UTAH LOW-LEVEL RADIOACTIVE MATERIAL LICENSE

(RML UT2300249) UPDATED

SITE-SPECIFIC PERFORMANCE ASSESSMENT

October 8, 2012

For
Utah Division of Radiation Control
195 North 1950 West
Salt Lake City, UT 84114-4850

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EXECUTIVE SUMMARY

Energy*Solutions*, LLC (Energy*Solutions*) operates a low-level radioactive waste (LLRW) disposal facility west of the Cedar Mountains in Clive, Utah. On 14 February 2011, Energy*Solutions* requested concurrence from the Utah Division of Radiation Control that previous licensing activities allowed for the receipt and disposal of blended ion-exchange resin waste on a large-scale at the Clive facility (Shrum, 2011). The Division reviewed Energy*Solutions*' request and determined that Energy*Solutions* could receive blended waste up to 40,000 cubic feet per year. In order to receive blended waste at volumes greater than 40,000 cubic feet per year, Energy*Solutions* would be required to conduct a new site-specific Performance Assessment that includes prediction of nuclide concentration and peak dose (at the time peak dose would occur) using updated dose conversion factors, and a suggested model time frame of 10,000 years, as well as any need to revisit/update the waste source term, receptor and exposure pathways.

The new site-specific Performance Assessment utilizes the HYDRUS and RESRAD platforms, replacing the previous HELP, UN-SATH, and PATHRAE platforms. In addition, updated climate, weather patterns, temperature records, wind reports, precipitation measurements, evaporation records, geology characteristics, hydrology logs, surface water observations, groundwater measurements, and ecologic field studies were used as input into the calculations. Two alternate cover designs were analyzed (in comparison to the site's traditional rock armored cover) and the list of Class A nuclides expanded by 19.

The new site-specific Performance Assessment demonstrates continued protection of the general public following embankment closure through consideration of possible contaminant transport via the atmosphere, site soils, groundwater, surface water, vegetation, and burrowing animal pathways. Similarly, the impact of viable inadvertent intrusion is demonstrated to be well below regulatory limits.

Doses to the general public during operations continue to be monitored and controlled according to Energy*Solutions*' Radiation Protection Program, Environmental Monitoring Program, and ALARA Program. Because of these administrative controls, inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance or reduce protection of the general public from plant or animal driven migration of contaminants during operations.

Energy*Solutions* has demonstrated in all previous license activities that the disposal site, disposal site design, land disposal facility operations, disposal site closure, and post-closure institutional control plans are adequate to protect the public health and safety. Design features do not require alteration to accommodate the disposal of blended ion-exchange resin waste in excess of 40,000 ft^3, annually.

The site-specific Performance Assessment also demonstrated that, because of the very low infiltration rates associated with the alternative cover designs, no water that infiltrates through the covers will reach the point of compliance within 10,000 years. Therefore, no class A radionuclide concentrations will arrive at the point of compliance well within the 10,000 year assessment period. As such, disposal of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the groundwater resource.

The design of the Containerized Waste Facility (CWF) exceeds regulatory requirements for disposal of Class A waste and provides intruder barriers for wastes above the Class A classification (e.g., engineered facility, disposal unit stability, and at least 5 meters depth to waste). Therefore, the CWF design, operation, and license support demonstrate protection of inadvertent intruders from the disposal of larger volumes of Class A blended resins.

Therefore, this site-specific Performance Assessment and the resulting findings demonstrate that Energy*Solutions*' proposed methods for disposal of blended ion-exchange resins in excess of 40,000 ft^3 annually will ensure that future operations, institutional control, and site closure can be conducted safely, and that the site will comply with the Division's radiological performance criteria contained in UAC R313-15 and UAC R313-25.

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1. INTRODUCTION

Energy*Solutions*, LLC (Energy*Solutions*) operates a low-level radioactive waste (LLRW) disposal facility west of the Cedar Mountains in Clive, Utah. Clive is located along Interstate-80, approximately 3 miles south of the highway, in Tooele County. The facility is approximately 50 miles east of Wendover, Utah and approximately 80 miles west of Salt Lake City, Utah. The facility sits at an elevation of 4,275 (ft) above mean sea level (amsl).

1.1 Purpose

On 14 February 2011, Energy*Solutions* requested concurrence from the Utah Division of Radiation Control (the Division) that previous licensing activities allowed for the receipt and disposal of blended ion-exchange resin waste on a large-scale at the Clive facility (Shrum, 2011). The Division reviewed Energy*Solutions*' analysis supporting this request and determined that Energy*Solutions* could receive blended waste up to 40,000 cubic feet per year. However, in order to receive blended waste at volumes greater than 40,000 cubic feet per year, Energy*Solutions* would be required to conduct a new performance assessment analyses that include "*prediction of nuclide concentration and peak dose (at the time peak dose would occur) using updated dose conversion factors, and a suggested model time frame of 10,000 years, as well as any need to revisit/update the waste source term, receptor and exposure pathways*" (Lundberg, 2011).

In compliance with these requirements, this Report documents a new site-specific Performance Assessment that has been conducted by Energy*Solutions*, which includes:

- Analysis of additional subsurface fate and transport of LLRW contaminants leached from the Embankment via contact with precipitation that has infiltrated through two possible embankment cover designs, and transported to a well at the point of compliance 90 feet from the outside edge of the LLRW material in the disposal cell;

- Modeling of expected groundwater well concentrations and comparison to groundwater protection levels (GWPLs) for a period of 500 years following embankment closure, and of projected peak groundwater well concentrations for each individual radionuclide for a time period of 10,000 years following embankment closure;

- Modeling of expected exposures and resulting doses to hypothetical inadvertent intruders within 1,000 years following embankment closure; and

- Evaluation of additional radionuclides that were not included in prior Class A Performance Assessments conducted in support of Clive licenses (see Table C-1 of Appendix C).

1.2 Other Associated Performance Assessments

In 2010, the Utah Radiation Control Board (the Board) promulgated a new rule (UAC R313-25-8, “Technical Analysis”) that required Energy*Solutions* to conduct a site-specific Performance Assessment before disposing of large volumes of depleted uranium (URCB, 2010). In compliance with the Board’s directive, Energy*Solutions* submitted a new depleted uranium site-specific Performance Assessment to the Division, based upon the GoldSim Platform (McCandless, 2011). The depleted uranium Performance Assessment evaluated quantitative doses to 10,000 years and qualitative effects out to geologic time frames to account for the far-future uranium chain in-growth influences. This Report’s site-specific Performance Assessment does not project the fate and transport through geologic time periods nor does it replace the depleted uranium Performance Assessment.

In 2012, Energy*Solutions* requested that the Division amend Radioactive Material License # UT 2300249 and Ground Water Quality Discharge Permit No. UGW450005 to combine the Class A and Class A North disposal embankments into one embankment (termed *Class A West*), (McCandless, 2012). To support this request, Energy*Solutions* utilized the same PATHRAE, UNSAT-H, and HELP methodology that was employed for previous Clive embankment licensing efforts, updating it to reflect the new Class A West geometry. Potential groundwater impacts from the Embankment with a traditional rock-armored cover system were similarly evaluated using the methodology consistent with previous groundwater models performed for other Clive facility embankments (Whetstone, 2011). While the site-specific Performance Assessment described herein is consistent with and supports the assessment conducted in justification for the embankment combination request, it has been prepared to address the disposal of blended resin volumes in excess of 40,000 ft^3.

1.3 Blended Ion-Exchange Resins

Spent resins from ion-exchange systems at nuclear power plants are low-level radioactive waste and require disposal at a licensed facility. Energy*Solutions* proposes to use the THermal Organic Reduction (THOR) process to blend low-activity resins with small amounts of higher-activity resins using heat to significantly volume-reduce spent resins into a solid-phase, compact, homogeneous, chemically and environmentally stable waste form known as reformed residue. The end result of the process is a homogeneous and environmentally-stable waste.

NRC issued direction encompassing disposal of blended ion-exchange resins in the form of a Staff Requirements Memorandum (SRM), to direct the Commission’s current position be risk-informed and performance-based through a combination of rulemaking and guidance. In its analysis of the disposal of blended waste, NRC staff expressed concern that the disposal of large quantities of waste at or near the Class A limit may not have been evaluated fully in the development of the initial regulations for the disposal of LLRW in 10 CFR 61. However, the staff acknowledged that actual disposal practices for such wastes were far more robust than the disposal techniques analyzed. In particular, staff recognized that current disposal at the Clive facility includes engineered barriers and increased depths that provide significant protection for an inadvertent intruder. Specifically, staff stated in their recommendation,

> *"The staff's preliminary independent analysis indicates that current practice at . . . disposal facilities may safely accommodate an increase in the amount of disposed waste at or just below the Class A limits. Site-specific intruder analyses could be used to confirm protection of individuals from inadvertent intrusion at these sites."* (NRC, 2010).

NRC also stated its position that "*large-scale LLRW blending may be conducted when it can be demonstrated to be safe*." (NRC, 2010).

Historically, Energy*Solutions* has directly disposed of spent ion-exchange resins from utility customers and THOR-processed resins under its current license from the Division. However, to address the disposal of a blended resin waste-stream in volumes greater than 40,000 cubic feet per year, Energy*Solutions* has prepared the site-specific Performance Assessment described herein.

1.4 Regulatory Context

In the context of disposal of radioactive waste, a performance assessment is a quantitative evaluation of potential releases of radioactivity from a disposal facility into the environment, and assessment of the resultant radiological doses. Energy*Solutions* conducts performance assessments to demonstrate that the Clive Disposal Facility meets its performance objectives throughout the required period of performance.

1.4.1 UAC R313-15-401: Periods of Performance

Several periods of performance applicable to this site-specific Performance Assessment have been promulgated by the Board for disposal of Class A waste.

1. "*Licensees shall determine the peak annual total effective dose equivalent to the general public within 1,000 years after decommissioning*." [UAC R313-15-401(4)]

2. While no specific time frame has been promulgated by the Board for protection of a hypothetical inadvertent intruder, NRC guidance assesses intruder scenarios for a time period equivalent to that indicated in UAC R313-15-401(4), (e.g., 1,000 years after facility closure), (NRC, 1986). An inadvertent intruder time frame of 1,000 years is further supported by the precedent time periods required by 10 CFR 20, Subpart E (for decommissioned sites), 10 CFR 40, Appendix A (for uranium mill tailings), and DOE Order 435.1. [UAC R313-25-20]

3. In addition to these radiological criteria, the Division also imposes limits on groundwater contamination, as stated in the Ground Water Quality Discharge Permit, derived from Ground Water Quality Standards listed in UAC R317-6-2. However, because UAC R317-6-3 classifies Clive's groundwater as Class IV, "saline ground water," well concentrations are compared to groundwater protection limits as "non degradation standards." Because of this, the limitation of this comparison is of concentration (not dose) for a period of 500 years following embankment closure, and of projected peak groundwater well concentrations for each individual radionuclide for a time period of 10,000 years following embankment closure. [UAC R317-6]

1.4.2 UAC R313-25: Performance Objectives

NUREG-1573 has been developed as a key NRC guidance document for conducting performance assessments (NRC, 2000), with more recent guidance contained in NUREG-1854, (NRC, 2007). The guidance NRC has issued to assist applicants and licensees in applying standards were incorporated in the execution of this site-specific Performance Assessment. This Performance Assessment demonstrates compliance with the performance objectives described below.

1.4.2.1 *UAC R313-25-19: Protection of the General Public*

The key endpoints of this site-specific Performance Assessment are estimated future potential doses to members of the public. The performance objectives specified in UAC R313-25-19 are the following:

> *"Concentrations of radioactive material which may be released to the general environment in ground water, surface water, air, soil, plants or animals shall not result in an annual dose exceeding an equivalent of 25 mrem to the whole body, 75 mrem to the thyroid, and 25 mrem to any other organ of any member of the public. No greater than 4 mrem committed effective dose equivalent or total effective dose equivalent to any member of the public shall come from groundwater. Reasonable efforts should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable, (ALARA)."*

However, the approach to dose assessment suggested by UAC R313-25-19 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). The Board's performance objective for protection of the general public set forth in UAC R313-25-19 is based on the 1959 standards of International Commission on Radiological Protection (ICRP) Publication 2 methodology, while UAC R313-15 rules are based on newer ICRP guidance in Publications 26 and 30. Part 20 uses the total effective dose equivalent (TEDE) rather than the whole body dose. NRC has recognized the inconsistency between the dose methodologies and has issued guidance to allow the use of newer guidance. This approach was taken for Yucca Mountain in 10 CFR Part 63, NUREG-1854 and NUREG-1573, and in the NRC Decommissioning Criteria for West Valley. As noted in NUREG-1573:

> *"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)."* (NRC, 1999, 64 FR 8644; see Footnote 1).

As such, this Performance Assessment does not consider organ doses individually because the low value of the total effective dose equivalent ensures that no organ dose will exceed the promulgated limitations. For internal uniformity, this Performance Assessment is consistent with the methodology approved by the NRC in Part 20 for comparison with the performance objective.

1.4.2.2 *UAC R313-25-20: Protection of the Inadvertent Intruder*

UAC R313-25-20 requires assurance of protecting individuals from the consequences of inadvertent intrusion into disposed waste. An inadvertent intruder is someone who is exposed to waste unintentionally and without realizing it is there (after loss of institutional control). This is distinct from an 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.

> *"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."* [UAC R313-25-20]

Another important term to define in evaluation of this Performance Objective is an intruder barrier:

> *"A sufficient depth of cover over the waste that inhibits contact with waste and helps to ensure that radiation exposure to an inadvertent intruder will meet the performance objectives set forth in this part, or engineered structures that provide equivalent protection to the inadvertent intruder."* [UAC R313-25-2]

Energy*Solutions* licensed the Clive Containerized Waste (CWF) disposal design to manage radioactive waste shipments with activity concentrations nearer to the Class A limit (but with relatively low volumes) in contrast to the waste typically disposed at Clive (higher volumes of low activity waste). Because the CWF disposal design is based on disposal practices for wastes above the Class A classification, it inherently provides barriers prerequisite for protection of an inadvertent intruder and is an ideal location for disposal of blended resins. Currently, typical resin wastes are disposed in either plastic or metal liner (high integrity container) and placed in the center of the disposal embankment. This disposal methodology exceeds the intruder barrier requirements of UAC R313-25 in the following ways.

- Resin liners are placed in either the first or second layer of the CWF. The containers are placed in a honeycomb pattern of concrete silos and backfilled with sand. At some interior locations in the CWF, the containers are placed in a temporary steel silo. The silo is used to administratively ensure the honeycomb spacing pattern, including minimum distances between adjacent containers, is achieved. After the steel silo is removed, voids around the containers are filled with the sand backfill. Once a specific area of containerized disposal is filled, additional compacted layers of sand and clay are placed above the container to complete and close the specific area.

- An engineered facility is an important component in intruder protection. Reliance on engineered features is based on the assumption that an intruder encountering the barrier would recognize it as something out of the ordinary and cease attempts at construction or agriculture (thereby reducing their exposure to radiation). The combination of the liner and CWF structure protects an intruder from penetrating the site and contacting the waste (which is in excess of the UAC R313-25's Class A requirements).

- The design and operation of the CWF provides more stable disposal than is required by UAC R313-25 for Class A waste. The placement of containerized waste, the sand backfill, the compacted sand, and clay above the containers, the placement and compaction of bulk waste above the layers of containerized waste, and the cover combine to form a stable disposal configuration. The CWF design provides stability to ensure the long-term compaction combine to resist slumping and differential settlement, which limits infiltration and reduces the potential for dispersion of the waste over time. In addition to improving the performance of the disposal site, this provides inherent protection for the inadvertent intruder, since it provides a "recognizable and nondispersible waste" as contemplated in UAC R313-15-1009.

- Energy*Solutions*' Class A license requires that containers are placed in either the first or second layer of the CWF and covered with multiple layers of compacted waste. The result is that even the top layer of ion-exchange resin waste is a minimum of 5 meters below the cover, which would be sufficient to satisfy disposal requirements for waste classified above Class A. The 5 meter thick barrier also inhibits access by an inadvertent intruder. This barrier is composed of earth, lower activity waste, and other similar materials.

The performance standard for protection of individuals from inadvertent intrusion (UACR313-25-20) requires "*…protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste.*" However, these regulations are silent on the specific dose standard to apply. Since UAC R313-25 has been issued, the standard used by NRC (and included in the pending revisions to 10 CFR 61 and associated Branch Technical Position analysis) and others for low-level radioactive waste disposal licensing has been an intruder standard of 500 mrem/yr. The 500 mrem/yr standard is also used in DOE's waste determinations implementing the 10 CFR 61 performance objectives (NUREG-1854). It is noted that 500 mrem/yr was also the standard proposed in 10 CFR 61 in 1981 (46 FR 38081, July 24, 1981). The Statement of Considerations for the final rule did not object to the number. It was removed apparently at the request of EPA, because of its concern of how one would monitor it or demonstrate compliance with it, but not because EPA disagreed with it (47 FR57446, 57449, December 27, 1982). A dose standard of 500 mrem/yr is also used as part of the license termination rule dose standard for intruders (10 CFR 20.1403). Consequently, this site-specific Performance Assessment uses a 500 mrem/yr threshold for the intruder dose for purposes of applying the performance standard for protection of individuals from inadvertent intrusion.

Although 10 CFR 61.42 requires that an inadvertent intruder be protected, NRC staff acknowledged that licensees are not expected to perform intruder dose analyses because the waste classification itself and segregation requirements found in 10 CFR 61.13(b) were developed to protect an inadvertent intruder, (NRC, 2000). Even so, the purpose of completing this site-specific Performance Assessment is in accommodation of a Board directive to demonstrate that public health and safety (including inadvertent intruders) is protected to prescribed limits, with an acceptable "reasonable assurance." As is further explained in Appendix A, regulatory bounding and contextual application of "reasonable assurance" are therefore paramount in the selection of "reasonable" inadvertent intruder scenarios for this Performance Assessment (e.g., an inadvertent intruder-driller).

1.4.2.3 *UAC R313-25-21: Protection of Individuals During Operations*

UAC R313-25-21 states that "*Operations at the land disposal facility shall be conducted in compliance with the standards for radiation protection set out in R313-15 of these rules, except for release of radioactivity in effluents from the land disposal facility, which shall be governed by R313-25-19.*" Historical records submitted annually to the Division demonstrate that Energy*Solutions'* existing operations have impacts that are maintained by administrative controls within the applicable regulatory limits. Furthermore, personnel and environmental monitoring data confirm that the applicable limits are met on a continuing basis. Since there is no change being proposed as part of this site-specific Performance Assessment in the types of waste or necessary administrative controls that will be managed, protection of individuals during operations will continue.

UAC R313-25-21 also states that "*every reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable, ALARA.*" The Clive Radiation Protection Program ensures that all reasonable actions are taken to reduce radiation exposures and effluent concentrations to levels that are considered, "As Low As Reasonably Achievable" (ALARA). Since there are no changes being proposed in the waste types and classifications that are being disposed of in the Embankment, the current ALARA Program will not require revision as part of this site-specific Performance Assessment.

1.4.2.4 *UAC R313-25-22: Stability of the Disposal Site After Closure*

To help achieve stability, NRC notes that to the extent practicable the waste should maintain gross physical properties and identity over 300 years, under the conditions of disposal. NRC believes that the use of design features to achieve stability is consistent with the concept of ALARA and the use of the best available technology. It is NRC's view that to the extent practicable, waste forms or containers should be designed to be stable (i.e., maintain gross physical properties and identity, over 300 years). NRC also notes that a site should be evaluated for at least a 500-year time frame to address the potential impacts of natural events or phenomena.

Consequently, Energy*Solutions* has implemented a disposal site and cover designs that provides reasonable assurance that long-term stability will be achieved and that the use of the best available technology in setting design standards in the range from 200 up to 1,000 years is appropriate to provide site stability to the extent practicable. Because the longevity of the cover designs demonstrate protection, this new site-specific Performance Assessment does not trigger the need to conduct additional stability analysis.

1.4.2.5 *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 (Energy*Solutions*, 2010). Part I.C.1 of the Permit specifies that GWPLs shall be used for the Embankment. The Permit specifies general mass and radioactivity concentrations for several constituents of interest to Class A 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.

It is important to 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. 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. Analysis conducted by the World Health Organization in 2003 suggested associations between TDS concentrations in drinking water and the incidence of cancer, coronary heart disease, arteriosclerotic heart disease, cardiovascular disease, and total mortality rates in studies conducted in Australia and the former Soviet Union (WHO, 2003). In the study in Australia, it was determined that mortality from all categories of ischaemic heart disease and acute myocardial infarction was increased in a community with high levels of soluble solids, calcium, magnesium, sulfate, chloride, fluoride, alkalinity, total hardness, and pH when compared with one in which levels were lower. Similarly, the results of an epidemiological study in the former Soviet Union indicated that the average number of cases of inflammation of the gallbladder and gallstones over a 5-year period increased with the mean level of dry residue in the groundwater.

Since the background water quality of the groundwater renders it unsafe for human consumption, groundwater protection standards are applied at the Clive site as a non-degradation, or Best Available Technology (BAT), standard. No dose is possible through the groundwater pathway, since its consumption is impossible without extensive treatment. The BAT standards for groundwater do not provide any additional protection in terms of human health.

This site-specific Performance Assessment calculates estimates of groundwater concentrations at a virtual point of compliance well near the Embankment for comparison with these GWPLs. The period of compliance for GWPLs, consistent with the established licensing basis for the Clive facility and with BAT, is 500 years. Even though groundwater concentrations beyond 500 years are calculated to inform the site-specific Performance Assessment, it is recognized that no dose can be realized from the groundwater pathway based on the background water quality.

1.5 Report Scope

This Report documents the site-specific Performance Assessment, conducted in compliance with UAC R313-25-8. Analysis includes evaluation of potential groundwater migration of contaminants to a Point of Compliance well for a period of 500 years following embankment closure, projected peak groundwater well concentrations for a period up to 10,000 years following embankment closure, doses to reasonable hypothetical individuals who have inadvertently intruded into the waste within 1,000 years following embankment closure, and an expanded source term of isotopes not considered in previous site-specific performance assessments.

This Report describes the methodology for achieving these objectives and the results of the analyses, including:

- Developing a long-term climate record representative of the site;
- Representation of near-surface processes that affect net infiltration, such as evaporation, runoff, and plant water uptake;
- Representation of movement of water through the cover layers, waste, and liner;
- Release of radionuclides and transport through the vadose zone to the saturated zone;
- Transport of radionuclides in the saturated zone to the point of compliance;
- Evaluation of groundwater concentrations over time at the point of compliance; and
- Evaluation of radiation dose for hypothetical inadvertent human intruder scenarios occurring upon the disposal embankment.

