fitzner et al. 1979, Gano et al., 1985). These studies indicate that large colonies of *Pogonomyrmex* spp. may nest to depths of 3 to 4 meters (10 to 13 ft) and may colonize areas with great densities of nests (over 100 per hectare), thus potentially excavating large volumes of contaminated soil to the ground surface.

How and where ant nests are constructed plays a role in quantifying the amount and rate of soil movement and the mixing of the soil column. Factors relating to the physical construction of the nests including the size, shape, and depth of the nest are necessary in order to quantify excavation volumes. Factors limiting the abundance and distribution of ant nests such as the abundance and distribution of plant species, and intra- and inter-species competition also can affect excavated soil volumes. Therefore, the amount and rate of soil movement is based on a variety of factors, including nest area, nest depth, rate of new nest additions, colony density and colony lifespan.

Due to its dominance at the Clive site, the initial model will be parameterized using available data for *Pogonomyrmex occidentalis*. The geometry and structure of ant nests appears to be more of a species-specific trait that does not exhibit significant flexibility in variable environments (MacKay 1981). The mound's height, width, distribution of particles, color, and exposure significantly impact the colony for predatory defense and environmental regulation, but for any given species, these mound traits are the same from place to place (MacKay 1981). Therefore, there is defensibility for using data collected elsewhere for the same species in order to parameterize the potential for ant-mediated transport in the Clive model. Site specific data collected by SWCA (2011) on mound surface dimensions will be used to predict overall nest volume and depth, and habitat-specific information of ant nest density will be used to help predict the overall rate of soil movement on a per hectare basis for each habitat type. Additional site specific data may be needed dependent on the outcome of the initial model.

A number of authors contend that it is reasonable to expect that over the 15 to 30-year life of some *Pogonomyrmex* colonies, the entire soil column of the nest is turned over at least once (Mandel and Sorenson 1981). For important and long-lived *Pogonomyrmex* ants in the desert southwestern U.S., Lavigne (1969) and MacKay (1981) have investigated nest structure rather extensively, and conclude that the net effect of soil movement within an ant colony's lifetime is a general homogenization of soils throughout the nest profile. In general, it is likely that this homogenization occurs more rapidly in the top third of the nest, as this is where most of the colony's burrowing takes place, but over the life of the nest, burrowing at the greatest depths of the nest can be extensive (Lavigne 1969, MacKay 1981). However, at the Clive site the top layers of the cap are comprised of riprap and gravel layers. It is expected that after these layers silt in, ants will colonize the cap. However, ants will not directly transport the larger particles comprising the riprap and gravel layers of the cap, and these will affect the size and distribution of chambers within the upper layers of the nest since gallery and chamber construction will be limited to the void spaces between cobbles. Therefore, mixing of the riprap and gravel particles downward will be minimal, though transport of soil and clay particles from lower layers of the cap upward through the gravel and riprap is expected.

Mammals

Burrowing mammals such as gophers, pocket gophers, moles, voles, squirrels, mice, rats, kangaroo rats, and their predators have a profound influence on soil mixing. Burrowing mammals rework the entire near-surface of soil over most of the North American continent on a persistent basis, but at varying rates (Nevo 1999). Each of these mammalian species contributes to soil turnover to a varying degree, depending upon their burrowing habits, geographic location,

and prevailing climate and soil conditions (Laundré and Reynolds 1993). Mammalian biotic transport of soils also includes the deposition of fecal material in soils, the intermixing of vegetation, and the significant aeration of upper layers. All of these actions dramatically affect soil fertility, permeability by air and water, and increase soils' susceptibility to invasion by microorganisms (e.g., bacteria, fungi, nematodes, microarthropods).

Some mammals such as pocket gophers (*Thomomys* spp.), ground squirrels (*Spermophilus* spp., *Sciuridae* spp., and others), and kangaroo rats are considered obligately fossorial, i.e., they spend most of their time underground, including foraging underground. Other organisms, however, will utilize burrows only for shelter (temporary or permanent) and reproduction. These include hares (*Lepus* spp.), rabbits (*Sylvilagus* spp.), sagebrush voles (*Lagurus curtatus*), pocket mice (*Perognathus* spp.), kangaroo mice (*Microdipodops* spp.), foxes (*Vulpes* spp., *Urocyon cinereoargenteus*), and coyotes (*Canis latrans*).

Biotic transport of soils by mammals at waste burial sites includes the potential direct movement of waste from the subsurface to the surface, as well as secondary transport, such as food chain transfer, transport by way of fecal deposition, and carcass degradation (Arthur and Markham 1982, Smallwood et al. 1998). Intrusion into buried wastes and active physical transport occur when animals penetrate protective barriers and cause vertical or horizontal redistribution of waste material (Hakonson et al. 1982, Arthur and Markham 1982). As animals excavate burrows they either relocate buried material to the surface, or relocate soils from depth into below-ground chambers lateral to the point of entry, as is common with pocket gophers or other obligately fossorial mammals (Smallwood et al. 1998).

Because mammal burrows facilitate natural ventilation and aeration of the soils, burrowing activity may also enhance the potential for contaminant release in gaseous form by allowing increased communication between the atmosphere and buried waste. Mammal burrows also provide preferential pathways for water infiltration, as studies have shown that recharge quantities and depth of recharge were positively correlated with burrow density, and also found that ground squirrels can increase precipitation infiltration into the soils by as much as 34% as a consequence of burrowing activity (Laundré, 1993).

Preliminary investigations of mammals at Clive have focused on surveying the different habitat associations for mammal burrows, quantification of the amount of soil excavated by burrowing mammals, and trapping to determine dominant small mammal species in each vegetative association. Results suggest that burrowing mammals are relatively scarce on the alkali flat habitats (greasewood, shadscale), becoming more abundant in the less saline soils associated with mixed grass and juniper-sage habitats. Deer mice were the most abundant mammals trapped in all habitat types, with lesser numbers of kangaroo rats (two species), and grasshoppper mice also found in the traps.

At Clive it is expected that small mammals such as mice may use the void spaces in the riprap as refugia. As gravel and riprap layers silt in, the cap may be utilized by small mammals such as mice, but the riprap and gravel are expected to create less than optimal conditions for burrow construction, and the gravel layers may well serve as a barrier to mammalian borrowing altogether.

7.2 Far-Future Conditions

The deep time frame over which the analysis is concerned is defined by the period of time beyond 10,000 years until radioactivity from the DU parents and its progeny is at its peak. This occurs when the progeny, identified in Section 9.1.2 , are in secular equilibrium with the parent. For decay of a refined U-238 parent (the longest-lived uranium isotope), progeny reach secular equilibrium at about 2.1 million years (My). With its exceedingly long half-life of over 4 billion years, the parent U-238 decays only by about one half-life before the end of the solar system, and the peak achieved at 2.1 My wanes only slightly in that time. The analysis devoted to deep time scenarios is sufficiently representative of this entire duration when considered out to only 2.1 My in the future, as changes in radioactivity are minor after that time.

The model developed to evaluate the ultra-long term performance of the Clive disposal facility will focus on concentrations in various media, and will not attempt to translate these concentrations into human dose metrics. This approach will be used because of the overwhelming uncertainty associated with evaluating human receptor scenarios that far into the future. This uncertainty is associated both with projecting human behavior and environmental conditions.

A scenario is considered that involves the return of large lakes in the Bonneville Basin over the next few million years, since secular equilibrium is reached at about 2.1 My. Following that, the radioactivity of the DU will persist effectively forever. When the duration of interest is expanded to billions of years, however, on such a time scale, such major geologic processes are at work to make any predictions absurd—even for a geologic repository.

Understanding the phases associated with the change from current climatic conditions to future climatic conditions can help construct a qualitative picture of how the Clive facility will respond to those changes. The following section provides a brief overview of how major environmental changes in the past are directly coupled to major shifts in climatic regimes. This section also provides context with respect to how these past changes may occur in the future and their implications on the stability of the Clive storage facility.

7.2.1 Background on Long-term Controls on Site Conditions

7.2.1.1 Climate processes

Large-scale climatic fluctuations over the last 2.58 My (the beginning of the Quaternary Period) have been studied extensively in order to understand the mechanism underlying those changes (Hays et al., 1976, Berger, 1988, Paillard, 2001, Berger and Loutre, 2002). These large-scale fluctuations in climate have resulted in glacial and interglacial cycles which have waxed and waned throughout the Quaternary Period. The causes of the onset of the Northern Hemisphere glaciation about 3 million years ago (3 Ma) remain uncertain, but several studies suggest that the closing of the Isthmus of Panama caused a marked reorganization of ocean circulation patterns that resulted in continental glaciation (Haug and Tiedemann, 1998, Driscoll and Haug, 1998).

Changes in the periodicity of glacial cycles have been linked to variations in Earth's orbit around the Sun. These variations were described by Milankovitch and are based on changes that occur due to:

- the eccentricity of Earth's orbit – around every 100,000 years (100 ky),
- the obliquity of Earth's axis every – around 41 ky, and,
- the precession of the equinoxes (or solstices) – around 21 ky.

For the first two million years of the Pleistocene (the first major Epoch of the Quaternary Period), Northern Hemispheric glacial cycles occurred about every 41 ky, while the last million years have indicated larger glacial cycles occurring about once every 100 ky, with strong cyclicity in solar radiation every ~23 ky (Berger and Loutre, 2002; Paillard, 2006). The results of Hays et al. (1976), who analyzed changes in the isotopic $\delta^{18}O$ composition of deep-sea sediment cores, suggest that major climatic changes have followed both the variations in obliquity and precession through their impact on planetary insolation. Variations in $\delta^{18}O$ reflect changes in oceanic isotopic composition caused by the waxing and waning of Northern Hemispheric ice sheets, and are thus used as a proxy for the climatic record. However, the shift from shorter to longer cycles is one of the greatest uncertainties associated with utilizing the Milankovitch orbital theory to explain the onset of glacial cycles alone (Paillard, 2006).

Various studies have highlighted the importance of atmospheric carbon dioxide (CO_2) variations in the dynamics of glaciations across the Northern Hemisphere in addition to the insolation due to orbital forcing (Clark et al., 2009; Paillard, 2006). Direct measurement of past CO_2 trapped in the Vostok and EPICA Dome C ice cores from Antarctica show that atmospheric CO_2 concentrations decreased during glacial periods due to greater storage in the deep ocean, thereby causing cooler temperatures from a reduction of the atmosphere's greenhouse effect (EPICA, 2004). Warmer temperatures resulting from elevated concentrations of CO_2 that are released from the ocean on the other hand contribute to further warming and could support hypotheses of rapid wasting at the end of glacial events (Hays et al., 1976). Berger and Loutre (2002) conducted simulations forced with insolation and CO_2 variations over the next 100 ky and report that the current interglacial period could last another 50 ky with the next glacial maximum occurring about 100 ky from now. They also report, however, that future increases in atmospheric CO_2 from anthropogenic activity along with small insolation variations could result in a transition between the Quaternary and the next geologic period due to the potential wasting of the Greenland and west Antarctic Ice Sheets.

There is a strong likelihood that there will be major climatic shifts within the next million years, and strong evidence that the 100 ky cycle has impacted the Bonneville basin in the form of large lake recurrence (Oviatt, 1997; Asmerom et al., 2010). Thus, due to the destructive potential of a lake to the waste embankment, the deep time scenarios of most interest are the return of large lakes in the Bonneville Basin.

7.2.1.2 Large Lake Cycle Events

The Clive facility is located in the Bonneville Basin where Lake Bonneville, the largest of the late Pleistocene pluvial lakes, last existed between 30-10 ka. Pluvial lakes are lakes that show evidence of expansion due to pluvial episodes (wetter climatic phases) as well as contraction due to what is assumed to reflect interpluvial episodes (warmer, dryer climatic phases). Various FEPs fall within the lake cycle scenario which include wave action, sedimentation, and site inundation.

At its maximum (between ~15-16 ka BP), Lake Bonneville is estimated to have covered an area of 51,300 km^2 (~19,800 sq mi) and was over 370 m (1200 ft) deep (Lowe and Walker, 1997). Following the Bonneville flood around ~14.5 ka, during which the lake level dropped by ~114 m (~375 ft) as it spilled over and eroded a spill point, the lake level continued to decline leaving behind modern-day Great Salt Lake. Geomorphological evidence is present that shows the variability in the levels of the last major lake cycle as indicated by the exposed shoreline features in areas of the Bonneville basin.

Oviatt et al. (1999) examined sediments from the Burmester core and suggested that a total of four deep-lake cycles occurred during the past 780 ky. They found that the four lake cycles correlated with marine oxygen isotope stages 2 (Bonneville lake cycle: ~24-12 ka), 6 (Little Valley lake cycle: ~186-128 ka), 12 (Pokes Point lake cycle: ~478-423 ka), and 16 (Lava Creek lake cycle: ~659-620 ka), which suggests that large lake formation in the Bonneville basin occurred only during the most extensive Northern Hemisphere glaciations. In addition to these large lake cycles, a smaller cycle known as the Cutler Dam cycle occurred between ~80-40 ka (Link et al., 1999). Each major lake cycle and its corresponding estimated maximum shoreline elevations are listed in Table 1. As a point of reference, the Clive facility is located at an elevation of 1302 m (4275 ft) amsl, and the airport at Salt Lake City, SLC, is at 1288 m (4227 ft).

During the large pluvial lake events, large amounts of calcium carbonate were precipitated as tufas, marls, shells (of mollusks), and ostracodes (Hart et al., 2004). Brimhall and Merritt (1981) reviewed previous studies that analyzed sediment cores of Utah Lake, a freshwater remnant of Lake Bonneville that formed ~10 ka. It is suggested that up to 8.5 m (28 ft) of sediment has accumulated since the beginning of Utah Lake, implying an average sedimentation rate of ~0.00085 m/y (nearly 1 mm/y) over 10 ky. Within the Bonneville basin as a whole it is suggested that the major lake cycles resulted in substantial accumulations of sediment based on the depth of the cores analyzed (e.g., 110-meter core that corresponds to the past 780 ky, or four major lake cycles for an average sedimentation rate of 0.00014 m/yr including non-lake phases; Oviatt et al., 1999).

Table 1: Known lake cycles in the Bonneville Basin

Lake Cycle	Approximate Age*	Maximum Elevation	Lake level control
Great Salt Lake (current level)	present	1284 m (4212 ft) in 1873	climate; human intervention
Gilbert	11–10 ka	1295 m (4250 ft)	climate
Provo	14.5–13.5 ka	1445 m (4740 ft)	threshold at Zenda near Red Rock Pass, Idaho
Bonneville	~28–12 ka (^{14}C)	1552 m (5090 ft)	threshold at Zenda near Red Rock Pass, Idaho
Stansbury	23–20 ka	1372 m (4500 ft)	climate
Cutler Dam	~80–40 ka	< 1380 m (< 4525 ft)	
Little Valley	~128–186 ka	1490 m (4887 ft)	
Pokes Point	417–478 ka	1428 m (4684 ft)	
Lava Creek	~620–659 ka	1420 m (4658 ft)	

*Approximate ages derived from Currey, et al. (1984) Link et al. (1999) and Oviatt et al. (1999).
Elevations are not corrected for isostatic variations

There is a lack of peer-reviewed literature that considers the direct effects of future climate change on major lake formation in the Bonneville basin. However, if the current geologic era continues, the probability of another major lake cycle occurring in the Bonneville basin within the next 100 ky in conjunction with variation in Earth's orbital characteristics is high, considering the correspondence between past global temperature fluctuations and past known lake events. Assuming that past conditions will apply in the future, variations in orbital characteristics are very likely lead to another major ice age and thus alter long-term climatic patterns in the Bonneville region making it suitable for lake formation. Each 100 ky glacial cycle is different, depending on orbital forcing, but it is clear from the historical record that the current period is inter-glacial, and colder conditions are likely in the future. Unless the current geologic period ends in response to anthropogenic forcing effects on atmospheric CO_2 concentrations (Berger and Loutre, 2002), it is expected that the Clive facility will be subjected to lake formation in the future. Return of a large lake is considered unlikely without climatic change.

7.2.1.3 Isostatic Rebound

Isostasy refers to the gravitational equilibrium between Earth's lithosphere (the rocky outer crust) and asthenosphere (the semiliquid layer below the crust) such that the lithosphere "floats" at an elevation that depends on its local thickness and density. When large amounts of sediment, water, (in the case of Lake Bonneville) or ice occur over a particular region over time, the weight of the new mass may cause the crust below to sink. Hetzel and Hampel (2005) examined the effects of the removal of Lake Bonneville on isostatic rebound of the lithosphere. They found that the

removal of Lake Bonneville triggered an increase in fault slip rates in the Wasatch region resulting in clustering of earthquakes during the early Holocene. Former islands present during the Lake Bonneville cycle also indicate that isostatic rebound occurred after the regression of the lake. This is evidenced by the palæo-shorelines on the islands which are located tens of meters above the palæo-shorelines along the lake periphery (Hetzel and Hampel, 2005).

Although it is difficult to predict potential impacts from future seismic events, it is expected that if isostatic rebound effects were to occur, the effects of future seismic events would be mitigated by the site's burial by lacustrine sediment.

7.2.1.4 Volcanism

The principal effects of volcanism on the Clive site are indirect. Hart et al. (1997) suggest that lava flows near Grace, Idaho during the Pleistocene diverted the upper Bear River between the Snake River drainage to the Bonneville Basin through the formation of lava dams. Link et al. (1999) report that the permanent addition of the Bear River discharge to Lake Bonneville likely occurred around 50 ka (±10 ka), and in conjunction with cooler and wetter conditions during this time, it is thought to be responsible for the lake reaching its highest level (i.e., the Bonneville shoreline). Although the lava dams resulted in the alteration of the path of the Bear River, at certain times during the Pleistocene the upper Bear River was diverted into the Snake River which deprived the Bonneville basin of significant discharge. Future changes in the regional hydrology in response to any future lava flows or regional volcanic activity could result in similar implications for future pluvial lake events (i.e., increase or decrease in discharge to the basin).

7.2.1.5 Ecological Changes

Changes in biotic assemblages have been shown to occur in the past (Davis and Moutoux, 1998) and will likely occur in the future in response to shifts in climatic regimes. Temperature and precipitation have a profound effect on plant community assemblages, as does soil chemistry. Areas where salt pans remain in place will remain largely unvegetated regardless of changes in temperature and precipitation. Valley areas around the margins of salt pans will remain restricted to halophytic plants until salinity levels drop. Because Clive is somewhat centrally located within the Great Basin cold desert biome, vegetation assemblage changes associated with climate change will occur more slowly than in areas closer to biome transition zones. As the climate changes, vegetation changes will occur on steppes and slopes, but soil chemistry will remain the constraining factor on the valley floors.

Pollen studies from sediment cores in the Great Salt Lake show that the vegetation of the Bonneville Basin and surrounding area has been desert for approximately the last 5 My (Davis and Moutoux, 1998). The pollen studies indicate that *Sarcobatus*, *Artemisia,* and various Chenopodaceae (the family that includes the various saltbush species) have dominated during interglacial periods, with montane conifers (*Picea*, *Abies*, and *Pseudotsuga*) increasing during glacial periods. For the purposes of this CSM, it is assumed that climatic shifts could occur resulting in any one of four different conditions: cooler-wetter, cooler-drier, warmer-wetter, warmer-drier. The direction of the climatic shift will affect both the vegetative and faunal assemblages occupying the site. Figure 7 illustrates a general biome diagram based on

temperature and precipitation, as well as the approximate location of the Clive site within this temperature-precipitation gradient.