The results of the site-specific Performance Assessment include:

- A description of the calculations and basis for the estimate of a steady-state infiltration rate applied in the transport model;
- A description of the transport model used to calculate groundwater concentrations over time;
- Identification of groundwater concentrations at the time of highest concentrations within 10,000 years, and comparison of groundwater concentrations within 500 years of site closure to groundwater protection limits; and
- Evaluation of dose for hypothetical inadvertent intruder scenarios within 1,000 years of embankment closure.

2. SITE-SPECIFIC PERFORMANCE ASSESSMENT COMPONENTS

This site-specific Performance Assessment includes analysis of the influences of alternative evapotranspirative cover designs on subsurface contaminant transport, modeling of expected exposures and resulting doses to hypothetically-viable inadvertent intruders, and evaluation of additional radionuclides not included in previous site-specific Performance Assessments. Components of this new site-specific Performance Assessment include a current long-term climate record representative of the Clive site; improved representation of near-surface processes that affect net infiltration, such as evaporation, runoff, and plant water uptake; representation of movement of water through improved evapotranspirative cover designs; and evaluation of radiation dose for hypothetical inadvertent human intruder scenarios occurring following the disposal embankment closure.

2.1 Site Characteristics

Energy*Solutions* low-level radioactive waste disposal facility is located west of the Cedar Mountains in Clive, Utah. Clive is located along Interstate-80, approximately 3 miles south of the highway, in Tooele County. The facility is approximately 50 air-miles east of Wendover, Utah and approximately 80 miles west of Salt Lake City, Utah. The facility sits at an elevation of approximately 4,275 feet above mean sea level (amsl) and is accessed by both highway and rail transportation. The Clive facility is adjacent to DOE's above-ground disposal embankment used for disposal of uranium mill tailings that were removed from the former Vitro Chemical company site in South Salt Lake City between 1984 and 1988.

Currently, the Clive facility receives waste shipped via truck and rail. Class A low-level radioactive waste is disposed in a permanent near surface engineered disposal embankment that is clay-lined with a proposed composite engineered cover. The disposal embankment is designed to perform for a minimum of 500 years based on requirements of 10 CFR 61.7(a)(2), which provides a long-term disposal with minimal need for active maintenance after site closure.

2.1.1 Climate

Energy*Solutions* has operated a weather station at Clive since July 1992. The station monitors wind speed and direction, 2-m and 10-m temperatures, precipitation, pan evaporation and solar radiation. A 19-year Summary Report from January 1, 1993 through December 31, 2011, provided to the Division on February 23, 2012, has been incorporated into this new site-specific Performance Assessment (MSI, 2012). Since the Embankment is located entirely within Section 32, this information adequately characterizes the site. Furthermore, the Embankment has no significant effects upon the meteorological conditions or air quality of the region.

2.1.2 Weather Patterns

The Clive region is in the Intermountain Plateau climatic zone that extends between the Cascade-Sierra Nevada Ranges and the Rocky Mountains and is classified as a middle-latitude dry climate or steppe. Hot dry summers, cool springs and falls, moderately cold winters, and a general year-round lack of precipitation characterize the climate. Mountain ranges tend to restrict the movement of weather systems into the area, but it is occasionally affected by well-developed storms in the prevailing regional westerlies. The mountains act as a barrier to frequent invasions of cold continental air. Precipitation is generally light during the summer and early fall and reaches a maximum in spring when storms from the Pacific Ocean are strong enough to move over the mountains. During the late fall and winter months, high pressure systems tend to settle in the area for as long as several weeks at a time.

2.1.3 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). Frequent invasions of cold air are restricted by the mountain ranges in the area. Data from the Clive facility from 1992 through 2011 indicate that monthly temperatures range from about -2°C (29°F) in December to 26°C (78°F) in July (MSI, 2012).

2.1.4 Winds

In the 19-year period of time (July 1993 through December 2011) the most frequent (and predominant) winds were from the south-southwest direction, with the second most frequent direction being the east-northeast, followed by the south. Wind Rose data incorporated into this new site-specific Performance Assessment has been obtained from the on-site weather station and checked for accuracy by a certified meteorologist (MSI, 2012).

2.1.5 Precipitation

The Clive site receives an average of 8.62 inches of precipitation per year. Measurements taken at the Clive site showed that the lowest monthly precipitation recorded was 0 inches in May 2001. The highest recorded monthly precipitation was 4.28 inches, in May 2011 (MSI, 2012).

2.1.6 Evaporation

Pan evaporation measurements are taken from April through October when ambient temperatures remain above freezing. Maximum hourly evaporation values usually occur in July. The 17-year average annual evaporation at the Clive site is 52.73 inches (excluding 2 years of reported instrument malfunction) (MSI, 2012).

2.1.7 Geology

The Energy*Solutions* Clive site is located on the eastern fringe of the Great Salt Lake Desert. The Energy*Solutions* site is located in, and is bounded by, the Great Salt Lake Desert to the west at approximate elevations of 4,250 to 4,300 feet amsl. Also to the west, low-lying hills rise 50 to 100 feet from the desert floor. To the east and southeast, the site is bounded by the north-south trending Lone Mountains, which rise to a height of 5,362 feet amsl. At the base of the Lone Mountains alluvial fans slope gently toward the west at a gradient of approximately 40 feet per mile. The site has topographic relief of approximately 11 feet, sloping in a southwest direction at a gradient of approximately 0.0019. The most recent characterization of the site geology and hydrogeology is reported in the Revised Hydrogeologic Report prepared by Energy*Solutions* in August, 2004 (Envirocare, 2004).

The Clive site rests on Quaternary lakebed deposits of Lake Bonneville. Site subsurface logs indicate that lacustrine deposits extend to at least 500 feet underneath the site. The underlying Tertiary and Quaternary age valley fill is composed of semi-consolidated clays, sands, and gravel where it comes in contact with bedrock. Although the exact depth to and relationships of various bedrock units are unknown, the presence of nearby outcrops and the regional block-faulted basins suggest that the valley-fill deposits are several hundred feet thick within the area of the site. Estimated down-dip projections from bedrock outcrop on the southwest corner of Section 31 and bedrock found at depth in Clean Harbors wells suggest that the contact may dip to the east about three degrees.

To the north of the site are the Grayback Hills, composed of limestone and quartzite mapped as Permian-Pennsylvanian Oquirrh Formation, which is as much as 10,000 feet thick in western Utah. Igneous extrusives form a resistant cover on the Grayback Hills, and are mapped as Pliocene-age basalt/rhyolite.

Geomorphic processes at the site are limited to micro processes that occur in the soil. For example the Great Salt Lake Desert is located in a semiarid to arid region where precipitation is less than evaporation. When the soil water evaporates, dissolved mineral matter is precipitated and forms calcium carbonate, gypsum and alkali (sodium and potassium carbonates) in the soil. Macro geomorphic processes are almost nonexistent where the general rate of weathering is very slow. This is due to the low amounts of precipitation, the lack of fluvial activities and the lack of relief at the site.

2.1.8 Hydrology

Alluvial and lacustrine sediments that fill the valley floor are estimated to extend to depths of greater than 500 feet with unconsolidated sediments ranging from 300 to over 500 feet. North-south trending mountains and outcrops define the hydrogeologic boundaries for the aquifer system. Lone Mountain located two miles east of the site, rises approximately 950 feet above the valley floor. The Grayback Hills located to the north and outcropping features to the west rise 500 feet and 230 feet respectively above the valley floor (Envirocare, 2004).

Four hydrostratigraphic units have been delineated in the unsaturated zone and shallow aquifer system at the Clive Facility, consisting of upper silty clay/clayey silt (Unit 4), upper silty sand (Unit 3), middle silty clay (Unit 2), and lower sand/silty sand (Unit 1). The site aquifer system consists of a shallow unconfined aquifer that extends through the upper 40 feet of lacustrine deposits. A confined aquifer begins around 40 to 45 feet below the ground surface and continues through the valley fill. Due to the low precipitation and relatively high evapotranspiration, little or no precipitation reaches the upper unconfined aquifer as direct vertical infiltration. Groundwater recharge is primarily due to infiltration at bedrock and alluvial fan deposits which then travels laterally and vertically through the unconfined and confined aquifers. Groundwater flow in this area is generally directed north to northeasterly.

Fresh water from the recharge zones along the mountain slopes develops progressively poorer chemical quality in response to dissolution of evaporate-minerals during its travel through the regional-scale flow systems. The groundwater quality in the unconfined aquifer at the Clive Facility is considered saline with concentrations of several chemical species (sulfate, chloride, total dissolved solids, iron, and manganese) significantly exceeding the EPA secondary drinking water standards.

2.1.9 Surface Water

The area containing the Clive facility lies within the Great Basin drainage, a closed basin having no outlet. The site drains into the normally-dry Ripple Valley depression on the eastern fringe of the Great Salt Lake Desert.

The nearest usable body of water east of the Clive site is 28.1 miles away. At this location, a perennial stream flows from Big Spring (1,000 feet south of I-80) to the Timpie Springs Waterfowl Management Area, about 2,000 feet north of I-80. Activities at the Energy*Solutions* Clive Facility have no effect on surface-water quantities or quality at the Clive site. There are no perennial surface-water systems associated with the Clive site. Water necessary for construction is provided by existing wells in the vicinity requiring transport to the site, or impounded water.

No surface water bodies are present on the Clive site. The nearest stream channel ends about two miles east of the site and is typical of all drainages along the transportation corridors within 20 miles of the site. Stream flows from higher elevations evaporate and infiltrate into the ground before reaching lower, flatter land. The stream channel reduces until there is no evidence of a stream. The watershed up-gradient of the site covers approximately 46 square miles.

2.1.10 Groundwater

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 is expected that some unsaturated zone (vadose zone) groundwater may actually moves 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 20 and 30 feet bgs at an approximate elevation of 4,250 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. Occasional transient shallow aquifer mounding occurs due to infiltration of surface water.

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). Groundwater beneath the Clive site ranges in total dissolved solids (TDS) from 30,000 mg/L to 100,000 mg/L, with a site-wide average TDS content of 40,500 mg/L. 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, thus the salinity content at the site is higher than average sea water.

2.1.11 Ecology

Ecological exploratory field studies were recently conducted in 2012 to quantify biogeography, quantify bioturbation, and biological communities near the Clive site assess local ecological analogs (SWCA, 2012). These studies observed average plant species cover consist of 14.3% black greasewood, 5.9% Sandberg bluegrass, and approximately 3% cover each of shadscale saltbrush and gray molly occurring in low densities with 1.6% and 1.3% cover, respectively. Ground cover is dominated by 79.2% biological soil crust cover.

Field studies also included small mammal trappings, with 83 deer mice and one kangaroo rat trapped. Small mammals were observed to have concentrated in the north of the Clive facility. Borrows of deer mice, kangaroo rats, ground squirrels, and badgers were also observed during the field studies.

Nineteen ant mounds were recorded and measured, with an average of 24 ant mounds observed per hectare. The average individual ant mound area estimate was approximately 2,683 cm^2 and 28,348 cm^3, respectively. The belowground area of the excavated ant mounds was found to be sparsely distributed, with most of the ant nests within 0.6 meters of the surface.

Analyses of plant species cover, small mammal densities, animal burrow volumes, ant mound volumes, and soil chemistry and nutrition parameters identified several relationships between the variables under consideration. Positive correlations were witnessed between total vegetation cover, mammal densities, and burrow volumes. In contrast, no correlation was observed between total vegetation cover and ant mound area or volume. There were also strong positive correlations between ant mound area, mound volume, and cover of weedy species. There was also a strong, negative correlation between ant mounds and soil silt, and somewhat strong negative correlations between animal densities, burrow volumes, and soil clay content. Field studies concluded that the high soil pH did not appear to be limiting for any of the native or weedy plant species observed. However, plant cover, particularly of shadscale saltbrush, showed strong, negative correlations with high soil salinity.

In support of the evapotranspirative cover designs under consideration, the field studies pointed to several key design features for the Clive site:

- The plant species selected for the evapotranspirative cover system should consist of native and desirable non-native, salt tolerant shrubs and grasses.

- Although a vegetation community of sufficient diversity and density is desired to maximize transpiration from the soil, vegetation density was positively correlated with small mammal and burrowing activity. As such, bioturbation should be expected to increase with increasing vegetation. Furthermore, the presence of badgers and a large family of burrowing owls indicates that the biota can potentially move large volumes of soil. Because of this, the bank-run borrow material layer has been included in both of the evapotranspirative cover designs as a bio-intrusion and bioturbation barrier (also serving to minimize the penetration by ants through the cover layers).

- Soil conditions on and near the Clive site are typical of soils formed in arid environments. Soils were mostly silty clay loams with elevated pH, elevated salinity, and low organic matter.

SWCA also examined the root density and maximum rooting depth of dominant plant species on the Clive Facility. Observed root densities were higher near the surface of the soil, where roots were mostly fibrous with few woody structures. A few large, woody roots were encountered in deeper soils. Rooting depths were shallower than expected, with the maximum rooting depth of dominant woody plant species ranging from 16 to 28 inches. Woody plant species maximum rooting depths were proportional to aboveground plant mass with an above-ground height root depth ratio of 1:1 and an above-ground width root depth ratio of approximately 1.4:1. The halogeton-disturbed plot had higher ratios of plant height and width to maximum rooting depth (1.4:1 and 1.7:1, respectively). The low proportion of roots to above-ground biomass is expected for annual plants, which invest the bulk of their energy in reproduction and little energy in root systems.

2.2 Embankment Cover Designs

Principle design features of the embankment provide long-term isolation of disposed waste, minimize the need for continued active maintenance after site closure, and improve the site's natural characteristics in order to protect public health and safety. The environment, site personnel, and the public are protected both during and after active disposal operations from unsafe levels of radiation. Long-term stabilization of the Embankment is accomplished through erosion control and flood protection. The controlled areas of the Embankment are fenced both during construction and after operation to prevent public access. Additionally, Embankment custodial maintenance and surveillance are performed to assure continued long-term compliance with applicable regulatory standards.

The Embankment cover design is a critical component in the isolation of waste from the leaching potential of infiltration. DOE's Vitro Embankment and Energy*Solutions*' LARW Embankment use a traditional rock armor cover design as a percolation barrier. However, as part of this updated Performance Assessment, the Division requested EnergySolutions evaluate alternative cover designs that more efficiently maximize the amount of time that precipitation is available for evapotranspiration within the alternative cover designs. These cover designs, combined with the natural climate system (with ten times the evaporation potential as annual precipitation), ensure that infiltration to the waste is minimized.

2.2.1 COVER DESIGN 1: Traditional Rock Armor

A rock armored cover is the design used at Clive's LARW embankment and DOE's neighboring Vitro embankment. It was also included in the initial design approved for the Class A West combined Embankment. In the rock armor cover design, the top slope consists of the following, from top to bottom:

- **Rip Rap cobbles**. Approximately 24 inches of Type-B rip rap will be placed on the top slopes, above the upper (Type-A) filter zone. The Type-B rip rap used on the top slopes ranges in size from 0.75 to 4.5 inches with a nominal diameter of approximately 1.25 to 2 inches. Engineering specifications indicate that not more than 50% of the Type B rip rap would pass a 1 1/4-inch sieve.

- **Filter Zone (Upper)**. Six inches of Type-A filter material, will be placed above the sacrificial soil in the top slope cover. The Type-A filter material ranges in size from 0.08 to 6.0 inches, with 100% passing a 6-inch sieve, 70% passing a 3-inch sieve, and not more than 10% passing a no. 10 sieve (0.079 inch). The Type-A size gradation corresponds to a poorly sorted mixture of coarse sand to coarse gravel and cobble, according to the Universal Soil Classification System.

- **Sacrificial Soil (Frost Protection Layer)**. A 12-inch layer consisting of a mixture of silty sand and gravel will be placed above the lower filter zone to protect the lower layers of the cover from freeze/thaw effects. The sacrificial soil material ranges in size from <0.003 to 0.75 inches, with 100% passing a 3/4-inch sieve, 50.2% passing a no. 8 sieve (0.093 inch), and 7.6% passing a no. 200 sieve (0.003 inch).

- **Filter Zone (Lower)**. Six inches of Type-B filter material will be placed above the radon barrier in the top slope cover. This filter material ranges in size from 0.2 to 1.5 inches, with 100% passing a 1 1/2- inch sieve, 24.5% passing a 3/4-inch sieve, and 0.4% passing a no. 4 sieve (0.187 inch). The Type-B size gradation corresponds to a coarse sand and fine gravel mix, according to the Universal Soil Classification System.

- **Radon Barrier**. The top slope cover design contains an upper radon barrier consisting of 12 inches of compacted clay with a maximum hydraulic conductivity of 5×10^{-8} cm/sec and a lower radon barrier consisting of 12 inches of compacted clay with a hydraulic conductivity of 1×10^{-6} cm/sec or less.

The design for the traditional rock armored side slope cover is different, but similar to the top slope, (except for the thickness of the waste layer and the material used in the rip rap layer). The layers used in the Embankment side slope cover consist of the following, from bottom to top:

- **Rip Rap cobbles**. Approximately 24-inches of Type-A rip rap will be placed on the side slopes above the Type-A filter zone. The Type-A rip rap ranges in size from 2 to 16 inches (equivalent to coarse gravel to boulders) with a nominal diameter of 12 inches. Engineering specifications indicate that 100% of the Type-A rip rap would pass a 16-inch screen and not more than 50% would pass a 4 1/2- inch screen.

- **Filter Zone (Upper)**. (Same design as top slope.)

- **Frost Protection Layer (Sacrificial Soil)**. (Same design as top slope.)

- **Filter Zone (Lower)**. The thickness of the Type B filter in the side slope will be 18 inches. The Type B filter material in the side slope will have the same size specifications as the top slope.

- **Radon Barrier**. (Same design as top slope.)

2.2.2 COVER DESIGN 2: Evapotranspirative Cover Design A

Evapotranspirative covers are increasingly being employed as alternative cover designs for municipal solid waste and hazardous waste sites in arid and semiarid climates. Unlike conventional rock armor cover systems, which use materials with low permeability to limit movement of water into waste, evapotranspirative cover systems minimize water percolation by storing and releasing water through evaporation from the soil surface and through transpiration from vegetation. The primary objective of evapotranspirative cover systems is to use the water balance components of soil and vegetation to hold precipitation and release it through soil surface evaporation or transpiration without allowing water percolation into waste layers.

The use of evapotranspirative cover designs is relatively new. Since the amendment of the Resource Conservation and Recovery Act Subtitle D (40 CFR 258.60) in March 2004, evapotranspirative cover systems and demonstration sites have been installed at hazardous and radioactive waste disposal facilities in the arid west, including Hill Air Force Base (Utah), Monticello Mill Tailings (Utah), Los Alamos National Laboratory (New Mexico), Sandia National Laboratories (New Mexico), Sierra Blanca (Texas), Rocky Mountain Arsenal (Colorado), and the Hanford Site (Washington) (Rock et.al, 2012). In addition to these facilities, evapotranspirative cover systems have been proposed for the U.S. Ecology Nevada Site (Nevada), the Molycorp Tailings Facility (New Mexico), and Clean Harbors (Utah).

The arrangement of the layers used for the Evapotranspirative Cover Design A are (beginning at the top of the cover):

- **Surface layer**. This layer is composed of native vegetated Unit 4 material with 15% gravel mixture. This layer is 6 inches thick. The functions of this layer are to control runoff, minimize erosion, and maximize water loss from evapotranspiration. This layer of silty clay used in both evapotranspirative designs provides storage for water accumulating from precipitation events, enhances losses due to evaporation, and provides a rooting zone for plants that will further decrease the water available for downward movement.

- **Evaporative Zone layer**. This layer is composed of Unit 4 material. The thickness of this layer is varied in the Performance Assessment from 6 inches to 18 inches, to evaluate the influence of additional thickness on the water flow into the waste layer. The purpose of this layer to provide additional storage for precipitation and additional depth for plant rooting zone to maximize evapotranspiration.

- **Frost Protection Layer**. This material ranges in size from 16 inches to clay size particles. This layer is 18 inches thick. The purpose of this layer is to protect layers below from freeze/thaw cycles, wetting/drying cycles, and inhibit plant, animal, or human intrusion.

- **Upper Radon Barrier**. This layer consists of 12 inches of compacted clay with a low hydraulic conductivity. This layer has the lowest conductivity of any layer in the cover system. This is a barrier layer that reduces the downward movement of water to the waste and the upward movement of gas out of the disposal cell.

- **Lower Radon Barrier**. This layer consists of 12 inches of compacted clay with a low hydraulic conductivity. This is a barrier layer placed directly above the waste that reduces the downward movement of water.

2.2.3 COVER DESIGN 3: Evapotranspirative Cover Design B

The only difference between Evapotranspirative Cover Designs A and B is the placement of a filter zone between the frost protection layer and the upper radon barrier. Six inches of Type-B filter material is placed below the frost protection material layer in Evapotranspirative Cover Design B. The filter material ranges in size from 0.2 to 1.5 inches. The Type-B size gradation corresponds to a coarse sand and fine gravel mix. This high conductivity layer is placed on the upper radon barrier which has the lowest conductivity of any layer in the cover system. The function of this coarse-to-fine interface is to collect water that has drained vertically from the layers above and direct it laterally to a surface drainage system.

2.3 Source Term

This Performance Assessment evaluates the 260 isotopes. The waste concentrations for each radionuclide were initially developed in 2000 from data supplied by the Manifest Information Management System (MIMS), a database managed by the Department of Energy (DOE) that summarizes national low-level radioactive waste disposal information. The list of radionuclides established from the MIMS database was then classified by R313-15-1009 and their respective maximum Class A concentrations determined. Those nuclides classified as Class A according to Tables I or II of UAC R313-15-1009 (or classified according to UAC R313-15-1009(2)(f) are listed in Table C-2 of Appendix C. Concentration limits for radionuclides not listed on Table I or Table II of R313-15-1009 are set at their respective specific activities (see Table C-3 of Appendix C).

2.3.1 Partitioning Coefficients (K_d)

The partitioning coefficient is the equilibrium ratio of the adsorbed contaminant concentration in soil or waste (mg/kg) to the concentration in the pore water or leachate (mg/l). Higher K_d values indicate that the specific radionuclide is more likely to partition to the soil and less likely to be released into groundwater. The K_d values used in the Performance Assessment have evolved over time, as radionuclide inventories changed and more information was obtained from the literature and from site-specific K_d testing. The modeling performed in this site-specific Performance Assessment incorporates the current approved K_d values for the site. The modeling preferentially uses

- Approved site-specific K_d values;
- The lowest measured soil K_d values published in the literature; and
- Published K_d values calculated from the soil:plant ratio.

Approved site-specific K_d values were available for Cs, Co, C-14, I-129, Np-237, Tc-99, U and Zn. The most conservative (lowest) K_d values found in the literature were used for nuclides that did not have site-specific K_d values. The soil:plant ratio was only used where actual measured soil K_d values are not available, and the published K_d value from the soil:plant ratio was decreased by two orders of magnitude to be conservative. The radionuclide K_d values used in this site-specific Performance Assessment are listed in Table C-4 of Appendix C.

2.3.2 Fractional Release Rate

The new site-specific Performance Assessment treats the embankment contaminated zone as a single homogeneous source of changing thickness and radionuclide concentrations as the result of leaching, erosion, and in-growth and decay. Erosion or human activities result in redistribution of the contaminated soil that, in turn, creates new contaminated zones.

As natural precipitation infiltrates through the cover and into the contaminated zone, radionuclides are leached from the waste and transported through the unsaturated (vadose) zone and saturated zone (aquifer) to a down-gradient point of compliance. Fractional releases of contamination from the embankment into the groundwater pathway are characterized by a water/soil concentration ratio for each radionuclide, which is defined as the ratio of the radionuclide concentration in the water to the radionuclide concentration in the contaminated zone.

2.3.3 Waste Containers

While they provide enhanced intruder barriers, no other waste isolation due to containerization is considered in the Performance Assessment. The Performance Assessment model considers the time required for the water to percolate through the cover. Although the initial waste moisture contents cannot be known with certainty, due to the inherent variability in the waste and in climatic conditions while the embankment is open, previous open-cell modeling suggests that drying of the waste occurs and that the moisture content in the waste at the time of cell closure will be well below the levels reached at eventual pseudo-steady-state.

3. ANALYSIS OF EMBANKMENT PERFORMANCE

As documented in the modeling report included in Appendix B, the two software platforms are used in this Performance Assessment include HYDRUS (Šimůnek and Šejna, 2011a; 2011b) and the RESidual RADioactivity (RESRAD) computer family, developed by Argonne National Laboratory (Yu, 2007; 2001). The HYDRUS platform was selected over the U.S. Environmental Protection Agency's Hydrologic Evaluation of Landfill Performance Model (HELP) (Schroeder et al. 1994a, 1994b) which has been used in previous site-specific Performance Assessments (including that supporting Energy*Solutions*' Class A West with rock armored cover embankment license amendment application), because of its ability to simulate complex processes known to have a significant role in water flow in landfill covers in arid regions, including water flow in variably-saturated porous media, material hydraulic property functions, atmospheric surface boundary conditions including precipitation and evapotranspiration, root water uptake, and free-drainage boundary conditions. The HYDRUS platform uses daily values of climate parameters and the properties of the proposed cover designs to provide long-term net infiltration input for the RESRAD transport platform.

The RESRAD platform is used to model in-growth, decay, and transport of radionuclides in the environment and radiation dose to potential human receptors. The RESRAD platform offers advantages over the previous Performance Assessment platform (e.g., PATHRAE), which included the risk of underestimating radionuclide migration into the aquifer due to the lack of consideration of vertical dispersion in the unsaturated zone. The RESRAD platform is also cited in DOE Order 458.1 as an example of dose assessment models that meet DOE quality assurance requirements under DOE Order 414.1C.

3.1 Protection of the General Public

Even though the assumption that a member of the general public would build a residence near the edge of the Clive site and use local groundwater for potable needs is extremely unreasonable, the site-specific Performance Assessment evaluates exposure of the general population to releases of radioactivity via the air, soil, groundwater, surface water, plant uptake, and exhumation by burrowing animals pathways (following closure and institutional control of the Embankment). The analyses identify and differentiate between the roles performed by the natural disposal site characteristics and design features in isolating and segregating the wastes. The Performance Assessment includes analyses demonstrating that the performance objectives of UAC R313-25-8(1) will continue to be met, even with the disposal of large volumes of blended ion-exchange resins. The analyses also demonstrate a reasonable assurance that the exposures to humans from the release of radioactivity will not exceed the limits set forth in UAC R313-25-19.

3.1.1 <u>Air Pathway</u>

Analyses conducted in support of the Class A West License amendment application and the 2008 Radioactive Material License renewal demonstrate that after final placement of the waste and closure of the Embankment with a rock armored cover, the facility design prevents any further migration of radioactivity through the air pathway. Analysis of the longevity of the alternate evapotranspirative cover designs, which provide equivalent isolation of waste from the atmosphere, also demonstrates that no such air-related doses are projected following closure and institutional control. Inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the general public from doses via the air pathway.

3.1.2 Soil Pathway

The design of the Embankment minimizes exposures to contaminated soil by members of the general public. After closure of the embankment, all waste is covered by a cover system designed to protect against erosion and losses of integrity due to waste settlement. Furthermore, administrative controls and design requirements have been developed to ensure that external radiation levels at the top of the final cover will be at or below background radiation for the site, so no such soil-related doses are projected. Inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the general public from doses via the soil pathway.

3.1.3 Groundwater Pathway

The primary site characteristics that prevent public exposures via the groundwater pathway are the very poor groundwater quality at the site, the low population density, arid meteorology, and the low yield of the aquifers. The groundwater is not potable because of its very high concentration of dissolved salts. This characteristic alone prevents any consumption of the water by humans or livestock. Additionally, the horizontal groundwater flow velocity is approximately 0.5 meters per year, resulting in groundwater travel times of approximately 60 years from the toe of the side slope region of the embankment to the Point-of-Compliance well. Water quality impacts associated with the components of this Performance Assessment are addressed below, within the context of protection of a natural resource degradation performance objective. The low-yield aquifers found beneath the Clive site would also limit human consumption as numerous wells would need to be installed in order to provide sustainable water for a household.

The candidate cover systems allow very little water to flow into the disposed waste. This limits the contamination of the groundwater by minimizing the contact of water with the waste. Another design feature of the disposal embankment is the bottom clay liner below the disposed waste. The clay absorbs many of the radionuclides and retards their potential release from the Embankment and subsequent transport to the water table aquifer. Inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not further compromise the already poor groundwater quality or impact the Embankment's performance and protection of the general public from doses via the groundwater pathway.

3.1.4 Surface Water Pathway

Due mainly to the natural site characteristics, there are no radioactive releases expected through the surface water pathway from non-intruder scenarios. The annual precipitation is low and the evaporation is high. No permanent surface water bodies exist in the site vicinity. In addition, the site is far from populated areas. The disposal embankment design features also minimize the potential for releases by the surface water pathway, including loss of cover integrity due to rill and gully erosion. Embankment design includes drainage ditches around the waste disposal areas. After precipitation events, these ditches divert runoff from the disposal embankment to areas away from the waste. Long-term surface water pathway doses are projected to be zero because of the absence of permanent surface water bodies at the site. Inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the general public from doses via the surface water pathway.

3.1.5 Vegetation Pathway

The plant uptake pathway is not a viable exposure pathway at the embankment because of natural site characteristics and design features of the embankment. Exposure by the plant uptake pathway could occur by (1) the production of food crops in contaminated soil at the site, and (2) root intrusion into the waste by native plants that are subsequently consumed by humans or animals. The natural site's characteristics prevent exposures via the plant uptake pathway because there is insufficient water at the site for the production of food crops. In addition, saline soils present at the site limit the number and type of plant species that can tolerate such conditions. Additionally, there are few deep-rooted native plants in the site vicinity.

Vegetation analysis developed for the previous Class A West license amendment application evaluated the redistribution of soils, and contaminants within the soil, by native flora and fauna. The biotic models are consistent with flora and fauna characteristic of Great Basin alkali flat and Great Basin desert shrub communities. In these analyses, vegetation had two primary effects on the cover system: increasing the hydraulic conductivity of the cover material and root clogging of the lateral drainage layers of the rock armor design. After final placement of the cover, releases and doses from the plant pathway are negligible, limited by the site's natural characteristics, which include low rainfall, thin plant cover, and the presence of plants that are highly efficient at removing water from the soil and transpiring the moisture back to the atmosphere.

Design features of the facility also help limit exposures via the plant uptake pathway. The candidate thick covers include capillary break, biointrusion, and bioturbation barriers that make the waste less accessible to plant roots after closure of the facility. The overall scarcity of deep-rooted plant species in the site vicinity and the configuration of the earthen cover will offer an inhospitable environment for extension of these types of roots into the waste. Inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the protection of the general public from doses via the vegetation pathway.

3.1.6 Burrowing Animal Pathway

In the arid environment of the Clive Facility, ants fill a broad ecological niche as predators, scavengers, trophobionts and granivores. Ants burrow for a variety of reasons but mostly for the procurement of shelter, the rearing of young and the storage of foodstuffs. How and where ant nests are constructed plays a role in quantifying the amount and rate of subsurface soil transport to the ground surface at the Clive site. Factors relating to the physical construction of the nests, including the size, shape, and depth of the nest, are key to quantifying excavation volumes. Factors limiting the abundance and distribution of ant nests such as the abundance and distribution of plant species, and intra-specific or inter-specific competitors, also can affect excavated soil volumes. Parameters related to ant burrowing activities include nest area, nest depth, rate of new nest additions, excavation volume, excavation rates, colony density, and colony lifespan. The site-specific Performance Assessment developed in support of the disposal of depleted uranium evaluated the impact of ant burrowing on the transport of contaminant and found no significant associated impact to the performance of the Embankment.

Other burrowing animals at the site include jackrabbits, mice, and foxes. The first deterrent to burrowing animals is the rock armor rip-rap erosion barrier and evapotranspirative bioturbation barrier. While these may be only partially effective in deterring animals, the primary protective barrier is the clay radon barrier. The burrowing species at the site are not known to dig to such a depth that their burrows could penetrate through the entire cover and into the waste. After final placement of the cover, the design features of the facility, primarily the thick soil cover that isolates the waste from burrowing animals, will control releases and doses. Because of this, the likelihood of any animals burrowing through the entire cover and exhuming waste materials is sufficiently low that it was not included in the safety assessment calculations. As such, the burrowing animal pathway is not projected to result in any exposures to humans. Additionally, inclusion of volumes of blended ion-exchange resins in excess of 40,000ft^3 annually does not compromise the Embankment's performance and protection of the general public from doses via the borrowing animal pathway.

3.1.7 Doses to the General Public

Because of the design components of the Embankment, inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the general public.

3.2 Protection of the Inadvertent Intruder

For purposes of demonstrating performance, it is important to note that occupation of the site by inadvertent intruders after site closure is not likely due to a lack of natural resources in the area, particularly a lack of potable water. As such, contacting the waste after site closure by an onsite resident is highly unlikely due to the lack of natural resources (no reason to drill or dig) and the design of the embankment cover system. Additionally, the design features and operations will minimize radiation dose to inadvertent intruders. Several design features provide the required protection. Overall features include:

- Site isolation and the resultant lack of nearby residential population;
- Embankment cover systems (rock armored rip-rap, evapotranspirative bioturbation/biointrusion); and
- Granite markers

While onsite occupation is unlikely, the impact on embankment performance of inadvertent intrusion is modeled in this site-specific Performance Assessment (e.g., drilling activities). The RESRAD platform projects annual radionuclide-specific doses related to the Intruder-Driller scenario within the assessment period of 1,000 years following embankment closure, (but not occurring within the first 100 years of institutional control – as outlined in NRC, 1981). After the institutional control period, it is assumed that inadvertent intrusion may occur at any time. Therefore, the modeling results of interest pertain to a model time period of 100 through 1,000 years. In principle, annual doses for viable intrusion scenarios are compared to an annual dose limit of 500 mrem/yr, as described in Section 5.1.1 of NRC (1981). As a result of this analysis, compliance with a performance objective of protection of an inadvertent intruder at levels well below 500 mrem/yr is clearly established for all three embankment cover configurations.

In this site-specific Performance Assessment, unit concentrations of radionuclides are evaluated to calculate ratios of dose per unit waste concentration (mrem/yr per pCi/g). Because dose is a linear function of radionuclide concentration, these ratios are then used to evaluate any proposed or actual radionuclide waste concentration to calculate scenario-specific doses as the product of the ratio and the waste concentration. Dose-to-source ratios are used for multiple model years in order to support evaluation of potential doses from varied waste receipt inventories of disposed radionuclides.

For the majority of Class A radionuclides and intrusion exposure scenarios, the time of highest potential radionuclide-specific dose and its progeny (if any) occurs immediately following the end of the institutional control period (e.g., 100 years). However, for a small subset of radionuclides, the time of highest potential radiation dose occurs at the end of the modeling period due to in-growth of progeny. Therefore, nuclide-specific dose-to-source ratios are calculated for modeling times of 100 years and 1,000 years. Depending on the exposure pathways modeled for a scenario, there are a relatively few radionuclides for which the time of maximum dose occurs between 100 and 1,000 years. Dose-to-source ratios at these times are also of interest because they represent a potential point in time where radiation dose may be limiting if the radionuclide in question represents a significant component of a radionuclide inventory being evaluated for disposal.

Dose-to-source ratios for the Intruder-Driller scenario are provided in Table C-6 of Appendix C. Exposure pathways evaluated for the driller scenario include external radiation dose to a water well driller from drill cuttings in an open “mud pit”, where the source term is diluted to account for the proportion of cuttings, cover material, unsaturated zone material, and saturated zone material comprising the cuttings. In addition to ratios calculated at 100 and 1,000 years, dose-to-source ratios are also included at the time of highest potential dose for Cm-244 (150 yr), Pa-231 (220 yr), and Np-236 (770 yr).

Application of these dose-to-source ratios to the current disposed Class A inventory (listed in Table C-5 of Appendix C) results in the radionuclide-specific doses listed in Table C-7 of Appendix C. Therefore, as currently performing, this site-specific Performance Assessment projects a maximum total effective dose equivalent to the intruder-driller of 0.0072 mrem/yr (well below the 500 mrem/yr criteria). In fact, if the entire Embankment were assumed to be filled with blended ion-exchange resins, the maximum projected dose to the intruder-driller would only be 0.11 mrem/yr (see Table C-8 of Appendix C).

3.3 Protection of Individuals During Operations

Energy*Solutions*' Radiation Protection Program that is required by UAC R313-15-101(1) outlines the facility's radiation protection program. Additionally, Energy*Solutions*' Safety and Health Manual describes site safety, incident reporting, emergency response, equipment operation, personal protective equipment, respiratory protection, medical surveillance, exposure monitoring, hazard communication, confined space entry, and other safety related programs. Included therein are descriptions of Energy*Solutions*' ALARA program, including dose goals that are significantly below the regulatory dose criteria for workers. Since its creation in the early 1980s, Energy*Solutions*' radiological control program has successfully maintained worker exposures as a fraction of the regulatory limit, as demonstrated by worker dosimetry records and calculation of committed effective dose equivalents (CEDE). Energy*Solutions* actively reviews work practices, performs operational radiological surveys and has a functional ALARA review committee. The Division has recognized Energy*Solutions*' proactive approach that has resulted in successfully maintaining worker doses ALARA.

Operation-related exposures from the soil pathway involve the exposure of the public to contaminated material from the facility. If an exposure occurs, doses for this pathway result from external radiation or ingestion of soil on dirty hands. The primary site characteristic that prevents the likelihood of such exposures during operations and institutional control is the site's remote location (the low population density in the site vicinity, and the lack of natural resources to provide for population expansion). During operation, the facility is monitored as described in Energy*Solutions*' Environmental Monitoring Program, to ensure that no releases or doses have occurred via the soil pathway. During operation, the facility is monitored to ensure that no releases or doses occur via the soil pathway. Because of these administrative controls, inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the general public from soil during operations.

Energy*Solutions*' engineering and operational controls also prevent the resuspension and dispersion of particulates during operations. Blended resins are shipped in containers and not be dumped in bulk. They are disposed in its shipping container and then surrounded by CLSM. Water spray is used in the cells as needed to prevent resuspension of radioactivity. Haul roads are also wetted and maintained to prevent the resuspension and dispersion of particulate waste. Polymers are spread on inactive, open areas to bind the surface and prevent resuspension. Energy*Solutions* also performs continuous air monitoring to identify excessive airborne releases that require corrective actions. Because of these administrative controls, inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the general public from atmospheric transport of contaminants during operations.

The nearest stream channel is greater than five miles east of the facility. Surface water from precipitation is directed away from the waste disposal embankment by drainage ditches and berms. During facility operations, possibly contaminated contact storm-water is recovered and conveyed to evaporation ponds where it is monitored and controlled. No contact storm-water is released offsite, thereby maintaining releases from surface water ALARA. During operation, the facility is monitored as described in

Energy*Solutions*' Environmental Monitoring Program, to ensure that no releases or doses have occurred via the surface water pathway. Because of these administrative controls, inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the general public from the surface water pathway during operations.

During operation of the Embankment, releases and doses through the plant pathway are limited by the design, operation, and maintenance of the facility. Plants on the site are removed and prevented from contacting waste materials. Similarly, releases and doses from the burrowing animal pathway are prevented by the design, operation, and maintenance of the facility. Burrowing animals are prevented from contacting the waste materials. Because of these administrative controls, inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the general public from plant or animal driven migration of contaminants during operations.

3.4 Stability of the Disposal Site After Closure

As part of the Class A West license amendment application, Energy*Solutions* demonstrated that the disposal site, disposal site design, land disposal facility operations, disposal site closure, and post-closure institutional control plans are adequate to protect the public health and safety in that they will provide reasonable assurance of the long-term stability of the disposed waste and the disposal site and will eliminate to the extent practicable the need for continued maintenance of the disposal site through the compliance period following closure in accordance with the requirements of UAC R313-25. The basis for this affirmative finding is presented in the description and justification of the design of the principal design features planned for the disposal facility. These principal design features have been designed to perform their required functions over an appropriate period of time such that the facility will meet applicable performance objectives without the need for ongoing active maintenance following facility closure. The basis for this performance demonstration is presented under UAC R313-25-7(2) through UAC R313-25-7(5), UAC R313-25-8(4), and UAC R313-25-22(1). Design features do not require alteration to accommodate the disposal of blended ion-exchange resin waste.

The design and operation of the CWF provides more stable disposal that is required by 10 CFR 61 for Class A waste. The placement of containerized wastes, the sand backfill, the compacted sand, and clay above the container; the placement and compaction of bulk waste above the layers of containerized waste, and the cover combine to form a stable disposal configuration. The CWF design provides stability to ensure the long-term viability of the disposal unit cover. The use of containers, sand backfill, and compaction combine to resist slumping and differential settlement, which limits infiltration and reduces the potential for dispersion of the waste over time.

3.5 Protection of the Groundwater Resource

The Embankment analysis for the rock armored cover design projects that 0.09 cm/yr and 0.168 cm/yr of water will infiltrate through the traditional rock armored cover's top and side slope, respectively (Whetstone, 2011), with the differences in infiltration rates due to the top and side slope design differences. It further demonstrates that at these levels, the Embankment with a rock armored cover will satisfy all of the groundwater protection criteria for radionuclide concentrations limited by what is necessary for the waste to qualify as Class A.

In this site-specific Performance Assessment, net water infiltration through the two alternate covers (as computed using the HYDRUS and RESRAD platforms) is projected to be several orders of magnitude lower than calculated for the traditional rock armored cover (as presented in Table C-9 of Appendix C). The new analysis also demonstrates an optimal maximum evaporative zone layer thickness of 30.5 cm (above which negligible improvement is seen with increased thickness).

Radionuclide transport, driven by the HYDRUS-calculated precipitation infiltration, was modeled with the RESRAD platform assuming a 4 mrem/year groundwater protection level. The RESRAD platform calculated the release and transport of Class A radionuclides from the Embankment, through the unsaturated zone, and horizontally through the shallow unconfined aquifer to a compliance-monitoring well located 90 feet from the edge of the Embankment. The groundwater modeling included many conservative assumptions that helped to ensure that the radionuclide concentrations at the compliance monitoring well were not underestimated. For example, no delay factors for waste container life were used to delay the onset of radionuclide releases from waste. Additionally, the thickness of the entire footprint of the contaminated zone was conservatively set as the maximum waste thickness at the center of the Embankment. In actuality, the waste thickness decreases with distance from the center of the embankment in proportion to the slope of the cover and reaches zero at the edges of the embankment. Also, longitudinal dispersivity in the unsaturated and saturated zones was set at a larger value than that suggested by RESRAD default values (where larger values of longitudinal dispersivity reduce the potential arrival time of contaminants at the Point of Compliance well). Conversely, lateral dispersivity was set to a very low value to eliminate this mechanism of contaminant dilution in the saturated zone.

The groundwater resource protection component of the site-specific Performance Assessment was conducted in a phased manner, with the first to determine whether any Class A radionuclide that may potentially be disposed in the Embankment could reach the well at the point of compliance within the 10,000-year modeling period. Because of the very low infiltration rates associated with the alternate evapotranspirative cover designs, it is projected that no water that infiltrates through the cover at the beginning of the modeling period will reach the point of compliance within 10,000 years. Therefore, no class A radionuclide concentrations were predicted to arrive at the Point-of-Compliance well within the 10,000 year assessment period. As such, inclusion of additional volumes of blended ion-exchange resins in excess of 40,000 ft^3 annually does not compromise the Embankment's performance and protection of the groundwater resource.

4. SUMMARY AND CONCLUSIONS

The Energy*Solutions* Embankment is sited, designed, and operated for the disposal of Class A waste. The proposed disposal of large quantities (i.e., greater than 40,000 ft^3 per year) of blended ion-exchange resin waste has been evaluated in this site-specific Performance Assessment, which confirms that this waste can be disposed of safely and in compliance with all applicable regulatory requirements. As such, it specifically demonstrates that:

- The embankment is suitably sited and licensed for the disposal of large quantities of blended ion-exchange resins at or near the Class A limits;
- Disposal of waste in the CWF provides inherent additional intruder protection;
- Protection of an inadvertent intruder is provided even though there are no credible intrusion scenarios; and
- Consumption of the groundwater will not result in a dose that exceeds standards, even though the groundwater is not potable.

Even though not required for the disposal of Class A waste, the design of the CWF exceeds regulatory requirements for disposal of Class A waste (including blended ion-exchange resins in volumes exceeding 40,000 ft^3 annually). Specifically, the CWF provides an intruder barrier (engineered facility, disposal unit stability, and at least 5 meters depth to waste) that meets requirements for radioactive waste in excess of Class A concentrations. Therefore, the CWF design, operation, and licensing demonstrate that it is safe for the disposal of blended ion-exchange Class A resins.

This site-specific Performance Assessment and the resulting findings demonstrate that Energy*Solutions*' proposed methods for disposal of blended ion-exchange resins will ensure that future operations, institutional control, and site closure can be conducted safely, and that the site will comply with the Division's radiological performance criteria contained in UAC R313-25.