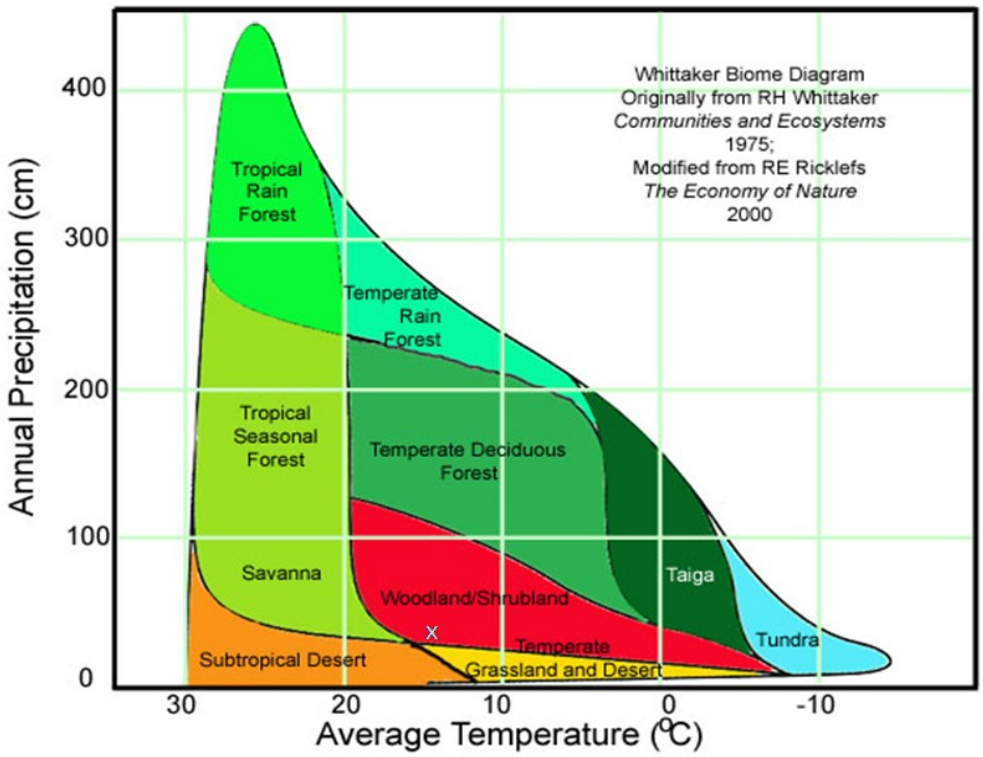

Figure 7: Whittaker Biome Diagram

Cooler, wetter conditions will likely result in transition first to *Artemisia* sage communities, then to Pinyon-Juniper woodland characterized by the presence of *Juniperus osteosperma* and *Pinus monophylla*, and finally to montane spruce/fir woodlands as seen during past glacial periods. These woodlands are not likely to ever occupy the valley floor unless profound changes in soil chemistry occur. All of these changes occur over geologic time, and prediction of the occurrence of specific species represents a great uncertainty. Cooler, drier conditions will likely maintain similar plant communities as are currently present, unless temperatures get cold enough to support taiga/tundra conditions.

Warmer, drier conditions will result in plant assemblages similar to those that occur in the Mojave desert, where valley floors are dominated by creosote bush (*Larrea tridentata*), white bursage (*Ambrosia dumosa),* and pale desert-thorn (*Lycium pallidum*). Warmer, wetter conditions could lead to establishment of grasslands, and eventually temperate forest, as existed more than 10 Ma when the pollen record shows that elm (*Ulmus*), hickory (*Carya*), yew (*Taxus*), and hemlock (Tsuga) were common in the area (Davis and Moutoux, 1998). Again, establishment of

these vegetative complexes on the valley floor would require a major shift in soil structure and chemistry.

7.2.1.6 Human Intervention

Various scenarios can be constructed that look at each of these impacts on the Clive facility in the ultra long-term future. One major difference between the past 3 My and the present is the existence of well-developed human civilization, technology, and greater ability to adapt to changing conditions. If the future is more in line with reentering another ice age similar to those that have occurred during the Pleistocene, human intervention could help to mitigate the effects of future events that could jeopardize the stability of the engineered facility at Clive. For example, the disposal cell could be protected by adding more rip-rap material, a seawall, or berm (or other engineered barriers) to prevent the deleterious effects of wave action in the event of future lake formation.

In the event of another major lake cycle, human intervention is likely to be employed in surrounding areas (e.g., Salt Lake City) and could result in modifying engineered features like those that were installed to alleviate the effects of flooding in the early 1980s, when a pumping system was built to divert flood waters into the west desert (see `www.water.utah.gov/Construction/GSL/GSLpage.htm`). In fact, the Utah Division of Water Resources proposed various options to handle flooding events of Great Salt Lake due to natural variations in precipitation (see `www.water.utah.gov/Construction/GSL/GSLflood.htm`). Some of the options that were proposed included the exportation of flood flows from the Great Salt Lake drainage basin to the Bear River and Sevier River drainages, consumption of water via evapotranspiration through the development of new agricultural lands, and creating a dike around the lake to protect major facilities and resources.

While it is difficult to predict the level of human intervention in response to these events, it should be taken into consideration for all future scenarios considered for the performance assessment of Clive facility.

7.2.2 Long-Term Scenarios

The primary scenario of concern in the deep time scenario is the return of a lake to the Bonneville Basin that reaches the elevation of the Clive facility. There is historical evidence of large lakes covering the Clive site with more than 100 meters of water, so large lakes will be modeled as recurring in the future. There is weaker historical record of intermediate-sized lakes, lakes that are relatively shallow at the Clive elevation. The lack of historical record for intermediate lakes is not necessarily surprising, since sedimentation from subsequent lakes is likely to bury evidence of intermediate lakes. However, there is evidence of two relatively recent intermediate lakes – Cutler Dam and Gilbert, as well as stratigraphy in sediment cores that suggest many lakes rising and falling at the Clive elevation (Oviatt, 1997), which might be associated with either intermediate lakes or fluctuations in large lake transgression and regression. The expected consequence of the formation of a lake in the Bonneville Basin is the destruction of the waste embankment due to wave energy, resulting in physical dispersal of the site material. Waste entrained in the sediment can partially dissolve into the lake, and contaminant complexes will precipitate from the lake water back into the sediment. This process is depicted in the conceptual model shown in Figure 8.

The deep time model is thus constructed to represent the following components:

- *Continuation of natural processes in the waste embankment.* After 10,000 years, natural processes such as air dispersal, groundwater transport, and biotic uptake will continue to be modeled as long as the embankment is intact.

- *Returns of large and intermediate lakes to the Clive site*. Large lakes will be treated as occurring regularly with the 100,000-year orbital cycle, while intermediate lakes will occur according to a random process between large lake cycles, with greater probability of occurrence further in time from the end of the inter-glacial period (i.e., as the temperature decreases and precipitation increases).

- *Site destruction*. When the first lake returns at or above the elevation of Clive, the waste embankment will be treated as destroyed. The result is dispersal of above-grade waste into the sediments near the site, along with dissolution into the lake water. Once the waste embankment is destroyed, the evolution of the waste embankment is no longer modeled.

- *Sedimentation and mixing*. The presence of a lake implies sedimentation at the site. As the waste is dispersed, it will be mixed with the embankment materials and sediment. Waste material that dissolves into the water column will be assumed to precipitate out of the water column back into the sediment at the site as the lake recedes. Subsequent lakes are likely to at least partially bury the waste beneath subsequent sediment. However, since the deep time model is intended to be qualitative, a conservative choice is made to model all sediments containing waste as mixing with sediments of subsequent lakes.

- *Activity levels*. The results tracked in the deep time model are the radioactive concentrations in lake water and in sediment.

8 Modeling of Engineered Features

The engineered features of the disposal facility are the waste form itself (including containment), and the liner and cap, which surround the wastes. Other than these, the natural environment is relied upon to moderate the migration of contaminants. These engineered features are expected to degrade with time, gradually assuming a form more like the natural surroundings. The model will attempt to capture the performance of the engineered features, including the essential processes contributing to their degradation, as described in this section.

8.1 Waste Form and Containment

The waste forms are discussed in detail in Section 6 , but a brief discussion is included here for completeness as an engineered feature. The waste form, for the purposes of this discussion, includes the matrix that contains radionuclides, and any drums, boxes, or other materials that contain that matrix. Generally, wastes are not designed with their long-term resistance to

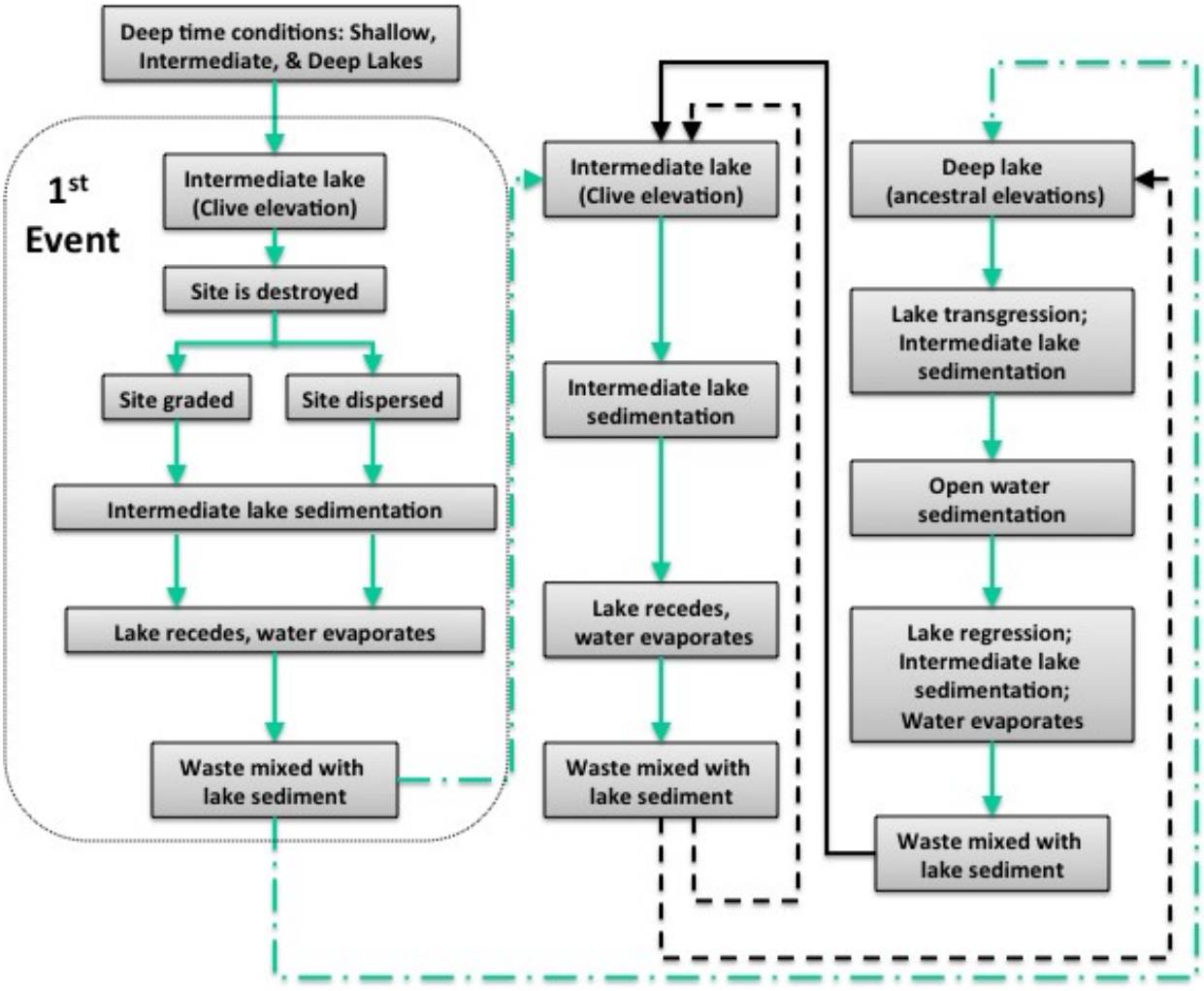

Figure 8: Scenarios for the long-term fate of the Clive facility

degradation in mind, but rather for the convenience of the generator and shipper. Also, waste form and containment on waste profiles or shipping manifests are sufficient for disposal purposes, but not necessarily for PA purposes.