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APPENDIX A

Regulatory Basis for Selecting Reasonable

Inadvertent Intruder Scenarios

TECHNICAL MEMORANDUM

Regulatory Basis for Selecting Reasonable Inadvertent Intruder Scenarios

Although 10 CFR 61.42 requires that an inadvertent intruder be protected, NRC staff acknowledged that applicants and licensees are not expected to perform intruder dose analyses because the waste classification itself and segregation requirements found in 10 CFR 61.13(b) were developed to protect an inadvertent intruder, (NRC, 2000). Even so, the purpose of completing this site-specific Performance Assessment is in compliance with a Board directive to demonstrate that public health and safety (including inadvertent intruders) is protected to prescribed limits, with an acceptable "reasonable assurance." Regulatory bounding and contextual application of "reasonable assurance" are therefore paramount in the selection of "reasonable" inadvertent intruder scenarios for this Performance Assessment. In NRC's terminology, that degree of confidence is described as "reasonable assurance."

- 10 CFR 61.13(b), "*Analyses of the protection of individuals from inadvertent intrusion must include demonstration that there is <u>reasonable assurance</u> the waste classification and segregation requirements will be met and that adequate barriers to inadvertent intrusion will be provided*," and

- 10 CFR 61.23(c), "*The applicant's proposed disposal site, disposal site design, land disposal facility operations (including equipment, facilities, and procedures), disposal site closure, and post-closure institutional control are adequate to protect the public health and safety in that they will provide <u>reasonable assurance</u> that individual inadvertent intruders are protected in accordance with the performance objective in § 61.42, Protection of individuals from inadvertent intrusion.*"

While NRC does not include a specific definition of "reasonable assurance" in its 10 CFR 61 requirements, it has included the following clarification as part guidance in NRC (2007),

> "*NRC has previously indicated . . . the term 'reasonable assurance' is not meant to indicate a specific statistical standard. Specifically, NRC noted that the term 'reasonable assurance' is not meant to imply a requirement that extreme values be used in analyses or that compliance be based on extreme values of predicted dose distributions. NRC also noted that the term 'reasonable assurance' was not meant to indicate a significantly different standard than would be indicated by the term 'reasonable expectation.'* "

NRC further defined "reasonable" in the fourth point of the high level radioactive waste requirements of 10 CFR 63.304, discouraging the modeling of unreasonably-extreme physical situations in performance assessments.

> "*Reasonable expectation means that the Commission is satisfied that compliance will be achieved based upon the full record before it. Characteristics of reasonable expectation include that it:*
>
> > *(4) Focuses performance assessments and analyses on the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values*."

NRC (2007) further bounds the importance of selecting "reasonable" inadvertent intruder scenarios in performance assessment to reflect the current practices and the site environment,

- "*Verify that conceptual models for the biosphere include consistent and defensible assumptions based on regional practices and characteristics (i.e., conditions known to exist or expected to exist at the site or surrounding region).*"
- "*Verify that intermediate results (e.g., fluxes, travel times) are physically reasonable*."
- "*The reviewer should evaluate the types of scenarios . . . considered in the intruder analysis and confirm that the scenarios considered are appropriate for the site*."
- "*Verify that assumptions and parameters used in defining the exposed intruder, including location and behavior of the intruder, timing of the intrusion, and exposure pathways, are consistent with the current regional practices*."
- "*If a garden is assumed in the scenario, verify that the garden size is appropriate and consistent with regional practices*."

NRC's Performance Assessment Working Group (PAWG) further clarified the importance of avoiding unrealistic intruder scenarios in NRC (2000):

> "*The overall intent is to discourage excessive speculation about future events and the PAWG does not intend for analysts to model long-term transient or dynamic site conditions, or to assign probabilities to natural occurrences. . . The parameter ranges and model assumptions selected for the LLW performance assessment should be sufficient to capture the variability in natural conditions, processes, and events. . . Therefore, PAWG recommends that new site conditions that may arise directly from significant changes to existing natural conditions, processes, and events do not need to be quantified in LLW performance assessment modeling . . . With respect to human behavior, it may be assumed that current local land-use practices and other human behaviors continue unchanged throughout the duration of the analysis. For instance, it is reasonable to assume that current local well-drilling techniques and/or water use practices will be followed at all times in the future*."

This guidance also echoes instruction considered in NRC (1986),

> "*It seems reasonable to expect that activities in at least the near future will parallel those in the near past.*"

An archeological survey of the Clive area was performed in 1981, as part of the siting criteria used for the Vitro disposal cell (AERC, 1981). This survey found no cultural resource sites. A similar cultural and archaeological resource survey was conducted in 2001 on a land adjacent south to Section 32 (Sagebrush, 2001). In addition to the new survey, Sagebrush's (2001) report also summarized five additional cultural resource inventories performed within a mile of the subject area, between the original 1981 and 2001 studies. In all surveys, Sagebrush reported no paleontological, prehistoric, or historic resources were discovered in the survey area. Therefore, no evidence has been discovered that suggests the Clive facility has ever been inhabited by permanent residents in the past (probably due to unfavorable conditions for human habitation). Because of this, NRC guidance suggests that it is "unreasonable" to include activities associated with the establishment of permanent residences in this Report's site-specific Performance Assessment, since they do not "*parallel those in the near past*."

Within NRC's context of "reasonability," it is also important to note that due to Clive's soil salinity, the unpotable groundwater, the unsuitability of groundwater for irrigation, and the inadequacy of precipitation to support agriculture, inadvertent intruder scenarios involving intruder residence are also not "reasonable" for the Clive site.

Traditional generic exposure scenarios typically used to evaluate potential inadvertent intruder doses are described in the draft Environmental Impact Statement supporting 10 CFR 61 (NRC 1981) and the Update of Part 61 Impacts Analysis Methodology (NRC 1986). The methodology described in NRC (1981, 1986) includes evaluation of exposure pathways within a group of four inadvertent intruder scenarios including intruder discovery, intruder drilling, intruder construction, and intruder agriculture. These inadvertent intrusion scenarios represent a potential series of events that are initiated by the successful completion of a water supply well and set a precedent for NRC's use of a standard of "reasonability," as described in Section 4.1.1.1 of NRC (1986):

> *"It would be <u>unreasonable</u> to expect the inadvertent intruder to initiate housing construction at a comparatively isolated location before assuring that water for home and garden use will be available. Thus, this scenario (intruder-driller) is assumed to precede the following three scenarios."*

The intruder-drilling scenario is assumed to be an initiating event for the intruder-construction and intruder-agriculture scenarios (NRC 1986, Section 4.1.1.1). This scenario assumes that waste is brought to the ground surface in a mixture with cover material, unsaturated zone material, and drilling mud and is then contained in a mud pit used by the driller. The driller (a separate individual from that in any subsequent exposure scenario) may be exposed by direct gamma radiation from the waste mixture in the mud pit (NRC, 1986). Attributes of this scenario such as the dimensions of the mud pit and depth of water above the cuttings are described in Section 4.2.1 of NRC (1986).

The intruder-discovery scenario described in Section 4.2.3 of NRC (1981) involves external exposure to discoverable wastes that are clearly distinguishable from natural materials. The dose assessment methodology described in NRC (1981) was updated in NUREG/CR-4370 (NRC, 1986). Exposure to the intruder-discoverer is assumed to be limited to the topmost waste layer, since the intruder "would likely stop excavating before digging too deep into the rest of the waste" (NRC 1986, Section 4.2.3). The intruder-discovery scenario for stable waste streams in the first 500 years after closure is assumed to preempt the intruder-agriculture scenario (and, presumably, the intruder-construction scenario) because construction and inhabitation of a home will not occur once the waste has been discovered and recognized (NRC 1986, Section 4.2.3).

The intruder-construction scenario involves direct intrusion into disposed wastes for activities associated with the construction of a house {(e.g., installing utilities, excavating basements, and similar activities [as described in Section 4.2.2 of NRC (1986)]}. However, because there is no historic evidence of prior residential construction at the Clive site, the extreme salinity of Clive's soils, the unpotable groundwater , the severe lack of irrigation sources, and the inadequacy of precipitation to support agriculture, the inadvertent intruder-construction scenario is not considered "reasonable" for the Clive site nor included in this Report's site-specific Performance Assessment.

The intruder-agriculture scenario assumes an individual is living in the home built under the intruder-construction scenario, and is also exposed from gardening activities involving the waste/soil mixture excavated during construction (NRC 1986, Section 4.2.4). As with the inadvertent intruder-construction scenario, the lack of historic evidence of prior residential agriculture at the Clive site, the extreme salinity of Clive's soils, the unpotable groundwater, the severe lack of irrigation sources, and the inadequacy of precipitation to support agriculture, the inadvertent intruder-agriculture scenario is not considered "reasonable" for the Clive site no included in this Report's site-specific Performance Assessment.

Therefore, assessment of reasonable inadvertent intruder scenarios in Clive-specific Performance Assessments focuses on the inadvertent intruder-driller. The other scenarios commonly examined in performance assessments (e.g., inadvertent intruder-discoverer, inadvertent intruder-construction and inadvertent intruder-agriculture) are not consistent with regulatory precedent and definition of "reasonable."

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APPENDIX B

Modeling Report: Fate and Transport of Contaminants from the Class A West Embankment to a Post-Closure Inadvertent Intruder At the Energy*Solutions* Clive, Utah Facility

NAC-0009_R1

Modeling Report: Fate and Transport of Contaminants from the Class A West Embankment and Exposure to a Post-Closure Traditional Inadvertent Human Intruder at the Energy*Solutions* Clive, Utah Facility

05 October 2012

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FIGURES

TABLES

1.0 Introduction

EnergySolutions, LLC (Energy*Solutions*) operates a low-level radioactive waste (LLW) disposal facility west of the Cedar Mountains in Clive, Utah. Clive is located along Interstate-80, approximately 3 miles south of the highway, in Tooele County. The facility is approximately 50 miles east of Wendover, Utah and approximately 66 miles west of Salt Lake City, Utah. The facility sits at an elevation of 4,275 feet (ft) above mean sea level (amsl). The Class A West (CAW) LLW disposal embankment at the facility is designed with a compacted clay liner and a cover composed of clay, soil, and cobble layers above the LLW.

The State of Utah Division of Radiation Control (DRC) has provided a review of Energy*Solutions*' analysis, "Justification for the Disposal of Blended Low-Level Radioactive Waste at the Clive Containerized Waste Facility." This review determined that in order to dispose of volumes of processed ion-exchange resins greater than 40,000 cubic ft, Energy*Solutions* is required to conduct new performance assessment (PA) analyses that will include "prediction of nuclide concentration and peak dose (at the time peak dose would occur) using updated dose conversion factors and a suggested model time frame of 10,000 years, as well as any need to revisit/update the waste source term, receptor and exposure pathways."

To address these requirements Energy*Solutions* has agreed to provide new analyses including:

- additional analysis of subsurface fate and transport of LLW contaminants leached from the Class A West embankment via contact with precipitation that has infiltrated through two proposed Class A West embankment cover designs, and transported to a well at the point of compliance 90 ft from the outside edge of the LLW material in the disposal cell,
- modeling of expected groundwater well concentrations and comparison to groundwater protection limits for a period of 500 years following embankment closure, and of projected peak groundwater well concentrations for each individual radionuclide for a time period of 10,000 years following embankment closure,
- modeling of expected exposures and resulting dose to a hypothetical inadvertent intruder for each individual radionuclide within 1,000 years following embankment closure,
- evaluation of additional radionuclides that have not been included in the Class A West PA work to date.

This report describes the methodology for achieving these objectives and the results of the analyses. The methodology includes an approach for:

- developing a long-term climate record representative of the site,
- representation of near-surface processes that affect net infiltration, such as evaporation, runoff, and plant water uptake,
- representation of movement of water through the cover layers, waste, and liner,
- release of radionuclides and transport through the vadose zone to the saturated zone,
- transport of radionuclides in the saturated zone to the point of compliance,
- evaluation of groundwater concentrations over time at the point of compliance, and

- evaluation of radiation dose for a traditional inadvertent human intruder (IHI) scenario occurring upon the disposal embankment.

The results of the analysis include:

- a description of the modeling that forms the basis for determining the adequacy of 1-dimensional calculations using HYDRUS,
- a description of the HYDRUS calculations and basis for the estimate of a steady-state infiltration rate applied in the RESRAD-OFFSITE transport model,
- a description of the RESRAD-OFFSITE transport model used to calculate groundwater concentrations over time,
- identification of groundwater concentrations at the time of highest concentrations within 10,000 years, and comparison of groundwater concentrations within 500 years of site closure to groundwater protection limits,
- evaluation of dose for an IHI scenario using RESRAD within 1,000 years following embankment closure.

2.0 Site Description and Disposal Cell Design

This section provides a brief overview of the hydrogeologic setting of the facility, climate, vegetation, and the evapotranspiration cover designs.

2.1 Site Description

The Energy*Solutions* site is located in, and is bounded by, the Great Salt Lake Desert to the west at approximate elevations of 4,250 to 4,300 ft amsl. Also to the west, low-lying hills rise 50 to 100 ft from the desert floor. To the east and southeast, the site is bounded by the north-south trending Lone Mountains, which rise to a height of 5,362 ft amsl. At the base of the Lone Mountains alluvial fans slope gently toward the west at a gradient of approximately 40 ft per mile. The site has topographic relief of approximately 11 ft, sloping in a southwest direction at a gradient of approximately 0.0019.

To the north of the site are the Grayback Hills, composed of limestone and quartzite mapped as Permian-Pennsylvanian Oquirrh Formation, which is as much as 10,000 ft thick in western Utah.

The location of the proposed Class A West cell at the site is shown in Figure 1.

Alluvial and lacustrine sediments that fill the valley floor are estimated to extend to depths of greater than 500 ft with unconsolidated sediments ranging from 300 to over 500 ft. North-south trending mountains and outcrops define the hydrogeologic boundaries for the aquifer system. Lone Mountain located two miles east of the site, rises approximately 950 ft above the valley floor. The Grayback Hills located to the north with outcropping features to the west rise 500 ft and 230 ft respectively above the valley floor.

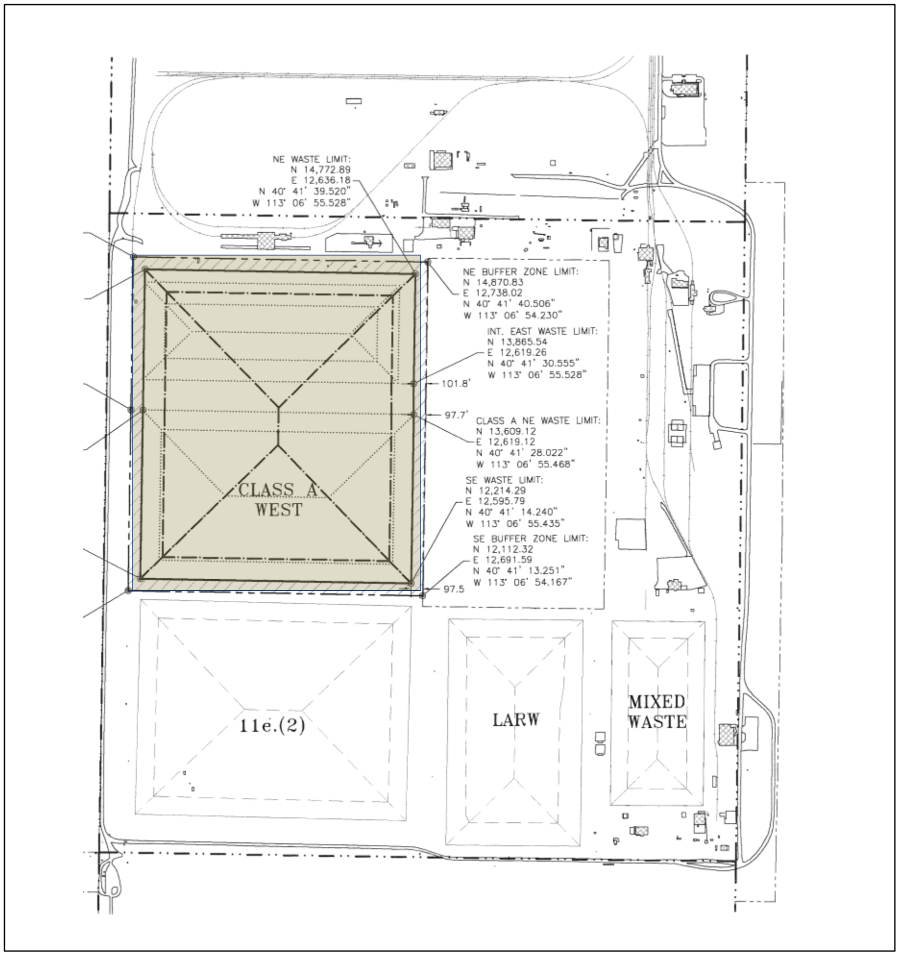


Figure 1: Location of the proposed Class A West Disposal Cell.

Four hydrostratigraphic units have been delineated in the unsaturated zone and shallow aquifer system at the Clive Facility. These units consist of an upper silty clay/clayey silt (Unit 4), an upper silty sand (Unit 3), a middle silty clay (Unit 2), and a lower sand/silty sand (Unit 1). The site aquifer system consists of a shallow unconfined aquifer that extends through the upper 40 ft of lacustrine deposits. A confined aquifer begins around 40 to 45 ft below the ground surface and continues through the valley fill. Due to the low precipitation and relatively high evapotranspiration, little or no precipitation reaches the upper unconfined aquifer as direct vertical infiltration. Groundwater recharge is primarily due to infiltration at bedrock and alluvial fan deposits which then travels laterally and vertically through the unconfined and confined aquifers. Groundwater flow in this area is generally directed northeasterly to northwesterly.

Fresh water from the recharge zones along the mountain slopes develops progressively poorer chemical quality in response to dissolution of evaporate-minerals during its travel through the regional-scale flow systems and through concentration by evaporation at the points of discharge. The groundwater quality in the unconfined aquifer at the Clive Facility is considered saline with concentrations of several chemical species (sulfate, chloride, total dissolved solids, iron, and manganese) significantly exceeding the EPA secondary drinking water standards.

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

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

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

Unit 2: Unit 2 underlies Unit 3 and ranges from 2.5 ft to 25 ft in thickness. The average thickness of this unit is 15 ft. Unit 2 is described as being composed of clay with occasional silty sand interbeds. A structure map was prepared by Envirocare (2004, Figure 5) with contours representing the elevations of the top of the unit. This map shows that the top surface of Unit 2 slopes downward gradually from east to west in the vicinity of the Class A West cell.

Unit 1: Unit 1 is the bottom layer of this sequence. This unit is described as silty sand interbedded with clay and silt layers. The thickness of this layer has not been estimated.

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

Unit	Sediment Texture Class	Thickness Range (ft)	Average Thickness (ft)
4	Silt and clay	6-16.5	10
3	Silty sand with interbedded silt and clay layers	7-25	15
2	Clay with occasional silty sand interbeds	2.5-25	15
1	Silty sand with interbedded clay and silt layers	?-?	?

Precipitation measurements taken at the site over the 17-year period 1992 to 2009 show a mean annual value of 8.53 inches (21.7 cm) (Whetstone 2011). The distribution of precipitation throughout the year shown in Figure 2. Precipitation exceeds the annual average from January through June and again in October and is below average for the remaining months. The nearest National Oceanographic and Atmospheric Administration (NOAA) station with a long-term record is located in Dugway, Utah approximately 40 miles to the south. The mean annual precipitation for the same 17-year period measured at the Dugway station is 8.24 inches (20.9 cm). A comparison of the Dugway precipitation data for the 17-year period 1992 to 2009 with the long-term average for Dugway was made by Whetstone (2011). This comparison indicated that annual average precipitation during this 17-year period has been greater than the long-term average at Dugway by 8 percent. Whetstone (2011) concluded that simulations of cover performance using precipitation data from this 17-year period might be overestimating this component of the site water balance.

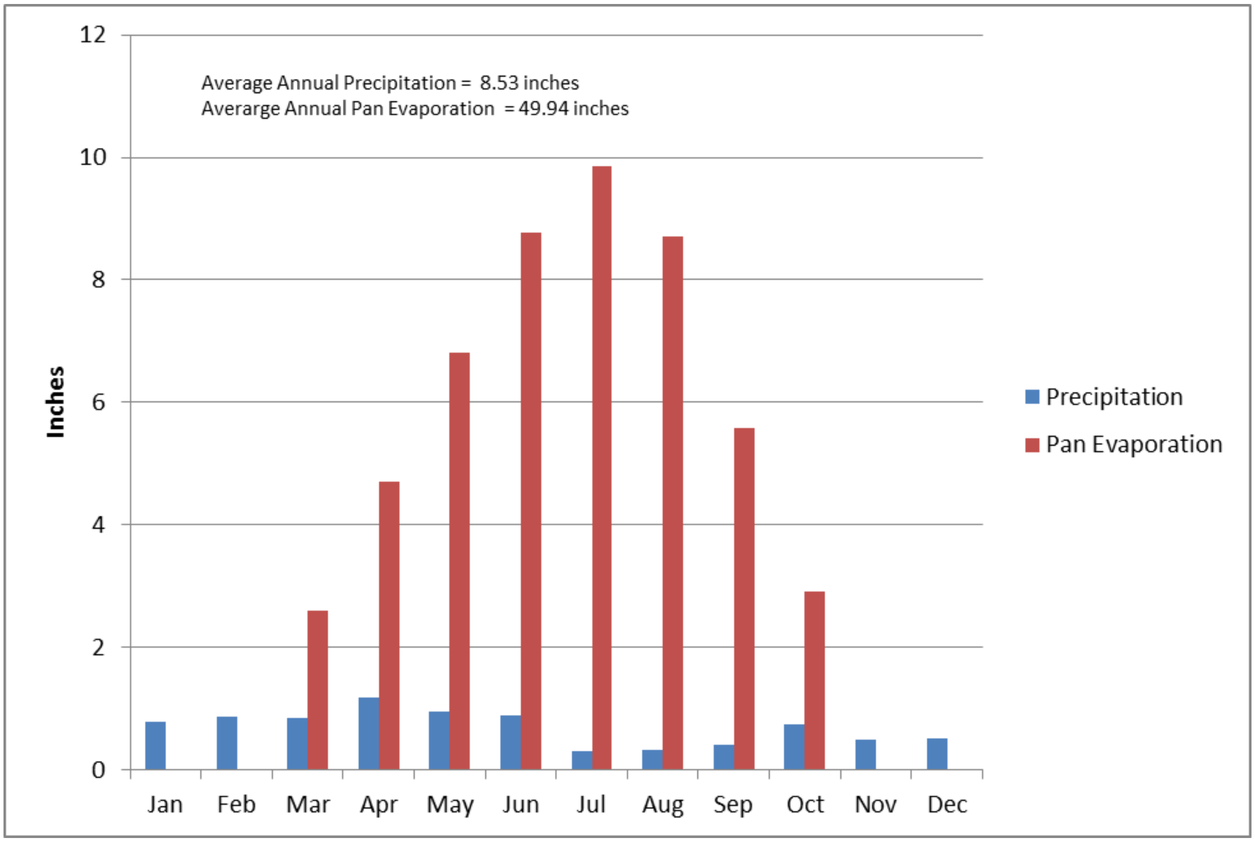


Figure 2: Mean monthly precipitation for the Clive site and mean monthly pan evaporation for the NOAA BYU station.

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

The close correspondence between mean monthly temperatures measured at the Clive site and the Dugway NOAA station was demonstrated by Whetstone (2011). Average monthly temperatures measured at the Clive site over the 17-year period 1992-2009 ranged from 27.7 $^{\circ}$F in December to 79.5 $^{\circ}$F in July.

Mean monthly values of pan evaporation measured at the BYU NOAA station in Provo, Utah over the period 1980 to 2005 are shown in Figure 2. Mean annual pan evaporation over this time period is 49.94 inches. This station is located 83 miles to the southeast of the Clive facility. Data from this station are used because pan evaporation data are not available for the Dugway station. Although the Clive site is warmer than Provo during the summer months as shown in Figure 3, the data provide insight into the water balance at the site.

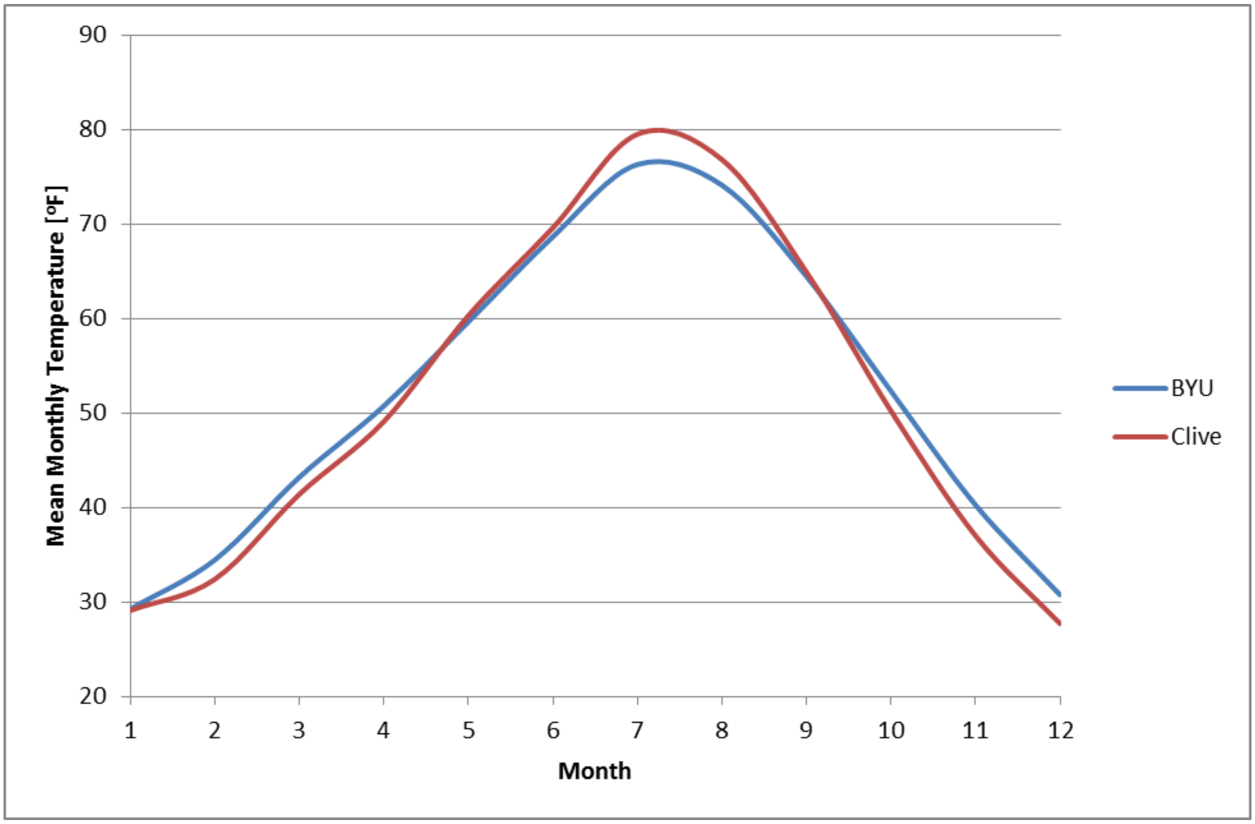


Figure 3: Monthly mean temperatures for the Clive Site and the NOAA BYU station at Provo, Utah.

Assuming pan evaporation is approximately equal to potential evapotranspiration (PET) the ratio of annual average precipitation to PET is 0.17. Although PET greatly exceeds precipitation on an annual basis, monthly means in Figure 2 show precipitation exceeds PET from November through February. This indicates the potential for recharge during these months under natural conditions at the site.

Actual transpiration is dependent on the characteristics of the plant communities at the site. Vegetation cover at the site is less than 20 percent with soils supporting a range of native and invasive shrubs. Excavations at the site have shown plant rooting depths extending to approximately 30 inches (70 cm) below the ground surface with root density decreasing with depth (SWCA 2011).

2.2 Disposal Cell Design

Engineered barriers are used at the Clive site to control the flow of water into the waste. The two evaporative (ET) cover designs (Design 1 and Design 2) considered in this report for the CAW cell differ from each other only in that an additional layer is included in Design 2. The outside dimensions and slopes are the same for both designs. North-south and east-west cross-sections prepared by Energy*Solutions* are shown in Figure 4. From north to south the cover is 2,558.9 ft in length. The cross-section is composed of a side-slope 183 ft long with a maximum slope of 5 to 1. The next section, the top slope, is 942 ft long with a slope of 4 percent. The crest of the cover in this cross-section is horizontal and is 308.9 ft long. South from the crest are sections of top slope and side slope of the same lengths and slopes as the sections north of the crest. The east-west cross-section is 2,250 ft in length and differs from the north-south cross-section only in that the crest is a line where the top-slopes east and west of the crest meet.

Disposal involves placing waste on a prepared clay liner that is approximately 12 ft below the ground surface. For the Class A West design, the depth of the waste below the top slope is a maximum of 76 ft (23 m). A cover system is constructed above the waste. The objective of the cover system is to limit contact of water with the waste. The cover is sloped to promote runoff and the cover can be designed to limit water flow by increasing evapotranspiration (ET) or through lateral diversion to a surface drainage system. The arrangement of the layers used for Design 1 and Design 2 are shown in Figure 5. Beginning at the top of the cover the layers used for Design 1 are:

- Surface layer: This layer is composed of native vegetated Unit 4 material with 15% gravel mixture. This layer is 6 inches thick. The functions of this layer are to control runoff, minimize erosion, and maximize water loss from ET. This layer of silty clay used in both designs provides storage for water accumulating from precipitation events, enhances losses due to evaporation, and provides a rooting zone for plants that will further decrease the water available for downward movement.
- Evaporative Zone layer: This layer is composed of Unit 4 material. The thickness of this layer is varied in the HYDRUS simulations from 6 inches to 18 inches to evaluate the influence of additional thickness on the water flow into the waste layer. The purpose of this layer to provide additional storage for precipitation and additional depth for plant rooting zone to maximize ET.
- Frost Protection Layer: This material ranges in size from 16 inches to clay size particles. This layer is 18 inches thick. The purpose of this layer is to protect layers below from freeze/thaw cycles, wetting/drying cycles, and inhibit plant, animal, or human intrusion.
- Upper Radon Barrier: This layer consists of 12 inches of compacted clay with a low hydraulic conductivity. This layer has the lowest conductivity of any layer in the cover system. This is a barrier layer that reduces the downward movement of water to the waste and the upward movement of gas out of the disposal cell.
- Lower Radon Barrier: This layer consists of 12 inches of compacted clay with a low hydraulic conductivity. This is a barrier layer placed directly above the waste that reduces the downward movement of water.

The only difference between Design 1 and Design 2 is the placement of a filter zone between the frost protection layer and the upper radon barrier. The filter material ranges in size from 0.2 to 1.5 inches. The Type-B size gradation corresponds to a coarse sand and fine gravel mix. This high conductivity layer is placed on the upper radon barrier which has the lowest conductivity of any layer in the cover system. The function of this coarse to fine interface is to collect water that has drained vertically from the layers above and direct it laterally to a surface drainage system. Six inches of Type-B filter material is placed below the frost protection material layer in Design 2.

The layer below the surface layer for both designs is referred to as the evaporative zone layer. This name is intended to reflect only the function of this layer to provide additional storage for precipitation and additional depth for plant rooting zone to maximize ET. This layer name should not be misinterpreted to be the evaporative zone depth (EZD) used as a parameter in HELP models. References in this report to evaporative zone, evaporative zone thickness, and evaporative zone depth refer only to the function and characteristics of a layer in the ET cover system designs.

The traditional rock armor cover is shown in Figure 5 and consists of the following layers from top to bottom (Whetstone 2011):

- Rip Rap cobbles. Approximately 24 inches of Type-B rip rap is placed on the top slopes, above the upper (Type-A) filter zone. The Type-B rip rap used on the top slopes ranges in size from 0.75 to 4.5 inches with a nominal diameter of approximately 1.25 to 2 inches.
- Filter Zone (Upper). Six inches of Type-A filter material is placed above the sacrificial soil in the top slope cover.
- Sacrificial Soil (Frost Protection Layer). A 12-inch layer consisting of a mixture of silty sand and gravel is placed above the lower filter zone to protect the lower layers of the cover from freeze/thaw effects.
- Filter Zone (Lower). Six inches of Type-B filter material is placed above the radon barrier in the top slope cover. This filter material ranges in size from 0.2 to 1.5 inches.
- Radon Barrier. The top slope cover design contains an upper radon barrier consisting of 12 inches of compacted clay and a lower radon barrier consisting of 12 inches of compacted clay.

The design for the side slope is similar to the top slope except for the thickness of the waste layer and the material used in the rip rap layer. The layers used in the CAW side slope cover consist of the following, from top to bottom (Whetstone 2011):

- Rip Rap cobbles. Approximately 24-inches of Type-A rip rap is placed on the side slopes above the Type-A filter zone. The Type-A rip rap ranges in size from 2 to 16 inches (equivalent to coarse gravel to boulders) with a nominal diameter of 12 inches.
- Filter Zone (Upper). (Same design as top slope.)
- Frost Protection Layer (Sacrificial Soil). (Same design as top slope.)
- Filter Zone (Lower). The thickness of the Type B filter in the side slope is 18 inches.
- Radon Barrier. (Same design as top slope.)

Evaluation of the performance of the rock armor cover design shown in Figure 5(c) is not addressed in this report but has been previously described in Whetstone (2011). The surface layers in Designs 1 and 2 do not inhibit evaporation. The rip rap surface layer inhibits evaporation, so more water is available for infiltration. Consequently, infiltration rates for the cover design employing rock armor are expected to be significantly greater than those employing a surface evaporative zone because the presence of rip rap inhibits evaporation of moisture from underlying soils.

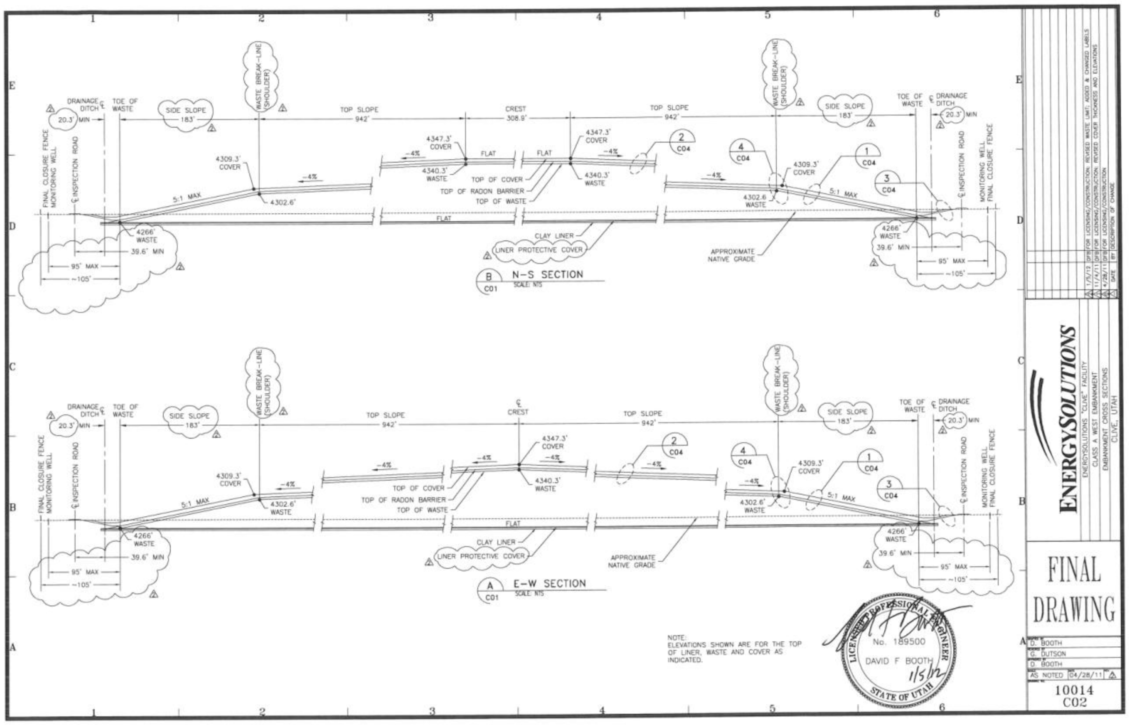


Figure 4: Class A West Cell cross-sections.

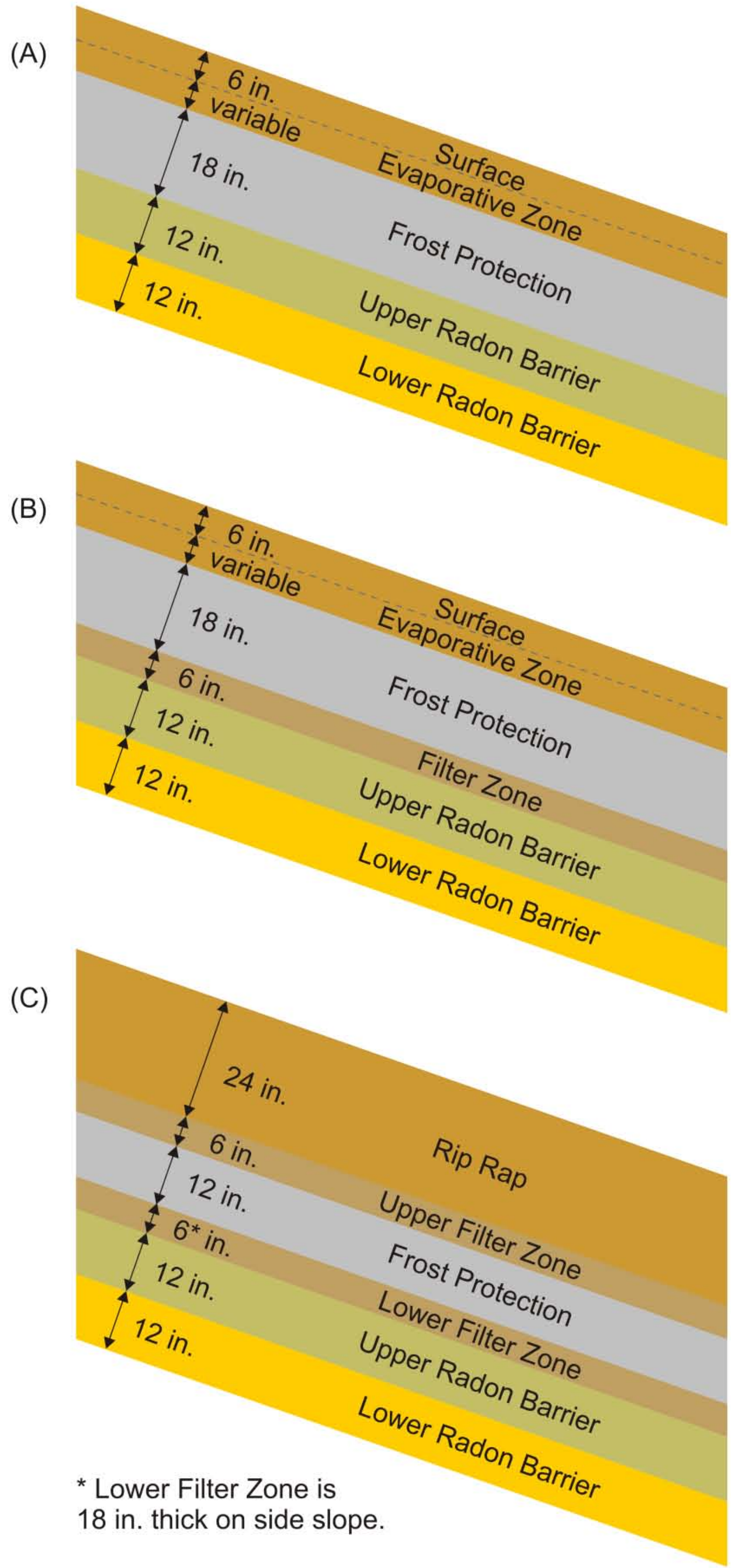


Figure 5: The arrangement and thickness of the layers for the evapotranspiration covers (A) design 1, (B) design 2 and (C) the traditional rock armored cover.

3.0 Technical Approach

Two software platforms are used for this analysis, HYDRUS (2D/3D) (Šimůnek and Šejna 2011a, 2011b) and the RESidual RADioactivity computer programs RESRAD and RESRAD-OFFSITE, developed by Argonne National Laboratory (http://web.ead.anl.gov/resrad/home2/offsite.cfm).

Previous simulations of net infiltration in cover systems at the site have used the U.S. Environmental Protection Agency's Hydrologic Evaluation of Landfill Performance Model (HELP) (Schroeder et al. 1994a, 1994b). Advantages of HELP include an interactive interface, fast execution times, associated databases containing meteorological data, vegetation parameters, material properties of soils and engineered materials, and parameters for estimating overland flow, and HELP is in the public domain (Khire et al. 1997).

HELP simulates water routing or storage in user defined layers. There are four operational layer types that can be modeled in HELP: 1) vertical percolation layers; 2) lateral drainage layers; 3) barrier soil liners; and 4) geomembrane liners. Each layer type has its own mechanism for flow and associated limitations (Schroeder et al. 1994a). Geomembrane liners are not used at the site and are not discussed further.

Vertical Percolation Layer

Flow in a vertical percolation layer is downward due to gravity drainage, or depending on the location of the layer in the vertical sequence, also upward due to evapotranspiration. Unsaturated vertical drainage under unit gradient conditions occurs when the soil moisture exceeds the specified field capacity or when the soil matric potential of the underlying layer is less than the soil matric potential in the vertical percolation layer. If the vertical percolation layer is located within the evaporative zone depth, evaporation is modeled as an extraction and can occur only until the specified wilting point moisture content has been reached. Extraction of water at moisture contents below the wilting point cannot occur. HELP cannot simulate upward movement of water due to capillarity so evapotranspiration losses are not modeled as capillary flow but are mimicked using a distributed extraction.

Lateral Drainage Layer

Lateral drainage layers allow saturated lateral flow to collection systems. Lateral drainage layers have high saturated hydraulic conductivities to promote lateral flow and have characteristics similar to capillary barriers. Vertical flow is modeled in the same manner in these layers as in vertical percolation layers with the result that vertical flow across lateral drainage layers at saturations below field capacity cannot be modeled in HELP. As a result the only types of layers allowed below a lateral drainage layer is another lateral drainage layer or a barrier soil layer.

Barrier Soil Layers

A barrier soil layer is assumed to be saturated at all times and allows flow only when there is a positive head on the top surface. The vertical flow rate through a barrier layer is a function of the hydraulic head on the top surface of the layer, the thickness of the layer, and the saturated hydraulic conductivity. HELP allows only downward saturated flow in barriers and no evapotranspiration.

The implications of these restrictions on modeling infiltration for the traditional rock armor cover are that since HELP is not capable of simulating flow across a capillary barrier, the sacrificial soil layer below the upper filter layer (lateral drainage layer) must be designated as a barrier layer in HELP. A barrier layer is assumed to be saturated at all times and allows flow only when there is a positive head on the top surface. HELP allows only downward saturated flow in barriers and no evapotranspiration. In addition, the upper radon barrier, located below the lower filter layer, must be saturated at all times.

Limitations of the HELP Code

Prediction errors in the application of HELP at arid sites are described by Meyer et al. (1996). These errors include underestimates of available water that lead to overestimates of net infiltration and recharge in the water balance calculation. Meyer et al. (1996) describe two ways in which HELP underestimates available water for evapotranspiration. The first is by specifying wilting points that are not characteristic of the native vegetation. Wilting points in HELP are set at the water content corresponding to -15 bars matric potential for the material. Under arid climate conditions native plants are adapted to extracting water at matric potentials much lower than the wilting points used by HELP. For example, two native species in an alluvial valley on the Nevada Test Site showed transpiration only becoming negligible at -50 bars. This underestimation of available water becomes more significant for materials composed of clays and silts. The second phenomenon not captured by HELP is the frequently very dry condition of the upper portion of the soil surface. The surface of the soil will dry to a point where the vapor pressure of water in the soil pores is in equilibrium with the atmospheric vapor pressure. In arid regions this condition would be equivalent to soil matric potentials of -1000 bars or lower (Meyer et al. 1996). This additional drying increases the storage capacity of the upper portion of the soil profile leading to overestimates of net infiltration by HELP.

Code Comparisons

A number of comparisons between HELP and unsaturated flow codes have been conducted for sites in arid and semi-arid climates. Predictions of net infiltration at a desert site in southern Nevada using HELP and UNSAT-H were made by Meyer et al. (1996). HELP consistently produced the largest values of net infiltration for all cases considered. Net infiltration estimates obtained using UNSAT-H was lower and in some cases indicated net upward flow. The estimates produced by UNSAT H were in better agreement with site estimates of net infiltration determined using chloride mass balance methods and estimated from water content and matric potential measurements.

Predictions from UNSAT-H were considered to be more accurate than those from HELP by Khire et al. (1997). These authors note that at their semi-arid site neither code properly represented the influence on the water balance of snow cover, snow melt, and the thermal conditions of the ground surface. Considering both the relative strengths and weaknesses of HELP and codes for variably saturated media with atmospheric boundary conditions, Khire et al. (1997) suggest the use of HELP during an initial phase to evaluate alternative designs then use of the more detailed mechanistic codes to inform a final decision and provide net infiltration estimates for the performance assessment modeling. However, with modern technology and programs, there is no need to evaluate alternative designs first using HELP.