Low-level radioactive waste matrices are in general quite heterogeneous, including bulk soils, debris from decontamination and decommissioning activities, protective equipment, tools, laboratory wastes, chemical residues, resins and filters, and such, but in the case of DU waste, the form is unusually uniform. Leachability and solubility can be modeled for well-documented DU oxide waste forms. Details on the chemical characteristics of DU waste are given in Section 6.6 .

Steel barrels and boxes, "burrito-wrap" fabrics, cardboard, or even bulk uncontainerized materials are common in LLW. Most of these offer little in the way of long-term containment, especially after compaction to reduce void spaces, which often crushes or otherwise compromises containment. Container integrity is not typically given credit in LLW PA models. In the case of DU, the containers, which consist of steel 200-L (55-gal) drums or the various specialized designs of steel UF_6 cylinders, are not expected to provide much in the way of long-term containment. Pitting, rusting, and other forms of corrosion have already been documented for the cylinders, and a number of steel drums have had to be repackaged. This degradation has taken place in the last few decades, so it would be unreasonable to assume that containers would remain intact for any appreciable length of time in the environment of the embankment cell. The model, therefore, will not take credit for containment. All wastes are assumed to have the characteristics of local Unit 3 sandy soil.

8.2 Liners

The Clive facility's embankment cells are constructed similarly to those designed for landfills under the Resource Conservation and Recovery Act (RCRA), using a variety of natural and engineered materials. Liners are constructed on the floor of the facility, and the waste is placed on top of them. Caps are constructed over the waste, and are designed to shed water. Despite careful construction to exacting standards and conscientious maintenance, both the caps and liners are subject to failure in the long-term (Smith et al., 1997), as entropy returns them to what approaches a natural state.

Previous PA modeling at the Clive site, which addressed a performance period of hundreds of years, included modeling of the installed performance of the cap and liner, degradation of the cap, and bio-intrusion scenarios (Whetstone, 2000). Liner degradation allows for increased contaminant transport from the waste layers to the UZ below the facility, and subsequently to the SZ through recharge. The performance of the liner is not expected to degrade significantly. The principal role of the liner in the contaminant transport model is to regulate flow from the waste to the underlying UZ, so all that matters, in the end, is the rate at which water may penetrate it, plus any chemical retardation involved as it flows through.

8.3 Cap

The engineered cap is likely to return to nature faster than the liner, due to biointrusion and erosion. These processes are discussed in the following paragraphs.

Changes in evapotranspiration fluxes due to time dependent evolution of the cap after closure will have the most significant influence on net infiltration. The potential changes in evapotranspiration and lateral drainage as the cap evolves are driven by the following processes:

- Aeolian dust begins to fill the void spaces between the armor (Layer 1) and the smaller cobbles in the upper filter (Layer 2), providing a soil base for plant cover on the top layer of the cap. The dust deposition process is augmented by fracturing of some large cobbles into smaller particles due to weathering. The presence of plant cover and soil on the cap is expected to increase evapotranspiration, thereby reducing the infiltration into the waste.

  The results of dust deposition, weathering, and plant growth were observed on the Vitro cell during a visit to the Clive site on September 16, 2010. The Vitro cell was closed in December 1988, and provides a site-specific measure of dust deposition, weathering, and plant growth since closure. A partial plant cover of grasses and small shrubs has been established within the past 22 years, based on the growth on the side slope and top slope of the Vitro cell.

  Evaporation will likely occur from greater depth once aeolian dust fills the void spaces between cobbles in the rip rap and plant cover is reestablished on the top surface of the cap. The measured moisture content in the Cover Test Cell at the site provides evidence for an evaporative zone depth greater than 18 in (Envirocare 2005). The measured data from the Cover Test Cell show that the middle of the sacrificial soil, at a depth of 30 in below the top of the cap, experiences seasonal drying during the six months with very low precipitation at the site (Envirocare 2005, Figures 3 and 4). Some of this drying is due to evapotranspiration, although drainage to the underlying clay layers (i.e., the radon barrier) may also play a role.

- Smaller mammals and ants are not expected to populate the cap in sufficient numbers to cause bioturbation and homogenization of the armor and upper filter (Layers 1 and 2). It is likely that smaller mammals may burrow to some extent in the silted rip rap, but not find the underlying cobbles hospitable compared to the virgin soil surrounding the cell. It is also unlikely that ants will find sufficient room amongst the cobbles and gravel to build chambers in Layers 1 and 2.

- The lower layers of the cap, Layers 3 and 4, will be a good habitat for deeper plant roots, based on a biological survey of the site. Observations made during a biological survey at the Clive facility (SWCA, 2011) indicate that plant roots often form on top of clay layers that are a meter or more below the top surface, such as the upper radon barrier (Layer 5). Some of these roots may penetrate the radon barriers, based on observations of plant roots in clay layers in boring logs, although the recent biological survey did not dig through clay layers to confirm this. It is possible that ants may also penetrate the clay layers by following root holes or possible cracks in the clay layers. On balance, the evidence suggests that bioturbation and homogenization of the radon barriers will probably occur very slowly relative to the 10,000-year time frame for the PA.

Sheet erosion is a uniform process over the area of the cap, and depends largely on its slope. In the central area of the embankment, where slopes are gradual, sheet erosion would be slower than on the steeper side slopes of the cell. As soil and loess move downslope, however, it is expected that their volumes would be replenished by deposition of clean loess from the surrounding environs. In the end, the soil volumes do not change, though there would be a slow movement of soils downslope, along with the contaminants they could potentially contain. Sheet erosion is not included in this model since the top slope of the cap is gradual (about 2%), and since the overall effect of sheet erosion is likely to be considerably less than the effect of gully erosion.

Gully erosion has the potential to move substantial quantities of both cap materials and waste. Once a "nick" is started somewhere on the surface of the cap, by an animal burrow or OHV track, for example, the feedback processes inherent in gully formation will cause erosion upward to the top of the slope, and downward to the surrounding grade. This process continues until the sides of the gully have met the angle of repose of the various materials within the facility, removing a wedge-shaped volume of material, and depositing it on the neighboring flat as a sort of small alluvial fan. As a first approximation of this volume, a simple wedge is calculated using the angle of repose.

Freeze/thaw cycles will also tend to degrade performance of the cap. This process is anticipated in the design, however, which includes a sacrificial layer to accommodate it (Whetstone, 2000). It is assumed in this model that although sacrificial soil will include plant roots and animal burrows, the overall effectiveness of the sacrificial soil layer is sufficient for this site.

Subsidence of the wastes could also contribute to decreased performance of the cap (Smith et al., 1997). Differential subsidence would be expected to cause vertical shearing of the cap layers, creating enhanced transport pathways, and the formation of depressions which could capture water, increasing local infiltration. However, it is expected that any depression would fill in rather quickly by windblown sediments. Subsidence is not expected to be an important process at the Clive facility, since the waste is aggressively compacted in order to prevent this occurrence (Energy*Solutions*, 2009c).

9 Radionuclide Transport

This section describes the aspects of modeling that involve radionuclides. The modeling of the natural environment, including groundwater flow, atmospheric dispersion, and other processes that are not specific to radionuclides, is discussed in Section 7 . Following the determination of the list of radionuclide species under consideration, this section discusses the mechanisms governing their fate and transport in the environment.

9.1 Modeled Radionuclides

Unlike general LLW, DU waste contains only a select number of radionuclides. These are mostly uranium isotopes (by mass), the most common of which is U-238. The non-uranium radionuclides are either fission products or actinides.

9.1.1 Reported Inventory

Based on laboratory analysis of the contents of DU waste (including all radionuclides in the containers), the species in the disposed inventory include (Beals, et al. 2002, Energy*Solutions* 2009b, Johnson 2010):

uranium isotopes	^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U
other actinides (and radium)	^{226}Ra, ^{241}Am, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu
fission products	^{90}Sr, ^{99}Tc, ^{129}I, ^{137}Cs

9.1.2 Radioactive Decay and In-growth

Radioactive decay and in-growth are fundamental physical processes. There are several types of radiological transformations, including alpha, beta, gamma, electron capture, spontaneous fission, etc. While these processes are not specifically detailed in this subsection, they are accounted for in terms of their dose effects on humans, and their change in elemental (chemical) nature. As they experience decay and in-growth, the radionuclides in the reported inventory will change and these progeny must also be included in the modeling.

Simplified decay chains for the actinides are shown in Figure 9. Decay and in-growth continue until a stable nuclide is reached. In the case of the actinides, the stable nuclide is always bismuth or lead.

9.1.3 Short-lived Radionuclides

Not all of the members of a decay chain are modeled in the fate and transport calculations. Given the long duration of the analysis, and the short half-life of many of the radionuclides, it is impractical to model their transport, as they could not travel any appreciable distance before decaying to the next nuclide of the decay chain. Attempting to include short-lived radionuclides in the fate and transport model adds unnecessary complexity to the model. Therefore, radionuclides with half-lives less than five years are excluded from the fate and transport analysis, with one exception: Rn-222. Radon is a special case, since as a noble gas it has unique transport characteristics, even though it has a half-life of under four days. It diffuses in both air and water, partitioning between the two, and can migrate significant distances.

It must be noted that while the short-lived radionuclides are not included in the fate and transport calculations, they are included in the dose assessment. It is often short-lived nuclides that contribute most to dose.

9.1.4 Radionuclides with Small Branching Fractions

Similar to the short-lived radionuclides, there are radionuclides that have exceedingly small branching fractions, in addition to being short-lived. These are included in neither the fate and transport calculations, nor the dose calculations, as their omission is invariably inconsequential and promotes computational efficiency. In addition, most of these small branching fraction radionuclides have no dose conversion factors available.