A comparison of four codes commonly used for landfill cover design was conducted by Albright et al. (2002). For their comparison tests HELP consistently produced the highest estimates of net infiltration with the over-prediction being as much as an order of magnitude at an arid site. These authors noted that the net infiltration responses of HELP to increases in available water capacity were not realistic and that the net infiltration response of HELP was insensitive to the thickness of the cover surface layer.

The HYDRUS (2D/3D) platform is recommended for this project because of its ability to simulate processes known to have a significant role in water flow in landfill covers in arid regions. HYDRUS includes the capabilities to simulate:

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

The flow component of unsaturated flow and transport programs with atmospheric boundary conditions such as HYDRUS solve modified forms of the Richards equation for variably saturated water flow. The flow equation incorporates a sink term to account for water uptake by plant roots. HYDRUS can be applied to one-, two-, and three-dimensional problems. The HYDRUS software includes grid generators for structured and unstructured finite element meshes. Programs such as HYDRUS require detailed data to represent the atmospheric boundary conditions and plant responses that are the dominant influences on flow in the cover in arid and semi-arid conditions. These programs use the infiltration capacity of the soil at any time as calculated in the model to partition precipitation into infiltration and overland flow. HYDRUS has been used for many applications for unsaturated zone modeling and has received numerous favorable reviews such as Diodato's (2000) review of HYDRUS 2D and McCray's (2007) review of the most recent program, HYDRUS (2D/3D). For this analysis the HYDRUS models will use daily values of climate parameters and the properties of the proposed covers to provide an estimate of long-term net infiltration for the RESRAD-OFFSITE transport model.

RESRAD is the basis of the programs that are used to model ingrowth, decay, and transport of radionuclides in the environment and radiation dose to potential human receptors. Specifically, RESRAD-OFFSITE is employed for the groundwater transport pathway because this program has the ability to model transport of radionuclides to locations beyond the area of contamination. This capability is required in order to assess radionuclide concentrations and associated dose at the groundwater point-of-compliance 90 ft (27 m) downgradient from the edge of the disposed LLW. RESRAD-OFFSITE models both advective and dispersive vertical transport in the unsaturated zone. PATHRAE, the computer program previously employed for this modeling, does not model vertical dispersion in the unsaturated zone, potentially underestimating the rate of radionuclide migration into the aquifer. For the evaluation of dose for the IHI scenarios occurring on the disposal embankment, the RESRAD (on-site) program is used. Both RESRAD and RESRAD-OFFSITE incorporate the most current dose conversion factors (DCFs) available from the International Commission on Radiation Protection (ICRP).

The computer programs comprising the RESRAD family are cited in DOE Order 458.1 as an example of dose assessment models that meet DOE quality assurance requirements under DOE Order 414.1C, *Quality Assurance*. In addition to RESRAD-OFFSITE, the MicroShield® computer program was employed to benchmark the RESRAD external dose calculations for the Intruder-driller scenario for external exposure to radionuclides in drill cuttings (http://www.radiationsoftware.com).

3.1 Modeling of Net Infiltration

HYDRUS models were developed for the two evapotranspiration cover designs for the CAW embankment (Figures 5a and 5b). Model development requires construction of a computational grid based on the geometry of the model domain. Hydraulic properties for each layer required for the model are available from previous studies at the site or can be estimated from site-specific measurements such as particle size distributions. HYDRUS requires daily values of precipitation, potential evaporation, and potential transpiration to represent the time-variable boundary conditions on the upper surface of the cover. Representative boundary conditions were developed from records of nearby meteorological observations. Parameters for describing root water uptake were available from vegetation surveys at the site. HYDRUS models were used to provide estimates of the long-term annual net infiltration of water into the waste for the RESRAD-OFFSITE transport and dose model.

3.2 Environmental Transport and Dose Modeling with RESRAD and RESRAD-OFFSITE

The conceptual framework and mathematical expressions for radionuclide transport in groundwater in the RESRAD-OFFSITE program is described in Yu, et al. (2007). The infiltration rate in RESRAD-OFFSITE is internally calculated from user inputs for the evapotranspiration coefficient, runoff coefficient, and precipitation rate. The RESRAD-OFFSITE infiltration rate is adjusted using the evapotranspiration coefficient to reflect the annual average net infiltration rate calculated by the HYDRUS models. RESRAD-OFFSITE calculates radionuclide release from the contaminated zone with infiltration using a first order uniform leach rate for desorption from a contaminated soil source term based on equilibrium soil-water distribution coefficients (K_ds). Radionuclide transport in the unsaturated zone below the waste is modeled as one-dimensional downward flux due to both advection by water and diffusion related to the concentration gradient. Radionuclides are released to the saturated zone as a pulse across a rectangular prism with an area equivalent to that of the contaminated zone specified by the model user. In the saturated zone, RESRAD-OFFSITE applies advection-dispersion calculations to model the migration of dissolved radionuclides in the direction of groundwater flow. RESRAD-OFFSITE is also equipped to model vertical and lateral dispersion in the saturated zone should these processes warrant evaluation.

RESRAD-OFFSITE is used to estimate groundwater concentrations, and associated radiological dose due to (hypothetical) ingestion of groundwater at a drinking water well assumed to be at the point of compliance. The on-site RESRAD and MicroShield® computer programs are used to support the calculation of Intruder-driller external exposures to drill cuttings in an open "mud pit". The MicroShield® computer program is used because it has the ability to more precisely estimate external exposures from a source that is shielded by a layer of water and for exposure geometries where a receptor is geometrically offset from the exposure source, such as may occur for drillers exposed to cuttings in the "mud pit" used with rotary drilling methods. Although on-site RESRAD calculations may overestimate such exposures by locating a receptor directly above the mud pit, RESRAD has the advantages of being freely accessible on-line and having a more user-friendly interface. External dose calculations for exposures at an open "mud pit" are performed using both RESRAD and MicroShield® to determine whether differences in modeled doses are significant.

The RESRAD and RESRAD-OFFSITE computer programs contain libraries of internal DCFs based on dosimetric models from Publication 60 of the ICRP (1991) as compiled in ICRP 72 (ICRP 1996), as well as DCFs published in Federal Guidance Report 11 (EPA 1988), which are based on older dosimetric models dating from 1979. Based on comments requesting the use of updated dose conversion factors made by DRC on Energy*Solutions*' analysis, "Justification for the Disposal of Blended Low-Level Radioactive Waste at the Clive Containerized Waste Facility", the more recent internal DCFs compiled in ICRP 72 and available in the RESRAD programs is used in the dose assessment. ICRP has recently updated the radiation and tissue weighting factors in Publication 60, and Publication 60 has been replaced by Publication 103 (ICRP 2007). However, internal DCFs have not yet been developed by ICRP from this newer dosimetry. The DCFs published in ICRP (1996) are the most current and widely accepted DCFs currently in use for environmental dose assessment.

3.3 Inadvertent Human Intruder Exposure Scenarios

Title 10 CFR 61 is the Federal regulation governing near-surface disposal of certain radioactive wastes at privately-operated facilities such as that evaluated in this PA. The following portions of 10 CFR 61 are relevant to development of IHI exposure scenarios.

10 CFR 61.2 Definitions

> *Inadvertent intruder* means a person who might occupy the disposal site after closure and engage in normal activities, such as agriculture, dwelling construction, or other pursuits in which the person might be unknowingly exposed to radiation from the waste.

10 CFR 61.42 Subpart C-Performance Objectives (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 institutional controls over the disposal site are removed.

The "traditional" generic exposure scenarios used to evaluate potential IHI doses are described in the draft Environmental Impact Statement supporting 10 CFR 61 (NRC 1981) and the *Update of*

Part 61 Impacts Analysis Methodology (NRC 1986). The methodology described in NRC (1981, 1986) includes evaluation of exposure pathways within a group of four coupled IHI scenarios including intruder drilling, intruder discovery, intruder construction, and intruder agriculture. These scenarios are extremely unlikely at the Clive site due to the absence of potable groundwater, which severely limits the viability of subsequent domestic construction and habitation. Agricultural activity is infeasible at the site due to soil salinity, the unsuitability of groundwater for irrigation, and the inadequacy of precipitation to support agriculture. The intruder drilling scenario is highly unlikely due to the nature of the embankment design, which as a raised mound covered with rip rap would be a very difficult place to site a drilling rig.

Human intrusion scenarios related to construction, agriculture, and discovery, were developed for the draft Environmental Impact Statement supporting 10 CFR 61 (NRC 1981). The conceptual framework and exposure pathways related to intruder-construction are described in Section 4.2.2.1 of NRC (1981) as follows:

> This scenario involves the assumed construction of a house directly into the disposed waste. During construction activities, some of the waste is assumed to be contacted by the workmen (this could happen, for example, through construction of a basement). During construction, some of the waste is assumed to be dispersed into the air and onto the immediate area around the house. Exposures would principally occur through such pathways as inhalation of contaminated dust and exposure to direct gamma radiation from standing on contaminated soil and being immersed in a contaminated dust cloud."

The conceptual framework and exposure pathways related to the intruder-agriculture scenario are described in Section 4.2.2.2 of NRC (1981) as follows:

> The second (agriculture) scenario involves a potential situation in which an individual or individuals live in the house thus constructed. In addition to the exposure pathways for the construction scenario, the potential intruder could be exposed through consumption of food grown in the contaminated soil.

The conceptual framework and exposure pathways related to intruder-discovery are described in Section 4.3.4.3 of NRC (1981) as follows:

> The two intruder scenarios (construction and agriculture) analyzed both contain one very large assumption – that the soil/waste mixture in which construction or agriculture takes place is more or less indistinguishable from dirt. […] If the wastes were placed into a stable form or package and were also segregated and disposed of in separate disposal cells so that waste degradation would be minimized, then the likelihood of inadvertent intrusion would be greatly reduced. […] Potential exposures would be limited to those received during discovery of the waste.

The intruder-discovery scenario described in NRC (1981) therefore involves external exposure to discoverable wastes that are clearly distinguishable from natural materials. The dose assessment methodology described in NRC (1981) was updated in NUREG/CR-4370 (NRC 1986). NRC (1986) provides additional guidance on development of the intruder- construction, intruder-agriculture, and intruder-discovery scenarios and introduces a separate, preceding intruder-drilling scenario. As described in Section 4.1.1.1 of NRC (1986):

> It would be unreasonable to expect the inadvertent intruder to initiate housing construction at a comparatively isolated location before assuring that water for home and garden use will be available. Thus, this scenario (intruder-driller) is assumed to precede the following three scenarios.

The exposure pathways related to these scenarios are described in Section 4.2 of NRC (1986) and shown graphically in Figure 6.

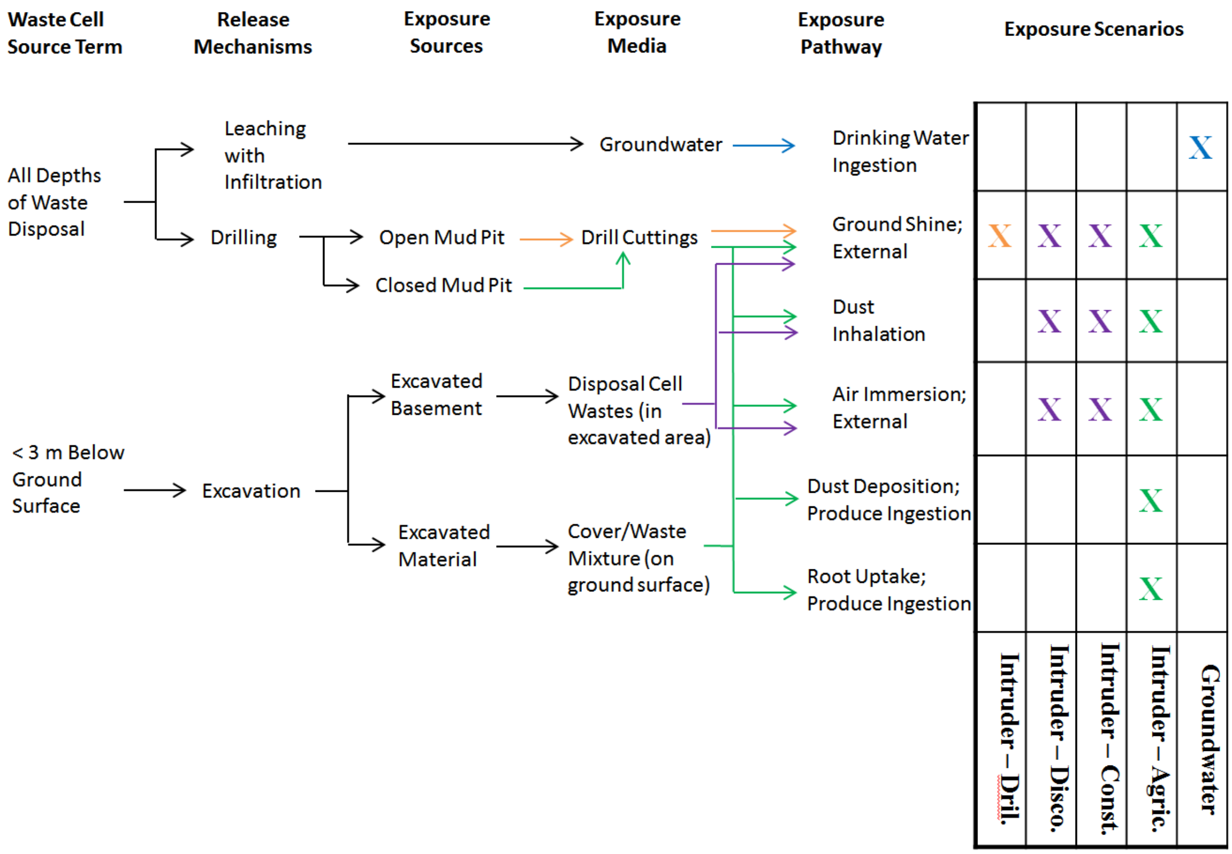


Figure 6: Exposure pathways for inadvertent intruder scenarios.

The intruder-drilling scenario assumes that waste is brought to the ground surface as drill cuttings as a mixture with cover material, unsaturated zone material, and drilling mud and is then contained in a mud pit used by the driller. The driller (a separate individual from that in any subsequent exposure scenario) may be exposed by direct gamma radiation from the waste mixture in the mud pit (NRC, 1986). Attributes of this scenario such as the dimensions of the mud pit and the depth of drilling fluid above the cuttings are described in Section 4.2.1 of NRC (1986).

The intruder-drilling scenario is assumed to be an initiating event for the intruder-discovery, intruder-construction, and intruder-agriculture scenarios (NRC 1986, Section 4.1.1.1). That potable groundwater is not present below the floor of the Great Salt Lake Desert where the disposal site is located is common knowledge today. However, there is a very remote but finite chance that someone in the future might drill a well to determine whether potable groundwater exists at the Clive, UT site. Even if this were to occur, it is also highly unlikely that a drilling rig would be sited upon the rip rap cap of the embankment, rather than on the flat-lying landscape surrounding the disposal facility. Nevertheless, the initiating scenario of intruder-drilling suggested as an example in NRC (1986) is evaluated in the IHI dose assessment. Consistent with Section 4.1.1.1 of NRC (1986), the three subsequent IHI scenarios are not assessed in this report because the prospective resident will be unable to secure potable water and therefore will not initiate construction of a home.

3.4 Groundwater Exposure Scenario

Exposure related to consumption of groundwater is discussed in Section 5 of NRC (1981) and Section 4.3 of NRC (1986). As described in NRC (1981), the groundwater well is assumed to be located on the disposal facility between the edge of the waste disposal area and the facility boundary. The hypothetical receptor of the groundwater exposure scenario is a resident like the receptor for the intruder-agriculture scenario, except that inadvertent intrusion into the waste does not occur because the groundwater point of compliance is outside the footprint of the disposal cell. Because groundwater at the site is not potable, the groundwater exposure scenario is incomplete. Nevertheless, modeled groundwater radionuclide concentrations are compared to groundwater protection limits described in the facility operating permit for a period of 500 years after embankment closure. Additionally, groundwater concentrations at the time of highest concentrations within 10,000 years are identified.

4.0 Groundwater and IHI Dose Assessment Source Terms

An existing source of Class A waste with known radionuclide inventory has not been defined for this modeling effort. Therefore, radionuclide inventory source terms for the modeling are defined in such a way as to allow the results of the assessments to be scaled to any potential Class A waste streams that may be disposed in the embankment in the future.

4.1 Groundwater Pathway Source Term

The first target of the groundwater pathway assessment is to determine whether any radionuclide that may potentially be disposed in the embankment could reach the hypothetical well at the point of compliance within the 10,000-year modeling period to identify maximum concentrations, given the very low infiltration rates associated with the disposal system. The source term concentration of a radionuclide in RESRAD-OFFSITE is linearly related to the modeled concentrations over time at the well. However, the specific concentration of a radionuclide in the disposal cell is not relevant to the question of whether radionuclide transport to the well occurs within 10,000 years because transport time is independent of source term concentration.

To address this question, a source concentration of 10,000 pCi/g of iodine-129 is used in RESRAD-OFFSITE and assigned to the entire potential waste volume in the CAW embankment at the time of cell closure. Iodine-129 has a half-life of approximately 16 million years, so the amount of radioactivity at the beginning of the modeling period and after 10,000 years is functionally identical. Iodine-129 is assigned a distribution coefficient (K_d) of zero in the contaminated, unsaturated, and saturated zones of the RESRAD-OFFSITE model, which indicates that no adsorption onto soil particles is modeled for transport to the groundwater well. The transport time of a radionuclide with a K_d of zero is identical to that of water itself. In other words, if iodine-129 does not arrive at the point of compliance within 10,000 years it is because no water infiltrating through the embankment cover has reached the point of compliance. The iodine-129 groundwater transport simulation therefore represents a bounding case for any radionuclide. If iodine-129 does not reach the point of compliance within 10,000 years no further evaluation of the groundwater pathway is warranted.

If iodine-129 is modeled to arrive at the point of compliance within 10,000 years, source term concentrations of the individual radionuclides in the embankment (activity per unit mass) for the groundwater modeling are based on Class A waste disposal limits (UAC R313-15-009, Tables 1 and 2) where applicable. The use of Class A limits represents an upper bound on radionuclide waste concentrations for embankment disposal. For radionuclides in potential waste streams that are not included in the Class A tables, source term concentrations for the groundwater pathway evaluation are based on specific activity, which is the radioactivity associated with the radionuclide in a hypothetical pure (e.g. metallic) form. If groundwater protection limits are exceeded at the point of compliance using a combination of Class A limits and specific activities, an evaluation of the groundwater pathway for these radionuclides using anticipated waste concentrations and inventory is warranted.

The list of radionuclides evaluated for the groundwater and IHI modeling include those identified as “to be modeled” in Table 22 of Whetstone Associates (2011), supplemented by additional radionuclides (Energy*Solutions* 2012) that have not been explicitly evaluated in the Class A West PA work to date. These radionuclides are described in Table 2.

Table 2: Radionuclides Evaluated for Groundwater and IHI Modeling

Radionuclide	Source	Half-Life[1] (yr)	Class A Limit (pCi/g)	Class A Limit (Ci/m^3)	Basis
Radionuclides with Class A Limits in UAC R313-15-009					
Am-241	Whetstone 2011	432.7	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Am-243	Whetstone 2011	7370	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Bk-247	Whetstone 2011	1400	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
C-14	Whetstone 2011	5715	4.4E+05	0.8	Class A; Table 1
Cf-249	Whetstone 2011	351	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Cf-250	Whetstone 2011	13.1	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Cf-251	Whetstone 2011	900	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Cf-252	Whetstone 2011	2.646	3.9E+08	700	Class A: < 5yr
Cm-243	Whetstone 2011	29.1	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Cm-244	Whetstone 2011	18.1	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Cm-245	Whetstone 2011	8500	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Cm-246	Whetstone 2011	4770	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Cm-247	Whetstone 2011	1.56E+07	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Cm-248	Whetstone 2011	3.48E+05	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Cm-250	Energy*Solutions* 2012	8300	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Co-60	Whetstone 2011	5.271	3.9E+08	700	Class A; Table 2
Cs-137	Whetstone 2011	30.07	5.6E+05	1	Class A; Table 2
Eu-155	Whetstone 2011	4.75	3.9E+08	700	Class A: < 5yr
Fe-55	Whetstone 2011	2.75	3.9E+08	700	Class A: < 5yr
H-3	Whetstone 2011	12.32	2.2E+07	40	Class A; Table 2
I-129	Whetstone 2011	1.57E+07	4.4E+03	0.008	Class A; Table 1
Na-22	Whetstone 2011	2.604	3.9E+08	700	Class A: < 5yr
Nb-94	Whetstone 2011	20000	1.1E+04	0.02	Class A; Table 1
Ni-59	Whetstone 2011	76000	1.2E+07	22	Class A; Table 1
Ni-63	Whetstone 2011	101	1.9E+06	3.5	Class A; Table 2
Np-237	Whetstone 2011	2.14E+06	1.00E+04	1.80E-02	Class A: > 5yr alpha emitter
Pb-210	Whetstone 2011	22.3	1.00E+04	1.80E-02	Class A; Table 1
Pm-147	Whetstone 2011	2.6234	3.9E+08	700	Class A: < 5yr
Ra-226	Whetstone 2011	1599	1.00E+04	1.80E-02	Class A; Table 1
Sr-90	Whetstone 2011	28.8	2.2E+04	0.04	Class A; Table 2
Tc-99	Whetstone 2011	2.13E+05	1.7E+05	0.3	Class A; Table 1
Tl-204	Whetstone 2011	3.78	3.9E+08	700	Class A: < 5yr
Radionuclides with Disposal License Limits					
Pu-236	Whetstone 2011	2.87	5.0E+02	9.00E-04	disposal license limit; special nuclear material
Pu-238	Whetstone 2011	87.7	1.00E+04	1.80E-02	disposal license limit; special nuclear material
Pu-239	Whetstone 2011	24100	1.00E+04	1.80E-02	disposal license limit; special nuclear material
Pu-240	Whetstone 2011	6560	1.00E+04	1.80E-02	disposal license limit; special nuclear material
Pu-241	Whetstone 2011	14.29	3.50E+05	6.30E-01	disposal license limit; special nuclear material