The detailed sections of the actinide decay chains that contain these radionuclides, showing all the short-lived and small-branching-fraction radionuclides, are provided in Figure 10.

List of Radionuclides Species for Fate and Transport

The complete list of radionuclides accounted for in the fate and transport model follows, organized into decay chains:

$^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}U \rightarrow {}^{229}Th$

$^{242}Pu \rightarrow {}^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{222}Rn \rightarrow {}^{210}Pb$

$^{238}Pu \rightarrow {}^{234}U \rightarrow$ (joins above chain)

$^{239}Pu \rightarrow {}^{235}U \rightarrow {}^{231}Pa \rightarrow {}^{227}Ac$

$^{236}U \rightarrow {}^{232}Th \rightarrow {}^{228}Ra \rightarrow {}^{228}Th$

$^{232}U \rightarrow {}^{228}Th \rightarrow$ (joins above chain)

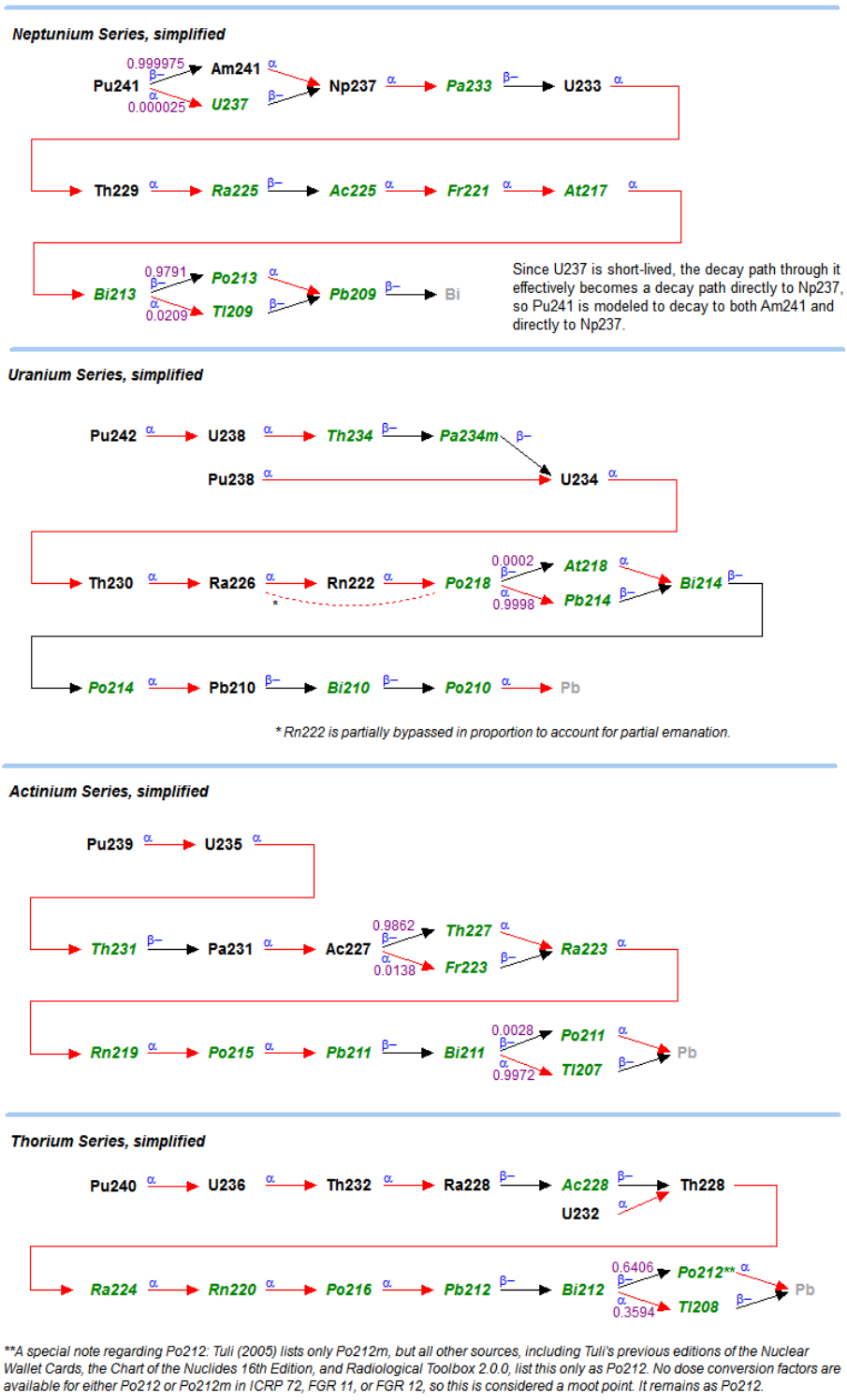

Figure 9: Principal decay chains for the four actinide series. Radionuclides in black are included in the fate and transport model, and those in green are considered only in the dose model.

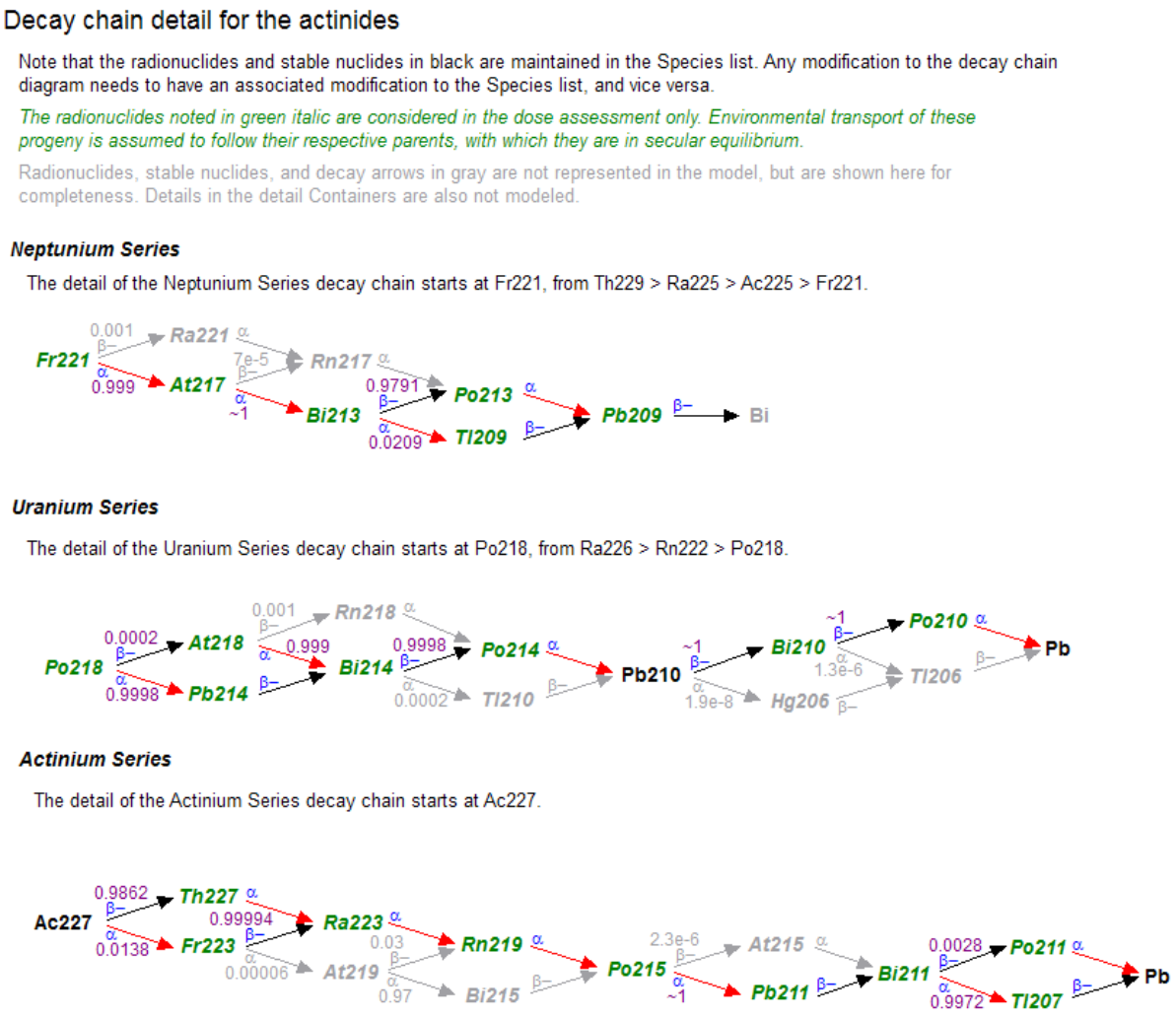

Figure 10: Detailed decay chains for actinides. Radionuclides in black are included in the fate and transport model, those in green are considered only in the dose model. and those in gray are not modeled.

Several radionuclides are not part of the actinide series:

$^{137}Cs \rightarrow {}^{137m}Ba$

^{129}I

$^{90}Sr \rightarrow {}^{90}Y$

^{99}Tc

The decay of the last species listed in the chain is also included in the fate and transport modeling.

9.2 Source Release

The disposed DU waste is assumed to be uncontainerized, since standard operations at the site include significant compaction of disposed waste.

9.2.1 Containment Degradation

As discussed in Section 8.1 , no credit will be given to the ability of steel containers to inhibit release of wastes.

9.2.2 Matrix Release

In the absence of detailed information regarding the chemical and physical form of the uranium oxides, release of radionuclides from the waste matrix will be assumed to be instantaneous. That is, release into infiltrating water that migrates through the waste will be controlled only by the geochemical constraints of the waste/water partition coefficient (K_d) and solubility (see Section 9.3). If information can be provided for a basis of a measured release from the waste matrix, that can also be incorporated into the model.

9.2.3 Radon Emanation

A special consideration for DU is the production and release of radon, especially Rn-222. As Rn-222 is produced by alpha decay from Ra-226, the recoil from the ejection of the alpha particle may be of sufficient energy to expel the Rn-222 atom from the waste matrix. If it is not so energetic, the radon atom will stay in the matrix, and will in a matter of days decay to Po-218 and then to other progeny, and will not be available for environmental transport as radon.

The fraction of decaying radium atoms that result in a radon atom being expelled into a transport medium (water or air) is called the radon emanation factor or the escape/production ratio (E/P) ratio, and has a value between 0 and 1. If the E/P ratio for a given waste form is 0, no radon ever escapes the matrix; if it is 1, all radon escapes. A dense solid matrix such as metal, crystal, or glass could have a low E/P ratio, and a fine powder or surface contamination would have a relatively high value.