Pu-242	Whetstone 2011	3.75E+05	1.00E+04	1.80E-02	disposal license limit; special nuclear material
Pu-244	Whetstone 2011	8.11E+07	5.0E+02	9.00E-04	disposal license limit; special nuclear material
U-233	Whetstone 2011	1.592E+05	7.50E+04	1.35E-01	disposal license limit; special nuclear material
U-235	Whetstone 2011	7.04E+08	1.60E+04	2.88E-02	disposal license limit; special nuclear material
Radionuclides without Class A or Disposal License Limits					
Radionuclide	**Source**	**Half-Life (yr)**	**Specific Activity (pCi/g)**	**Specific Activity (Ci/m^3)**	
Ac-227	Whetstone 2011	21.772	7.23E+13	1.30E+08	
Ag-108m	Whetstone 2011	438	7.55E+12	1.36E+07	
Al-26	Whetstone 2011	7.1E+05	1.93E+10	3.48E+04	
Am-242m	Whetstone 2011	141	1.05E+13	1.88E+07	
Ar-39	Energy*Solutions* 2012	269	3.40E+13	6.13E+07	
Ba-133	Whetstone 2011	10.538	2.55E+14	4.59E+08	
Be-10	Whetstone 2011	1.5E+06	2.38E+10	4.29E+04	
Bi-207	Whetstone 2011	32	5.39E+13	9.70E+07	
Bi-210m	Whetstone 2011	3.0E+06	5.67E+08	1.02E+03	
Ca-41	Whetstone 2011	1.03E+05	8.46E+10	1.52E+05	
Cd-113	Whetstone 2011	8.04E+15	3.93E-01	7.08E-07	
Cd-113m	Whetstone 2011	14.1	2.24E+14	4.03E+08	
Cl-36	Whetstone 2011	3.01E+05	3.30E+10	5.93E+04	
Cs-135	Whetstone 2011	2.3E+06	1.15E+09	2.07E+03	
Eu-150	Energy*Solutions* 2012	36	6.61E+13	1.19E+08	
Eu-152	Whetstone 2011	13.54	1.74E+14	3.12E+08	
Eu-154	Whetstone 2011	8.60	2.70E+14	4.85E+08	
Fe-60	Whetstone 2011	1.5E+06	3.97E+09	7.14E+03	
Gd-148	Whetstone 2011	70.9	3.40E+13	6.13E+07	
Hg-194	Whetstone 2011	520	3.54E+12	6.37E+06	
Ho-166m	Whetstone 2011	1200	1.79E+12	3.23E+06	
In-115	Energy*Solutions* 2012	4.4E+14	7.06E+00	1.27E-05	
Mn-53	Whetstone 2011	3.7E+06	1.82E+09	3.28E+03	
Mo-93	Energy*Solutions* 2012	3500	1.10E+12	1.97E+06	
Nb-93m	Whetstone 2011	16.1	2.39E+14	4.29E+08	
Np-236	Energy*Solutions* 2012	1.55E+05	9.76E+09	1.76E+04	
Os-194	Whetstone 2011	6.0	3.07E+14	5.52E+08	
Pa-231	Whetstone 2011	32800	4.71E+10	8.48E+04	
Pb-202	Whetstone 2011	53000	3.34E+10	6.00E+04	
Pb-205	Energy*Solutions* 2012	1.5E+07	1.16E+08	2.09E+02	
Pd-107	Whetstone 2011	6.5E+06	5.13E+08	9.24E+02	
Pm-145	Whetstone 2011	17.7	1.39E+14	2.50E+08	
Pt-193	Whetstone 2011	50	3.70E+13	6.66E+07	
Ra-228	Whetstone 2011	5.76	2.72E+14	4.89E+08	

Rb-87	Energy*Solutions* 2012	4.9E+10	8.38E+04	1.51E-01	
Re-187	Whetstone 2011	4.12E+10	4.64E+04	8.34E-02	
Se-79	Whetstone 2011	3.5E+05	1.29E+10	2.32E+04	
Si-32	Whetstone 2011	160	6.98E+13	1.26E+08	
Sm-146	Energy*Solutions* 2012	1.03E+08	2.37E+07	4.27E+01	
Sm-147	Energy*Solutions* 2012	1.17E+11	2.08E+04	3.74E-02	
Sm-151	Whetstone 2011	90	2.63E+13	4.73E+07	
Sn-121m	Whetstone 2011	44	6.71E+13	1.21E+08	
Sn-126	Whetstone 2011	230000	1.23E+10	2.22E+04	
Tb-157	Whetstone 2011	70	3.25E+13	5.85E+07	
Tb-158	Whetstone 2011	180	1.26E+13	2.26E+07	
Tc-98	Energy*Solutions* 2012	4.2E+06	8.68E+08	1.56E+03	
Te-123	Whetstone 2011	9E+16	3.23E-02	5.81E-08	
Th-229	Whetstone 2011	7400	2.11E+11	3.79E+05	
Th-230	Whetstone 2011	75600	2.05E+10	3.70E+04	
Th-232	Whetstone 2011	1.40E+10	1.10E+05	1.98E-01	
Ti-44	Whetstone 2011	59.2	1.37E+14	2.47E+08	
U-232	Whetstone 2011	69.8	2.21E+13	3.97E+07	
U-234	Whetstone 2011	2.46E+05	6.20E+09	1.12E+04	
U-236	Whetstone 2011	2.342E+07	6.46E+07	1.16E+02	
U-238	Whetstone 2011	4.468E+09	3.36E+05	6.05E-01	
Zr-93	Whetstone 2011	1.5E+06	2.56E+09	4.61E+03	
Radionuclides Not Modeled in RESRAD / RESRAD-OFFSITE					
Radionuclide	**Source**	**Half-Life (yr)**			**Reason why radionuclide was not modeled**
Ba-137	Energy*Solutions* 2012	NA			Stable isotope.
Bi-208	Energy*Solutions* 2012	3.68E+05			Not available in RESRAD or RESRAD-OFFSITE nuclide database; no DCFs published by EPA or ICRP.
Co-59	Energy*Solutions* 2012	NA			Stable isotope.
In-113	Energy*Solutions* 2012	NA			Stable isotope.
Nb-91	Whetstone 2011	700			Not available in RESRAD or RESRAD-OFFSITE nuclide database; no DCFs published by EPA or ICRP.
Nb-92	Whetstone 2011	3.5E+07			Not available in RESRAD or RESRAD-OFFSITE nuclide database; no DCFs published by EPA or ICRP.
Po-208	Whetstone 2011	2.898			Not available in RESRAD or RESRAD-OFFSITE nuclide database.

Po-209	Whetstone 2011	102			Not available in RESRAD or RESRAD-OFFSITE nuclide database; no DCFs published by EPA or ICRP.
Sm-148	Energy*Solutions* 2012	7.00E+15			Not available in RESRAD or RESRAD-OFFSITE nuclide database; no DCFs published by EPA or ICRP.
Sm-149	Energy*Solutions* 2012	NA			Stable isotope.
Sn-117	Energy*Solutions* 2012	NA			Stable isotope.
Tm-170	Whetstone 2011	0.3521			Not available in RESRAD nuclide database. Available in RESRAD-OFFSITE.
V-50	Whetstone 2011	1.4E+17			Not available in RESRAD or RESRAD-OFFSITE nuclide database; no DCFs published by EPA or ICRP.

[1] Half-life values from Chart of the Nuclides, Knolls Atomic Power Laboratory, 17th edition, 2010.
NA: not applicable

4.2 IHI Dose Assessment Source Term

For the IHI dose evaluation, the source term concentrations of all radionuclides shown in Table 2 that can be modeled using the RESRAD computer program will be represented by unit concentrations. Because dose is a linear function of the source term radionuclide concentration, the ratio of concentration to dose for each radionuclide can be used when evaluating waste packages for disposal. These values are reported in RESRAD output files as “Dose/Source Ratios” with units of mrem/yr per pCi/g.

The IHI dose calculations do not proceed from the waste inventory of the entire disposal cell like the groundwater calculations do. Instead, the intruder-driller IHI scenario uses a limited exposure source term related to an open drilling “mud pit” with a defined geometry.

5.0 HYDRUS Infiltration Modeling

This section describes the development of a conceptual model for flow in the evapotranspiration cover system and the 2-D HYDRUS modeling done to test the importance of 2-D flow effects in the current cover designs. The results of the 2-D modeling form the basis for the dimensionality of the water balance calculations using HYDRUS. Additional 1-D HYDRUS calculations are described that provide the basis for the estimate of a steady-state infiltration rate applied in the RESRAD transport model. Input and output files related to the 1-D HYDRUS modeling are provided as an electronic attachment to this modeling report.

5.1 Conceptual Model

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

5.2 Model Dimensionality

While EnergySolutions' Class A West disposal facility is a three-dimensional (3-D) structure, models used to evaluate the embankment's performance may be simplified to one- and two-dimensions (1-D) (2-D), if there is justification. The dimensionality required of the model to demonstrate satisfaction of the embankment's performance objectives depends on the uncertainties associated with the geometry of the cell design and the water balance processes at the site. If water flow in the CAW disposal facility is predominantly vertically downward, a 1-D model will adequately represent the important water balance processes. However, a cover system that includes regions of varied slopes and a lateral drainage layer may require a 2-D or possibly a 3-D model to represent the spatially-dependent horizontal and vertical flow regimes. For CAW performance modeling results to be useful, the dimensionality of the model must be adequate to capture the behavior of the actual system. The following section provides a detailed explanation of how the 3-D water flow systems of the Class A West cell can be accurately represented by analysis in 1 dimension. The CAW geometry is reviewed, significant flow processes are considered, and flow model simplification is justified through multi-dimensional simulations.

As is presented in Figure 4 the two alternate evapotranspiration cover designs considered in this analysis differ in the presence of an additional layer. In general, if a facility design is symmetrical, the design would allow for a two-dimensional (2-D) model of a cross-section to be used that would capture the flow behavior the actual system.

EnergySolutions' cover Design 2 includes a sloping subsurface drainage layer directly above a fine-grained layer (referred to as a filter layer) that generally increases lateral flow along the coarse-grained layer and out of the cover system (Meyer et al. 1996). In such a design, lateral flow is induced by the slope of the filter zone while the fine layer below reduces vertical flow. The capacity flow rate of a drainage layer sloping at an angle β is given by Meyer et al. (1996) as

$$Q^{cap} = K_s \cdot T \cdot i$$

where

K_s = in-plane saturated hydraulic conductivity of the drainage material

T = thickness of the drainage layer

i = gravitational gradient [= sin $\beta \approx$ slope].

This relationship demonstrates that the horizontal flow in a saturated sloping drainage layer increases as the slope increases. Such a filter zone generally requires a 2-D model to accurately represent both the vertical flow due to gravity and capillarity and the lateral flow in the sloping filter zone due to gravity. However, in this case the combination of climate and cover layer properties may maintain flow in the cover system as one-dimensional.

Previous modeling of a non-vegetated rip-rap cover design for the CAW embankment predicts significant flow in the filter layer (Whetstone 2011). Analysis of the traditional rock armored cover showed that lateral drainage is a significant feature of this cover design, with 18 to 19 percent of the average annual precipitation being removed from the cover system by lateral drainage. In fact, lateral drainage was sufficiently significant (and the related vertical infiltration spatially varied) to warrant separate models for the top slope and side slope flow regimes.

The evapotranspiration cover designs considered in this analysis, however, are quite different. Both of the evapotranspiration designs have features that facilitate evapotranspiration of water from the system before it reaches the lateral transport layer. Both evapotranspiration designs have an upper layer of vegetated silty clay 6 inches thick overlying another silty clay layer at least another 6 inches thick above an 18 inch frost protection layer of mixed cobbles to fines (bank-run borrow material). In design 1 this frost protection layer is above the clay radon barriers and in design 2 there is a filter zone between the frost protection layer and the clay radon barriers.

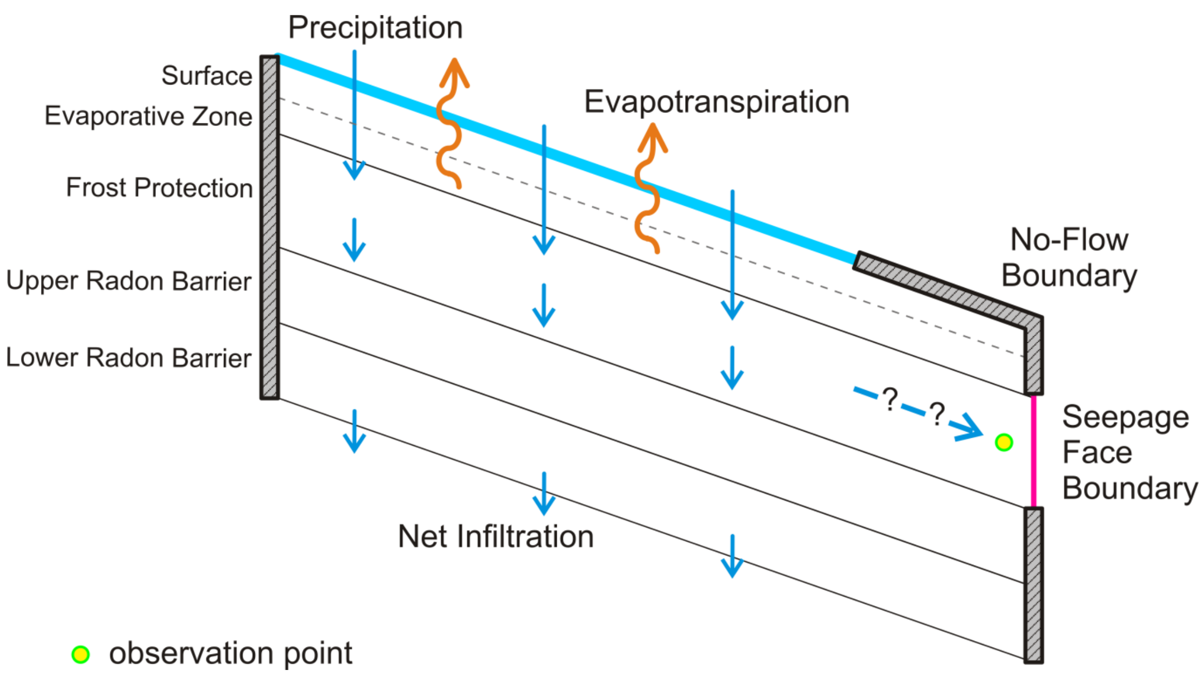
The thick layer of silty clay used in both designs for the surface layer provides storage for water accumulating from precipitation events, enhances losses due to evaporation, and provides a rooting zone for plants that will further decrease the water available for downward movement.

Differences between traditional rock armored design and the alternative evapotranspiration designs considered in this analysis suggest that lateral drainage may not be as important. While there is no filter layer in design 1, some horizontal migration of water may occur in sloped sections of the frost protection layer because of its higher hydraulic conductivity, but this layer was not designed to provide lateral drainage. Design 2 does contain a filter layer, however, near-surface processes of evaporation and root water uptake may be more effective at removing water from the system than in the unvegetated traditional rock armored design. With more water removed from the upper layers of the covers it is less likely that water saturations at depth could increase to the point where the filter layer would laterally divert water.

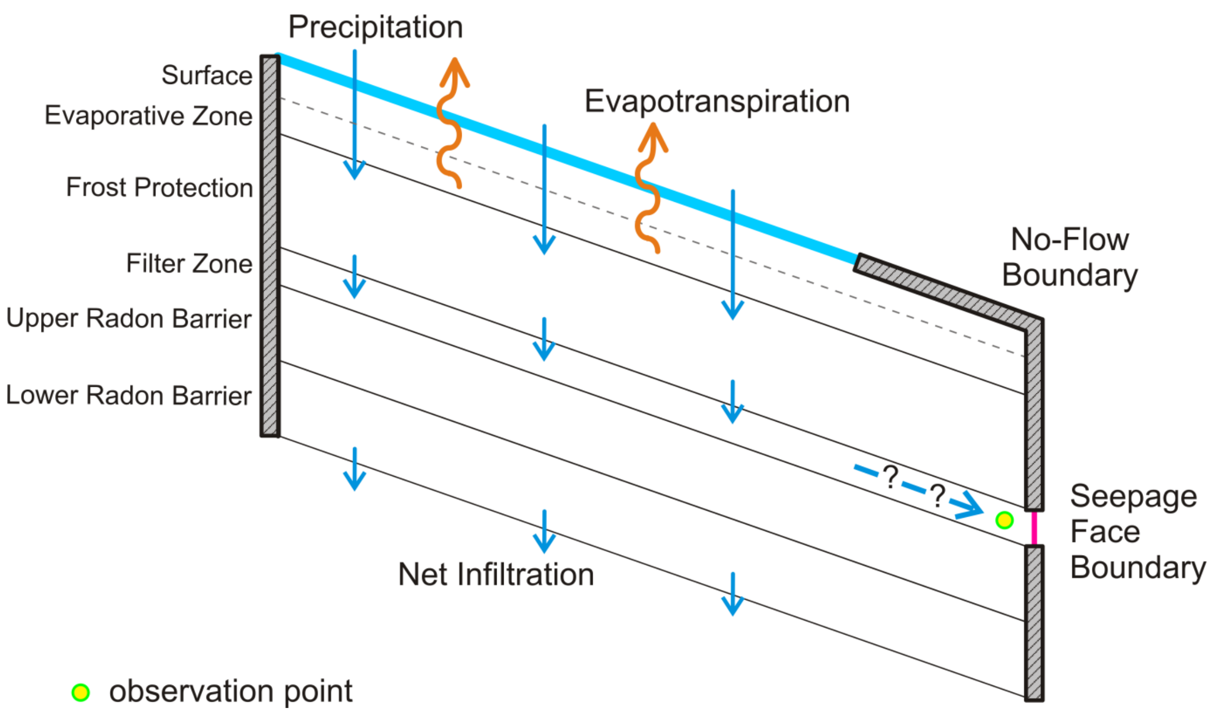
5.3 2-D Models

To test the importance of 2-D flow effects in the current cover designs 2-D transient flow simulations were conducted for representative sections of the both designs. The approach taken was to model a section of the side slope in two-dimensions. The side slope was chosen for the test for two reasons. The first reason is that the 20 percent slope is more likely to induce observable flow than the 4 percent slope sections given the relationship between flow and slope described above. The second reason is that if no lateral flow is seen for a 20 percent slope, then no lateral flow for a 4 percent slope would occur and there would be no contribution from top slope lateral drainage to the side slope that would have to be accounted for.

The procedure for the tests was to assign an atmospheric boundary condition to the upslope portion of the surface layer as shown in Figure 7. The atmospheric boundary condition provides a source of water to the surface through time-varying climate conditions. The surface down slope from the atmospheric boundary condition is maintained as a no-flow boundary such that water cannot enter through this surface. An observation point is placed in the frost protection and filter zone layers down slope from the source of water at a point that can only be reached from the source by lateral flow. The model is run with a daily 100-year atmospheric boundary condition and water content is recorded at the observation point with time. If no change in water content with time is seen over the simulation period, lateral drainage is not occurring. Time-varying changes at the observation point are evidence of lateral drainage.



(A)



(B)

Figure 7: Conceptual models for 2-D HYDRUS flow models for (A) design 1 and (B) design 2.

5.3.1 Climate and Vegetation Parameters

Infiltration of precipitation, surface runoff, and evaporation under time-varying climate conditions are modeled by HYDRUS. The data required includes daily values of precipitation, potential evaporation, and potential transpiration to represent the time-variable boundary conditions on the upper surface of the cover. The location of nearby meteorological stations and the time period of available records were discussed in Section 2. The long-term evaluation period for this analysis makes it necessary to generate a representative climate record with a longer term than the existing data.

The WGEN model (Richardson and Wright 1984) was used to generate a 100-year synthetic precipitation record for the site. The WGEN model is a component of the HELP model (Schroeder et al. 1994a, 1994b). A 100-year precipitation record was generated using the monthly average values from measurements at the site based on 17 years of observations. This 100-year record is shown in Figure 8. The annual mean was 8.42 inches (21.38 cm/yr) with a maximum daily precipitation of 1.09 inches (2.77 cm).

Daily potential evapotranspiration (PET) was calculated with values of daily maximum (T_{max}), minimum (T_{min}), and mean (T_{mean}) temperatures and extraterrestrial radiation using the Hargreaves method (Neitsch et al. 2005). This approach is used extensively and is documented in the HYDRUS manuals (Šimůnek et al. 2009). Using the Hargreaves method, PET is calculated as

$$\lambda E_0 = 0.0023 \cdot H_0 \cdot (T_{\max} - T_{\min})^{1/2} \cdot (\overline{T}_{mean} + 17.8)$$

where

λ = latent heat of vaporization [MJ kg^{-1}]

E_0 = potential evapotranspiration [mm d^{-1}]

H_0 = extraterrestrial radiation [MJ m^{-2} d^{-1}]

T_{max} = maximum air temperature for the day [$^{\circ}$C]

T_{min} = minimum air temperature for the day [$^{\circ}$C]

T_{mean} = mean temperature for the day [$^{\circ}$C].

Monthly mean values for T_{max} and T_{min} based on a 30-year record are available from the Dugway, Utah NOAA station (WRRC 2012). Monthly average temperatures were used from this long-term record in HELP to provide daily 100-year records for T_{max} and $T_{min.}$ The daily 100-year values are shown in Figure 9. T_{max} ranged from 14.7 to 110.7°F with a mean of 66.4 ^{o}F. T_{min} ranged from -9.1 to 75.3°F with a mean of 36.5°F. T_{mean} ranged from 2.8 to 93°F with a mean of 51.4°F. Daily PET values for a 100-year record were then calculated from these temperature data using the Hargreaves method described above. The daily 100-year PET record is shown in Figure 10.

The HYDRUS atmospheric boundary condition requires that potential soil evaporation and potential transpiration be specified separately. Potential evaporation (E_p) and potential transpiration (T_p) can be calculated from PET using the Beer-Lambert law (Varado et al. 2006; Wang et al. 2009). This calculation requires an estimate of the vegetation leaf area (LAI) index. The leaf area index is the one-sided active leaf area per unit ground surface area. Using the Beer-Lambert law

$$T_p = PET \cdot (1 - \exp(-a_{bl} \cdot LAI))$$
$$E_p = PET \cdot \exp(-a_{bl} \cdot LAI)$$

Where the a_{bl} coefficient accounts for radiation intercepted by vegetation and is given the default value of 0.5 (Varado et al. 2006). Estimates of LAI are not available for the site so E_p and T_p were calculated using the method of Šimůnek et al. (2009). This method uses an estimate of vegetated soil cover fraction (SCF) to calculate E_p and T_p as

$$T_p = PET \cdot SCF$$
$$E_p = PET \cdot (1 - SCF)$$

The soil cover fraction was estimated from vegetation surveys conducted in the vicinity of the site. The data used were obtained from vegetation plot summaries for surveys conducted on plots 6 through 13 in 2012 provided by SWCA (personal communication) and an earlier survey of plot 3 (SWCA 2011). Percent cover data is shown in Table 3.

Table 3: Percent cover by type for SWCA vegetation survey plots at the Clive Site.