9.3 Waterborne Radionuclide Transport

Water enters the modeled system as infiltration from meteoric waters (precipitation) at the embankment cell surface, and as groundwater below the ground surface. The approach to modeling different groundwater zones is discussed in Section 7.1.1 . This section focuses on the transport of radionuclides within that water system. For many contaminants waterborne transport is influenced by geochemical processes.

While the radiogeochemistry of contaminant transport is in reality exceedingly complex, it is typically simplified for the purposes of PA. A full geochemical model considers the mineralogy of neighboring geological materials and the full geochemical makeup of water, on a highly refined scale. It considers the speciation and complexation of ions, which is especially involved for those cations with multiple valence states, such as uranium and plutonium. It considers the formation and transport of colloids, and the fine-scale adsorption of chemical species onto sediment particles and fracture coatings. For the PA modeling, the geochemistry of contaminant transport in groundwater is approached at the macro scale, and a few key concepts are assumed

to account for all the small-scale variation. A simple equilibrium sorption model using soil/water partition coefficients or K_ds is used to model the partitioning process. While simplified, the K_d approach is conservatively representative of the solid-water partitioning process and is in common usage in PA models. The K_d model assumes that a given constituent dissolved in the water (e.g. uranium) has some propensity to sorb to the solid phase of a porous medium, while maintaining some presence dissolved in the aqueous phase as well. The definition of the solid/water distribution coefficient, with units of mL/g (or sometimes m^3/kg) is:

$$K_d = \frac{mass\ of\ constituent\ sorbed\ on\ a\ unit\ mass\ of\ solid\ (g/g)}{mass\ of\ constituent\ within\ a\ unit\ volume\ of\ water\ (g/mL)}. \quad (1)$$

The sorption is assumed to be instantaneously reversible and independent of concentration. That is, no dynamics are accounted for, and the ratio is always simply linear—a constituent's concentration in water is always the same ratio with respect to its sorbed concentration onto the solid, and it takes no time for the change between solid or liquid phases to occur. This is the linear isotherm assumption, and is commonly employed.

Aqueous solubility, however, places limits on the amount of a constituent that can be dissolved in the water phase. Each chemical species (in this case, each chemical element, including all isotopes) has a limit as to how much of that chemical can exist in the water phase. Solubility is expressed in moles per unit volume of water (typically mol/L), where one mole is Avogadro's number of atoms (or molecules). If, then, the solubility of uranium were 1 mol/L, one liter of water could hold one mole of uranium, which could be a mix of U-235, U-236, U-238, or other isotopes. Any attempt to add uranium to the water will result in the precipitation of uranium.

The K_d model expressed in Equation 1 is applied only when the solubility limit for a given constituent is not in effect. This is a particularly important point to keep in mind when modeling the leaching of a concentrated waste form, such as uranium oxides. At first, the leaching is likely to be solubility-limited with respect to uranium, and the leachate will migrate away with uranium at the solubility limit. Eventually, as enough uranium is removed from the source, the leachate concentration will be limited only by K_d, and will be less and less concentrated until the source is depleted. This occurs for all other elements as well, though the synergistic effect of various similar chemicals (e.g. other heavy metals like plutonium and lead) is not modeled.

Note that partitioning and solubility are independent of isotopic variation, as the radiological aspect of contaminants does not enter into their chemistry. That is, isotopes all behave identically, chemically speaking. U-234, U-235 and U-238 are isotopes, and therefore compete together for sorption sites, or for aqueous solubility. A model that considers U-235 and U-238 in separate simulations cannot couple these effects, and may produce inaccurate results, especially in the presence of solubility limitations. GoldSim recognizes the concept of isotopes, and accounts for their interrelated chemical behavior.

9.4 Airborne transport

As discussed in the section on modeling the natural environment (Section 7.1.3), the two distinct types of airborne transport include diffusion in the air-filled pore spaces of porous media, and

dispersion above the ground surface by wind. Radiological aspects of these processes are discussed below.

9.4.1 Diffusion Through Porous Media

Diffusion within porous media, in either air or water, is driven by concentration gradients. Diffusion is mediated by diffusion coefficients, and it follows tortuous paths through the specific medium. Partitioning between air and water phases also occurs, which adds to the number of simultaneous equations to be solved.

The principal radionuclides of interest in the modeling of DU waste are the isotopes of radon, since radon, a noble gas, is the only radionuclide to be found in a gaseous form. The parents and progeny of radon isotopes are of interest as well. Radon has several isotopes that occur in the various actinide decay series, including: Rn-217, -218, -219, -220, and -222 (see Figures 8 and 10). Radon isotopes with half-lives ranging from milliseconds to just under 1 minute quickly undergo decay to polonium and therefore can travel no appreciable distance. Radon-222, however, has a half-life of just under 4 days, and is able to migrate for some distance by diffusion in interstitial air before it, too, decays to polonium. When regulations such as DOE's Radioactive Waste Management Order 435.1 address radon ground surface flux as a performance objective, Rn-222 is the isotope of concern.

Since Rn-222 is a direct descendent of U-238 and U-234, and hence Th-230 and Ra-226, it will be generated anywhere in the environment that Ra-226 occurs. As the radium migrates into the embankment cell cap, either by diffusion in the water phase or translocation by biotic processes (see Section 9.5), it provides a source for Rn-222 in more locations than just the disposed waste. This form of translocation and transport is accounted for in the modeling.

A phenomenon unique to the production and release of radon is the E/P ratio, introduced in Section 9.2.3 with respect to release from the waste form. If, however, the Ra-226 parent is present in other locations, such as cap materials or surface soils, radon will be in water or adsorbed onto solids, rather than bound in some crystalline matrix. The E/P ratio in the environment is assumed to be 1, and thereby all of the decay of Ra-226 outside the waste form results in Rn-222 that is available for transport.

Radon readily partitions into both air and water, per its Henry's Law constant (K_H) and exhibits preference for the water phase. For this reason, wet soils are much better at attenuating radon migration than dry soils. To mitigate the diffusion of radon through the engineered cap, the layering within the cap design includes a substantial layer of clay. Clay has a low permeability to air and to water, and also can maintain a high moisture content, which retards the migration of radon as it partitions into soil (Ota et al., 2007). The effectiveness of this clay radon barrier, however, depends on its resistance to degradation by erosion and biotic processes. Cracks, fissures, animal burrows, and plant roots can all provide fast diffusion pathways that reduce the effectiveness of the radon barrier.

Diffusion in the porous medium air phase, as well as the water phase, is implemented in the Clive DU PA Model through diffusive flux links between all GoldSim Cells in a column, from the atmosphere to the water table.

9.4.2 Atmospheric Dispersion

The basic modeling of atmospheric dispersion is covered in Section 7.1.3.2 . The only effect of radon and radionuclides attached to particles that is related to radioactive processes is that during transport, as in other transport pathways, radionuclides undergo radioactive decay and in-growth. For the purposes of this model, however, the assumption is made that atmospheric transport is sufficiently fast relative to rates of decay that no decay need be accounted for during the transport.

9.5 Biotically-Induced Transport

Plants and fossorial (burrowing) animals have the potential to move radioactive material in addition to the more commonly implemented waterborne and airborne transport pathways. The full conceptual model of biota at the site is discussed in Section 7.1.4 , and the relevance to radionuclide transport is discussed here.

9.5.1 Transport via Plants

Plants obtain many nutrients and minerals from the soil, through root uptake. Some chemical species are preferred over others, and this preference differs between plant species, as does the effectiveness of uptake. This selective uptake is coupled with radioactive decay and in-growth. Plants are conceived to selectively absorb chemical species from the soils, with roots exposed to different soil layers and thus different suites of chemicals at various depths. The absorbed radionuclides, then, are distributed evenly within the plant tissues, both above-ground and below-ground.

When the plant dies, the below-ground parts return radionuclides to whatever soil layer they are in, and the above-ground plant parts all return their constituents to the top layer of soil.

9.5.2 Burrowing Animals

Burrowing animals include various mammals, reptiles, and insect species. They move bulk soil from the depths where they construct burrows directly to the ground surface. Bulk soil includes soil and any interstitial water and air, and all radionuclides contained in the volume that the animals remove.

After a burrow is abandoned, it eventually collapses, moving bulk soils back down from the surface, in accordance with the volume excavated. This preserves the mass balance of soil in the soil column. The overall effect of this burrowing activity is a consistent churning of the soil layers (bioturbation). This effect may be surprisingly deep, with ant nests having been observed to penetrate over 4 meters (~13 ft) below the ground surface at another western radioactive waste disposal site (see Section 7.1.5).

10 Modeling Dose and Risk to Humans

Evaluation of radiation dose (with implied risk) to potential human receptors is a requirement of the PA. The individual dose assessment addresses potential radiation dose to any member of the public who may come in contact with radioactivity released from the disposal facility into the general environment (10 CFR 61.41). Radiation dose limits for protection of the general population are defined in 10 CFR 61.41. Design, operation, and closure of the land disposal

facility must also ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste at any time after loss of active institutional control of the site (10 CFR 61.42). Because the definition of inadvertent intruders encompasses exposure of individuals who engage in normal activities without knowing that they are receiving radiation exposure (10 CFR 61.2), there is no practical distinction made in the dose assessment between any MOP and inadvertent intruders with regard to modeling radiation dose for protection of the general population.

Protection of inadvertent intruders from the consequences of disturbing disposed waste can involve two principal controls: 1) institutional control over the site after operations by the site owner to ensure that no such occupation or improper use of the site occurs, or 2) designating which waste could present an unacceptable risk to an intruder, and disposing of this waste in a manner that provides some form of intruder barrier that is intended to prevent contact with the waste (10 CFR 61.7(3)).

The objective of modeling annual radiation dose to an individual in a radiological PA is to provide estimates of potential doses to humans, in terms of an "average" member of the critical group, from radioactive releases from a disposal facility after closure, as described in Section 3.3.7 of NUREG-1573, *A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities* (NRC, 2000). As described below, the critical groups in this PA are defined as Ranchers, Sport OHVers, and Hunters. An "average" member of such a group may be considered as either a statistical construct, or more subjectively as simply a hypothetical individual whose behavioral and physiological attributes do not place them on either the lower of higher extreme of the range of possible individual doses.

NUREG-1573 describes two aspects of dose modeling: First, the mechanisms of radionuclide transfer through the biosphere, to humans, needs to be identified and modeled. This is termed the pathway analysis. Second, the dosimetry of the exposed individual must be modeled. This is termed the individual dose assessment.

Pathway analysis, as defined in NUREG-1573, results in the determination of the total intake of radionuclides by the average member of the critical group. The critical group is defined as the group of individuals reasonably expected to receive the greatest dose from radioactive releases from the disposal facility over time, given the circumstances under which the analysis would be carried out. Modeling of radionuclide transport by plants and animals, and of human activities, is captured within the scope of this pathway analysis. The dosimetry component of the dose modeling refers to estimation of the effective dose equivalent from internal radiation dose following radionuclide intake, and from external radiation dose.

In order to estimate collective doses for the purpose of determining whether disposal options satisfy ALARA, a population needs to be assessed. A population is comprised of multiple individuals, so individual doses need to be added over some period of time to estimate the collective dose. The 'answer', at the end of the performance period (10,000 years post-closure, in this case) might then be the individual annual doses added up over a period of 10,000 years. Although there is no collective dose performance metric that currently exists, this analysis may be useful in the context of comparing how one site or disposal option might perform compared to another.

10.1 Period of Performance

No specific time frame is defined in 10 CFR 61 for the dose assessment. In the context of inadvertent human intrusion, Section 61.42 states,

> "Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste *at any time* after active institutional controls over the disposal site are removed." (emphasis added.)

Proposed modifications to UAC Rule R313-25-8 are more specific, requiring a PA for DU to have a minimum compliance period of 10,000 years, with additional simulations for a qualitative analysis for the period where peak hypothetical dose occurs. The estimation of doses at such long time frames is tenuous at best, but if total radioactivity is used for a proxy, accounting for decay and ingrowth from the disposed DU, then a peak value would occur once the progeny of U-238 have reached secular equilibrium in about 2.1 million years.

The scope of this PA is to model the disposal system performance to the time of peak hypothetical radiological dose (or peak radioactivity, as a proxy), but to quantify dose only within the regulatory time frame of 10,000 yr. This approach is consistent with the proposed amendments to UAC R313-25-8(2).

10.2 Site Characteristics and Assumptions

Key land use characteristics and assumptions for the Clive facility that pertain to the development of receptor scenarios and dose modeling are summarized in the Site Description (Section 3).

As addressed in *FEP Analysis for Disposal of Depleted Uranium at the Clive Facility*, the distinction between deliberate and inadvertent intrusion for this PA is based on the motive underlying the activity. Intrusive activities not related to a deliberate attempt to excavate materials underlying the protective cover will be considered inadvertent. The performance objectives of 10 CFR 61.43 specifically address protection of individuals from the consequences of inadvertent intrusion after active institutional controls are removed. Because deliberate intrusion at the site is omitted from the performance objectives, whereas inadvertent intrusion is specifically mentioned, modeling of dose resulting from deliberate intrusion into the disposal site is not included in this PA. Therefore, radiation doses due to intrusion based on motives such as archeology, sabotage, or waste retrieval for constructive or malicious reasons, are not evaluated.

10.3 Receptor Scenarios

Potential activities of interest for this model are based on the predominant present day uses of the general area as identified in the FEP analysis: ranching and recreation. Other scenarios that are often considered for PAs, including agriculture and homesteading, are not applicable for the Clive site for reasons described below. There are other populations that might be exposed at locations remote from the disposal embankment, such as drivers along Interstate 80, a resident caretaker at the Aragonite rest area off I-80, rail workers and riders, and workers at the Utah Test and Training Range. Although these receptors are likely exposed for short amounts of time

and/or at lower concentrations compared to ranchers and recreationists, these off-site receptors will also be evaluated in the PA model.

From a regulatory perspective, two categories of receptors require consideration. These are often labeled "member of the public" (MOP) and "inadvertent human intruder" (IHI). Both categories are described in related guidance: the MOP essentially as a receptor who resides at the boundary of the facility, and the IHI as someone who directly contacts the waste (e.g., by well drilling, or basement construction). There is no historical evidence of non-transient human activities in the near vicinity of Clive, however, other than current activities and a temporary maintenance camp at the nearby railroad over 50 years ago. Furthermore, while the area in which the site is located is zoned for hazardous waste disposal by Tooele County, the lack of potable water makes the surrounding area an unlikely location for other residential, commercial, or industrial developments (Baird et al., 1990). Consequently, an IHI or MOP receptor as described in regulatory guidance is extremely unlikely. Therefore, consideration will be given to ranching and recreational scenarios to describe plausible human activities under current conditions. The potential for these human activities to result in inadvertent human intrusion will also be considered.

10.3.1 Ranching Scenario

The land surrounding the disposal facility is used for cattle and sheep grazing (NRC, 1993; BLM, 2010). Leases are administered by the BLM, and are generally up to 6 months in length, from autumn to spring. The ranching exposure scenario includes exposure to radionuclides that have entered the available environment due to natural processes described in the transport model. Receptors may be directly exposed while working upon or in the vicinity of the disposal unit. Evaluation of potential radiation dose in this scenario is partially dependent upon assumptions regarding the nature of plant community succession on the disposal unit over time. Because ecological succession on the disposal unit over time could potentially result in grazing habitat upon the disposal unit, a variety of potential future plant community assemblages are evaluated in the PA model.

Inputs for developing exposure parameter values under the ranching scenario include information on the characteristic activities of ranch hands and restrictions related to BLM leases for ranching. Activities are expected to include herding, maintenance of fencing and other infrastructure, and assistance in calving and weaning. The primary exposure pathways for the ranching scenario include incidental ingestion of soil, inhalation, external irradiation, and ingestion of beef from cattle grazing in contaminated areas. Exposure to respirable particulates may occur from natural wind disturbance of surface soil as well as mechanical disturbance due to rancher use of off-highway vehicles (OHVs) for transportation within the impacted area.

10.3.2 Recreational Scenario

The recreational exposure scenario encompasses receptors such as hunters and recreational OHV riders on, or in the vicinity of, the disposal unit. Based upon discussions with the BLM and reasonable judgment regarding anticipated land use, all recreational activities are likely to involve some OHV use and may encompass sport OHV riding, hunting, target shooting of

inanimate objects, rock-hounding, wild-horse viewing, looking for ghost towns, and limited camping. The recreational scenario evaluated in the PA model includes two distinct receptor groups:

1. "Sport OHVers" who use their vehicles primarily for recreation and who may visit the area as either a day trip or by camping overnight; and,
2. "Hunters" who, in addition to purely recreational visits, also visit the area for the purpose of hunting game and who may also visit the area as either a day trip or by camping overnight.

The desirability of recreational activities on or around the Clive facility is, like suitability for ranching, dependent on assumptions regarding ecological succession at the Clive facility over time. With the possible exception of OHV use and use of the cap as a vantage point for hunting, recreational uses of Clive facility in an as-closed state of bare rip rap surfaces is likely to be minimal. As soil develops on the cap and plant succession proceeds, the Clive facility may become more attractive for activities such as camping and therefore support higher exposure intensity.

The primary exposure pathways for the Sport OHV scenario modeled in the PA (described in more detail below) include incidental ingestion of soil, inhalation, and external irradiation. The Hunter scenario includes these same pathways and adds ingestion of game meat from animals grazing in contaminated areas. Exposure to respirable particulates is evaluated for both natural wind disturbance of surface soil as well as mechanical disturbance due to Sport OHV and Hunter use of OHVs for transportation within the impacted area.

10.3.3 Remote Off-Site Receptors

The ranching and recreation scenarios are characterized by potential exposure related to activities both on the disposal site and in the adjoining area. Specific off-site points of potential exposure also exist for other receptors based upon present-day conditions and infrastructure. Unlike ranching and recreational receptors who may be exposed by a variety of pathways, these off-site receptors are likely to be exposed solely to wind-dispersed contamination, for which inhalation exposures are likely to predominate. The remote locations and receptors for which inhalation exposures are evaluated in the PA model include:

- Travelers on Interstate-80, which passes 4 km to the north of the site;
- Travelers on the main east-west rail line, which passes 2 km to the north of the site;
- Workers at the Utah Test and Training Range (a military facility) to the south of the Clive facility, who may occasionally drive on an access road immediately to the west of the Clive facility fenceline;
- The resident caretaker at the east-bound Interstate-80 rest facility (Aragonite [Grassy Mountain]) approximately 12 km to the northeast of the site, and,
- Recreational OHVers at the Knolls OHV area (BLM land that is specifically managed for OHV recreation) 12 km to the west of the site.

10.4 Transport Pathways

Various considerations should be taken into account when analyzing the transport of radionuclides through the biosphere to humans. Pathway identification is discussed in various literature sources, such as Volume 1 of NUREG/CR-5453 (NRC, 1989) and NUREG-1200 (NRC, 1994), and NUREG-1573 (NRC, 2000). Components of the disposal system that can affect transport include aspects of the source term and engineered barriers. Principal transport media at many low-level waste disposal sites include groundwater, surface water, and air (NRC, 2000).

Pathways that will be evaluated for the protection of exposed individuals from releases of radioactivity include those related to air (gas diffusion, air dispersion, and aeolian erosion of soil), soil (contaminant migration via upward flux from subsurface soil, deposition of wind-borne material), groundwater (groundwater flow, geochemical effects, radon emanation), surface water (water erosion leading to gullies, infiltration), plants (uptake of contaminants in the waste, engineered cap, or soil), and animals (exhumation by burrowing). . Exposure media subsequently affected by transport processes include air, surface soil, plants, game, and livestock. Figure 11 depicts the conceptual model for contaminant transport at the Clive facility.

The transport processes figure depicts those processes relating contaminant release mechanisms to environmental media that are the subject of the dose assessment. Many of these transport pathways may not be complete or may not contribute sufficiently to exposures to warrant explicit modeling.

10.5 Exposure Pathways

Exposure pathways describe the activities and exposure routes between the environmental media described in Section 7 and human receptors in the ranching and recreation exposure scenarios. The primary exposure routes related to radionuclides in environmental media include ingestion, inhalation, and external irradiation.

The ingestion exposure route may pertain to inadvertent ingestion of contaminated soil at either on-site or off-site locations for the ranching and recreation scenarios. In addition to incidental ingestion of soil, ingestion of meat containing radionuclides taken up from contaminated soil by grazing animals is possible. Ingestion of meat from livestock grazing on or around the Clive facility is characterized in the Ranching scenario. Ingestion of hunted meat from pronghorn grazing in the region of the Clive facility is characterized for the Hunter receptor in the recreational scenario.

The inhalation exposure route consists of the inhalation of either gas-phase radiological contaminants or of respirable particulates originating from contaminated soil. The inhalation exposure route is evaluated for both the ranching and recreational scenarios. Concentrations of respirable particulates in air is assessed as a function of both wind erosion and mechanical disturbance from the use of OHVs for all potential receptors.

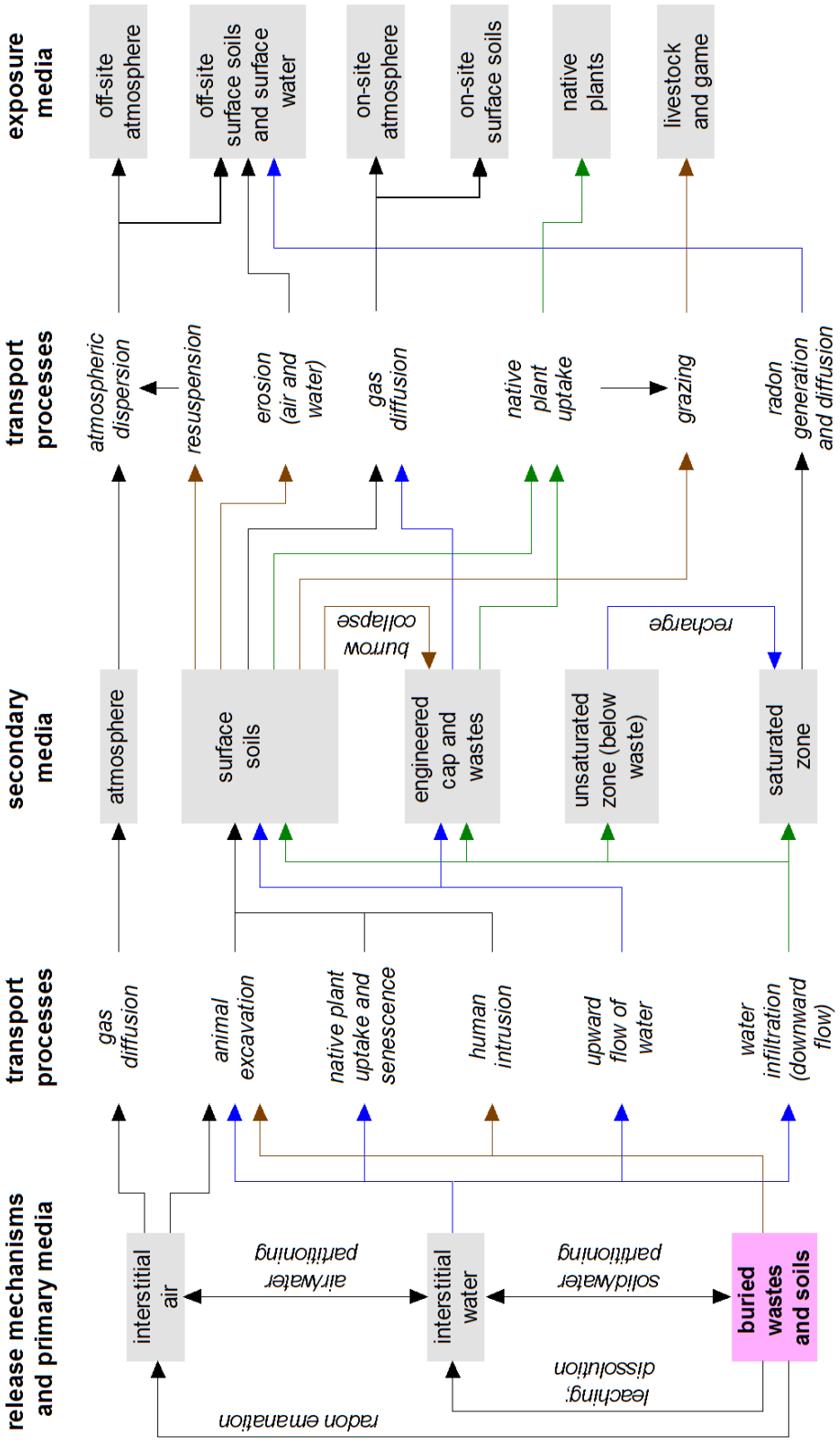

Figure 11. Conceptual model for contaminant transport at the Clive facility

External irradiation refers to the external exposure to a radiological source such as contaminated surface soil (a two-dimensional source) or air (a three-dimensional source). External irradiation from contaminated soil may occur when a receptor travels across the ground surface during either ranching or recreational activities. Atmospheric immersion occurs when a receptor is exposed to external irradiation via bodily immersion in contaminated air. Atmospheric immersion is tied to the gaseous diffusion and air dispersion transport pathways, and is a viable exposure route for both the ranching and recreational scenarios.

10.6 Risk Assessment Endpoints

Title 10 CFR 61.41 specifies assessment endpoints related to radiation dose. The specific metrics described in §61.41 are organ-specific doses, and restrict the annual dose to an equivalent of 0.25 mSv (25 mrem) to the whole body, 0.75 mSv (75 mrem) to the thyroid, and 0.25 mSv (25 mrem) to any other organ of any member of the public. However, as described below, the dose assessment for the PA will employ a total effective dose equivalent (TEDE) for comparison with the 0.25-mSv/yr threshold.

As discussed in Section 3.3.7.1.2 of NUREG-1573 (NRC, 2000), the radiation dosimetry underlying these dose metrics was based on a methodology published by the International Commission on Radiation Protection (ICRP) in 1959. More recent dose assessment methodology has been published as ICRP Publication 30 (ICRP, 1979) and ICRP Publication 56 (ICRP, 1989), employing the TEDE approach. The TEDE uses weighting factors related to the radiosensitivity of each target organ to arrive at an effective dose equivalent across all organs. The text of Section 3.3.7.1.2 of NUREG-1573 (NRC, 2000) states

> "As a matter of policy, the Commission considers 0.25 mSv/year (25 mrem/year) TEDE as the appropriate dose limit to compare with the range of potential doses represented by the older limits... Applicants do not need to consider organ doses individually because the low value of TEDE should ensure that no organ dose will exceed 0.50 mSv/year (50 mrem/year)."

Radiation dose conversion factors (DCFs) applicable for calculating the TEDE are published by DOE, EPA, and the ICRP. Section 3.3.7.3 of NUREG-1573 specifies DCFs published by EPA in Federal Guidance Reports 11 (EPA, 1988) and 12 (EPA, 1993). EPA subsequently made use of age-specific DCFs published in ICRP Publication 72 (ICRP, 1996) to compute radionuclide cancer slope factors in Federal Guidance Report 13 (EPA, 1999). DCFs published in Federal Guidance Report 13 are employed in this PA where possible.

DU waste can also be associated with toxicological risks that are independent of radioactive properties. Unlike carcinogenic agents, EPA typically views toxicants with non-cancer effects as having thresholds; i.e., levels below which effects would be unlikely. Reference doses (RfDs) essentially amount to such thresholds, usually with several layers of 'safety' factors added. The basic modeling process for evaluating uranium toxicity is very similar to that conducted for radionuclides, except that kidney toxicity (as opposed to radiation dose) of DU is evaluated, and the toxicity of DU does not change over time (as radioactive decay is not important in this context).

11 Summary

This CSM describes the dynamic systems model that will be implemented for the Clive DU PA. The CSM describes the regulatory environment that constrains the PA, and the technical components that transport radionuclides associated with the DU waste to the accessible environment. Transport starts with characterization of the waste, and continues with release of radionuclides from the waste, migration through the engineered barriers system that initially confines the waste, fate and transport through the local environment to the accessible environment where human receptors might be exposed, including radioactive decay and ingrowth through time and space. The dynamic systems model will be implemented using the GoldSim systems modeling platform, which facilitates fully-coupled dynamic systems modeling and is ideally suited to performing radiological performance assessments. The modeling will be performed in a probabilistic manner so that uncertainties are fully captured and global sensitivity analysis can be performed in order to identify the critical parameters. Consideration will be given to spatio-temporal scaling and correlation in the modeling, so that input probability distributions are properly specified. For some inputs to the model (e.g., radon diffusion, water content in the unsaturated zone, erosion of the cover) process-level models may be developed and then abstracted into the GoldSim systems-level model so that these model components are fully integrated into the overall model.

The modeling effort will be split into two overlapping but distinct time frames of primary interest. The regulatory compliance period for the first time frame is 10,000 years, requiring a quantitative model that predicts radioactive dose to potential receptors. For this model, current conditions of society and the environment will be projected into the future. Potential receptors of interest for this model are based on present day use of the general area, as discussed in Section 10.3 , including ranching, hunting, and recreation.

The second modeling time frame will consider much longer term consequences of disposal of DU waste at Clive, since peak radioactivity of the DU waste occurs beyond 2 million years into the future. This model will overlap the short term assessment in that it will share many of the same modeling components, such as waste inventory, source release, and fate and transport through the local environment. However, this model will consider changes in the general environment that might effect major changes in the environmental conditions of Clive. For example, climate change is inevitable within this time frame, so its consequences will be considered. Earth is in a glacial epoch, consisting of long glacial periods interspersed with shorter interglacial periods. For example, the current interglacial period is one in which the population of the human race has expanded to unprecedented levels. This interglacial period is likely to continue for tens of thousand of years. However, based on the historical record, return of a glacial period is inevitable. Based on geological evidence, the return of a glacial period will probably result in the re-formation of a large lake covering most of northwestern Utah, so lake recurrence is included in this model. Human exposure scenarios, however, will not be evaluated that far into the future, because receptor scenarios cannot be defensibly developed and the consequences of radioactive dose cannot be reasonably understood that far into the future. Many changes in climate will have occurred within the next 2.1 My, the period over which it takes DU to reach secular equilibrium. During such a long time frame there is likely to be massive disruption in human society and changes in human evolution. Consequently, instead of

attempting to model dose to hypothetical human receptors that far into the future, the spatial distribution and concentrations of radionuclides that might migrate from the disposal cells to the environment will be modeled. The processes by which the radionuclides might move around , include the formation of large lakes and the return to lower lake levels once the lake subsides again. Consideration will also be given to the potential effects of wave action at the Clive facility as the lake forms.

This two-tiered approach is consistent with the requirements of the Utah regulations to perform fully quantitative modeling for 10,000 years, and qualitative modeling until peak activity. Consequently, these two models will be used together to support the required regulatory analysis of DU waste disposal at the Clive facility.

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