Cover Type	Plot 3 (2010)	Plot 6	Plot 7	Plot 8	Plot 9	Plot 10	Plot 11	Plot 12	Plot 13	Mean
Bare ground	2.3	3.8	2.8	2.3	1.2	59.5	5.5	1.3	0	8.7
Biological soil crust	84.8	85	80	87.1	84.9	25.4	83	80.8	84	77.2
Black greasewood	4.5	16.6	19	0	0	0	0	18.4	17.7	8.5
Bud sagebrush	0	0	0	0	0	0	0	1.3	0	0.1
Clasping pepperweed	0	0	1.6	0	0	0	0	0	0	0.2
Fivehorn smotherweed	0	0	0	0	0	0	0	0	0	0.0
Fourwing saltbush	0	0.7	0	0	0	0	3.5	0	0	0.5
Gray molly	0.2	0.8	0.9	1.3	2.3	1.3	3.8	1.2	1.7	1.5
Halogeton	0.7	0	0.5	0.5	0.6	0.7	0	0.5	0	0.4
Herb sophia	0	0	0.5		0	0	0	0	0	0.1
Litter	6.1	3.4	9	6.9	13.1	11.9	9.5	7.4	8.9	8.5
Mojave seablite	0.3	1.3	3.4	7.4	4.8	2	0.8	0.8	1.2	2.4
Rock (cobble)	0	0	7.5	0	0	0	0	5	0	1.4
Sandberg bluegrass	0	0	0	0	0	5.9	0	0	0	0.7
Shadscale saltbush	0.1	1.3	1.5	5.1	1.6	2.3	2.3	17.3	2.1	3.7

The value of SCF used for the model was estimated by averaging the percent cover for each cover type and adding the mean values of cover types corresponding to vegetation. The final estimate for SCF was 18 percent. The sensitivity of the modeled net infiltration rate to this estimate is evaluated in Section 5.4.2.

The 100-year daily records of precipitation, maximum temperature, and minimum temperature for the site generated by HELP are included in the attached electronic files. The attached files also include the 100-year PET record and the atmosph.in file required by HYDRUS to provide time-varying atmospheric boundary conditions.

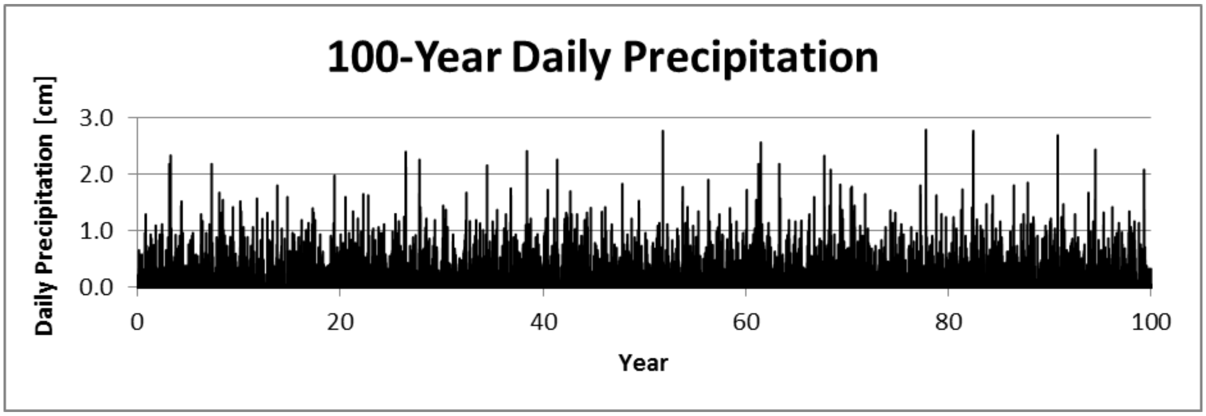


Figure 8: 100-year daily precipitation record generated from monthly average values of daily measurements at the site based on 17 years of observations.

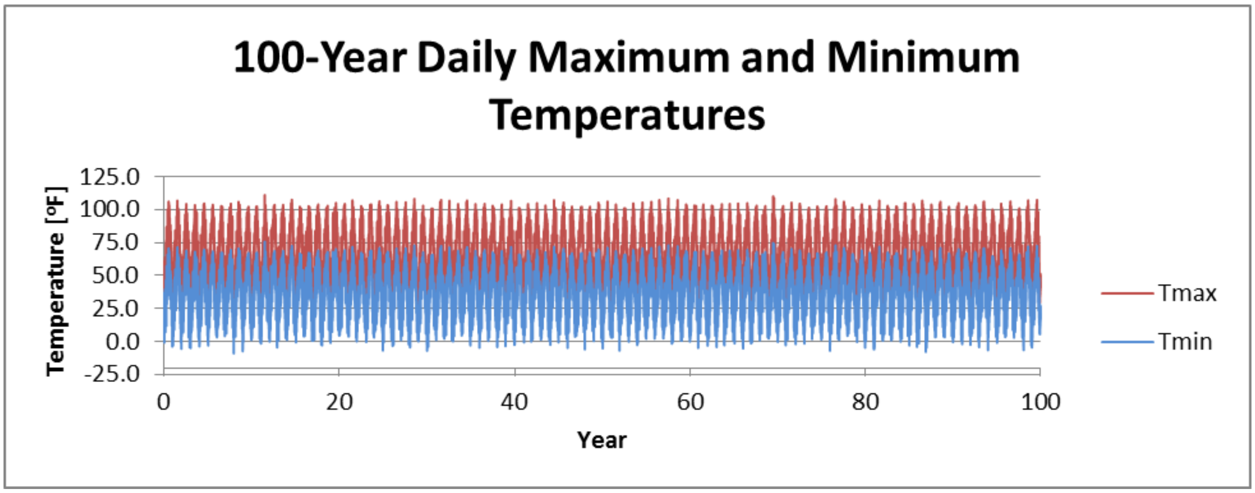


Figure 9: 100-year daily T_{max} and T_{min} record generated from a 30-year record available from the Dugway, Utah NOAA station.

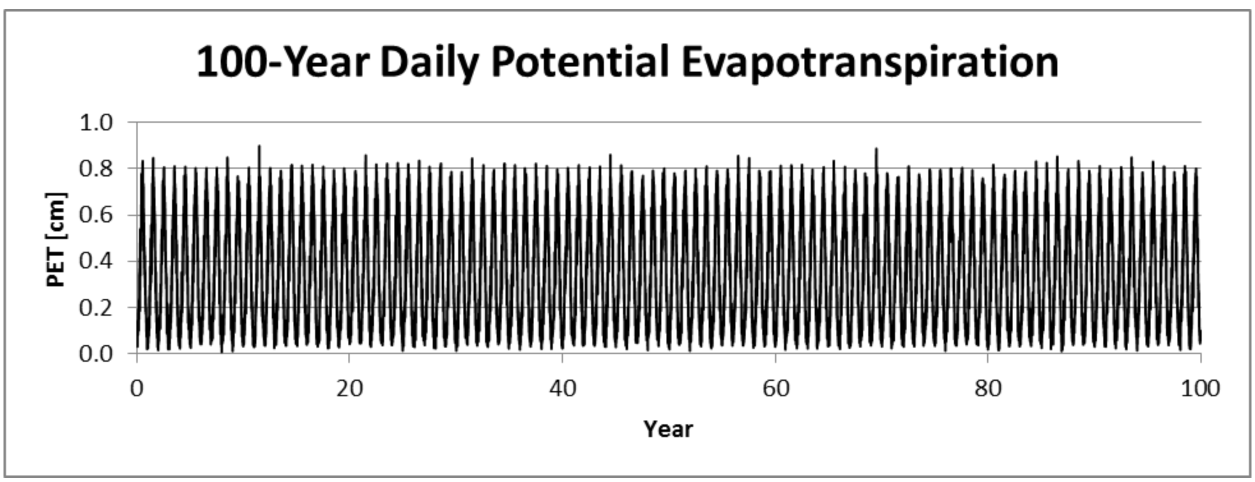


Figure 10: 100-year daily potential evaporation generated using the Hargreaves method.

5.3.2 Root Water Uptake Model

Root water uptake depends on the estimation of daily potential transpiration described above in Section 5.3.1, the depth of the rooting zone, the variation of root density with depth, and the parameters used to describe the water stress function. Measurements of rooting depth and root distribution were conducted in two excavations by SWCA (2011). Rooting depths and density for the two most prevalent species are shown in Figure 11.

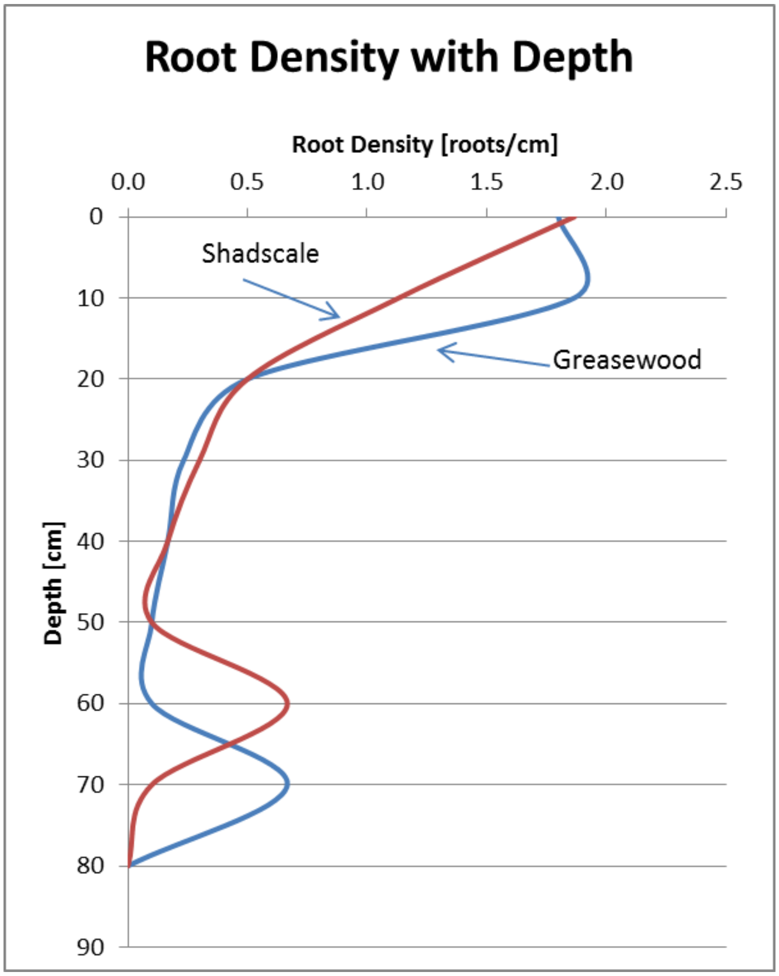


Figure 11: Root density with depth at the Clive Site for Shadscale and Black Greasewood [SWCA 2011].

Root distribution was modeled as extending to the bottom of the evaporative zone layer with a maximum depth of 31 inches (80 cm). Root density was modeled as decreasing linearly with depth.

The van Genuchten S-shaped model (Šimůnek et al. 2009) was used to model root water uptake. In this model the actual root water uptake is given by the potential transpiration multiplied by a water stress response function. For soil water pressures above the wilting point the water stress response function is given by

$$\alpha(h,h_{\phi}) = \frac{1}{1+\left(\frac{h+h_{\phi}}{h_{50}}\right)^{p}}$$

where h is the soil pressure head, h_{φ} is the osmotic head and h_{50} and p are parameters. Osmotic stress is assumed to be negligible for these simulations so h_{φ} is zero. The parameter h_{50} corresponds to the pressure head at which water uptake is reduced by 50 percent. A value of -200 cm was used for these simulations. This value is larger (less negative) than may be typical for desert plants. However, model convergence was difficult with more negative values. The use of a less negative value reduces the amount of water available for root water uptake and thus underestimates losses from the cover system due to transpiration. A HYDRUS default value of 3 was used for the exponent p. The water stress response function with these parameters is shown in Figure 12.

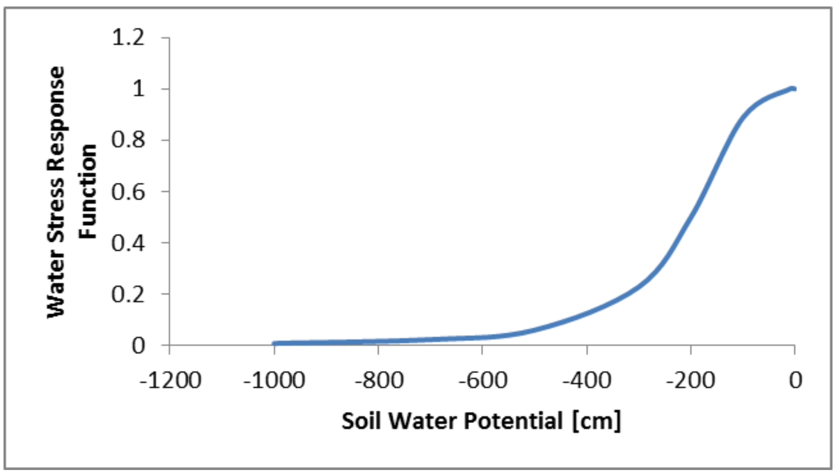
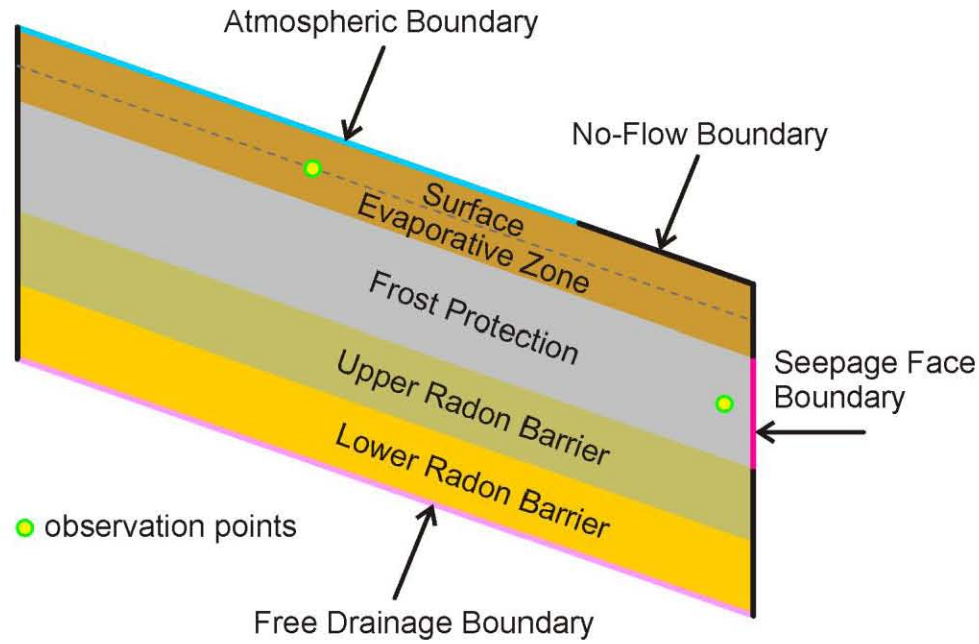


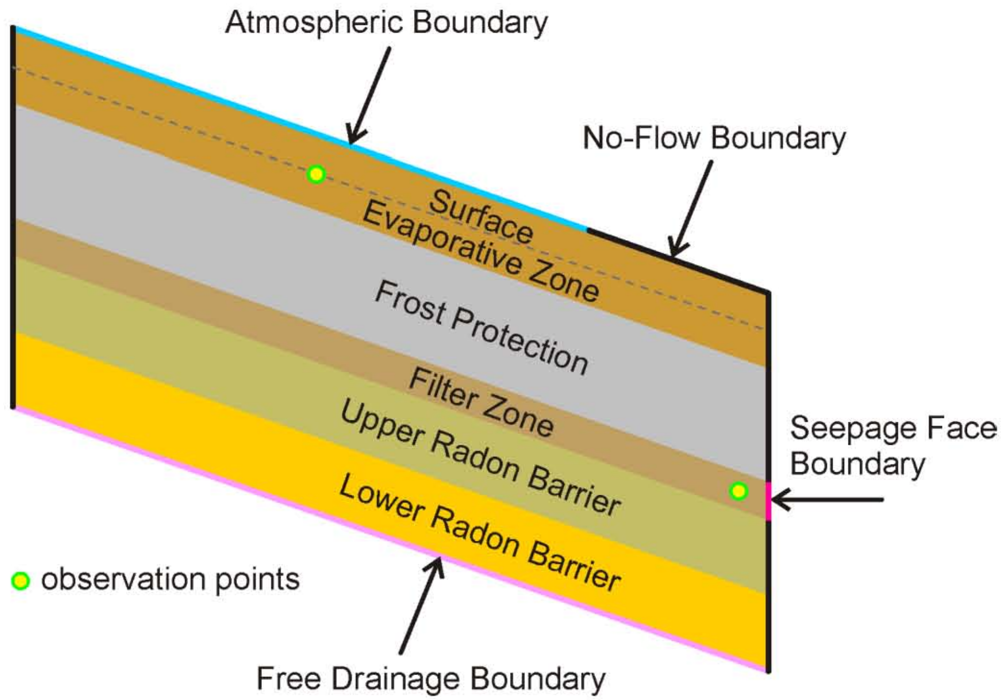
Figure 12: Water stress response function for root water uptake model.

5.3.3 Model Geometry and FE Mesh Discretization

An approximately 30 ft (1000 cm) long section of the 20 percent side slope was modeled in 2-D using HYDRUS 2-D for both designs. Four different layers were modeled for design 1 and five layers for design 2. The surface layer and the evaporative zone for both designs are modeled as having the same hydraulic properties. The composition of the layers and the specification of layer thicknesses were described in Section 2.2. The model domains are shown in Figure 13. The model domain was discretized using a structured finite element (FE) mesh using the HYDRUS mesh generator. A rectangular domain was specified with a 20 percent slope. Horizontal discretization was 10 cm and vertical discretization was set to produce proportionally smaller elements near the surface.



(A)



(B)

Figure 13: Model domain and boundary conditions for the 2-D simulation of (A) design 1 and (B) design 2.

5.3.4 Material Properties

This section provides the material properties used for the analytical hydraulic model. The hydraulic model is a submodel within HYDRUS that provides relationships between water content, water potential, and hydraulic conductivity. The van Genuchten -Mualem (van Genuchten 1980) model was used for all of the flow models. This model requires values for saturated water content (θ_s), residual water content (θ_r), saturated hydraulic conductivity (K_s) and two parameters, α and n. These parameters can be obtained from laboratory analysis of cores, literature values, soil hydraulic property databases, and from inverse modeling. The layers used for the two cover designs were described in Section 2.2 and are shown in Figure 5 (A) and (B). Hydraulic model parameters used for this modeling are shown in Table 4. Hydrogeologic data for the material properties was obtained from previous modeling work at the site (Bingham Environmental 1991) and (Whetstone Associates 2011) and literature values for similar materials (Carsel and Parrish 1988) and (Meyer et al. 1996). The saturated hydraulic conductivity of the filter layer had to be reduced to a value of 864 cm/day for the 2-D model in order to reach model convergence. Extremely large values of hydraulic conductivity result in nearly instantaneous desaturation of the layer and make the simulations unstable. The value of saturated hydraulic conductivity used is large enough to allow any lateral flow for the 2-D models to be simulated. For saturated gravity-driven flow a saturated hydraulic conductivity of 864 cm/day corresponds to a pore water velocity of 109 ft/day. The value of saturated hydraulic conductivity was set to the value in Table 4 for the 1-D simulations where a more highly discretized finite element mesh could be used.

Surface layer: Material properties are assumed to be the same as for Unit 4 material without the small amount of added gravel. Parameters for the Unit 4 material were obtained from water retention measurements on cores obtained from the site (Bingham 1991).

Evaporative Zone layer: This layer is composed of Unit 4 material and is assigned the same properties as the surface layer.

Frost Protection layer: This material ranges in size from 16 inches to clay size particles. When in place the smaller size particles will fill the voids between the cobbles and flow will be determined by the properties of the smaller size fractions. Gradation test results indicated that the particle size fractions were similar to a sandy loam. Relationships between texture and van Genuchten parameters provided in Carsel and Parrish (1988) were used to estimate appropriate properties for this layer.

Filter Zone : The filter material ranges in size from 0.2 to 1.5 inches. The Type-B size gradation corresponds to a coarse sand and fine gravel mix. Material properties were taken from the gravel properties used by Meyer et al. (1996).

Upper Radon Barrier: The engineering design specification for a maximum hydraulic conductivity is 5×10^{-8} cm/s (4.32×10^{-3} cm/day) for this clay barrier. Other parameters for the hydraulic functions were obtained from Whetstone (2011).

Lower Radon Barrier: The engineering design specification for a maximum hydraulic conductivity is 1×10^{-6} cm/s (8.64×10^{-2} cm/day) for this clay barrier. Other parameters for the hydraulic functions were obtained from Whetstone (2011).

Table 4: Material properties for cover system layers.

Layer	Parameter	Value	Units	Source
Surface/Evaporative Zone				
	θ_r	0.0	[-]	Bingham (1991)
	θ_s	0.432	[-]	Bingham (1991)
	α	0.00295	1/cm	Bingham (1991)
	n	1.1202	[-]	Bingham (1991)
	K_s	4.46	cm/day	Bingham (1991)
Frost Protection				
	θ_r	0.065	[-]	Carsel and Parrish (1988)
	θ_s	0.410	[-]	Carsel and Parrish (1988)
	α	0.075	1/cm	Carsel and Parrish (1988)
	n	1.89	[-]	Carsel and Parrish (1988)
	K_s	106.1	cm/day	Carsel and Parrish (1988)
Filter Zone				
	θ_r	0.03	[-]	Meyer et al. (1996)
	θ_s	0.26	[-]	Meyer et al. (1996)
	α	4.695	1/cm	Meyer et al. (1996)
	n	2.572	[-]	Meyer et al. (1996)
	K_s	86,400	cm/day	Meyer et al. (1996)
Upper Radon Barrier				
	θ_r	0.1	[-]	Whetstone (2011)
	θ_s	0.432	[-]	Whetstone (2011)
	α	0.003	1/cm	Whetstone (2011)
	n	1.172	[-]	Whetstone (2011)
	K_s	0.00432	cm/day	Design specifications
Lower Radon Barrier				
	θ_r	0.1	[-]	Whetstone (2011)
	θ_s	0.432	[-]	Whetstone (2011)
	α	0.003	1/cm	Whetstone (2011)
	n	1.172	[-]	Whetstone (2011)
	K_s	0.0864	cm/day	Design specifications

5.3.5 Boundary Conditions

The atmospheric boundary condition in HYDRUS provides the model with daily values of precipitation and evaporation at the soil-air interface. A seepage face boundary condition allows water to leave a saturated portion of the flow domain by moving across a soil-air interface. It is assumed in HYDRUS that water leaving across a seepage face is immediately removed by overland flow or some other process and is no longer considered in the flow domain. The free drainage boundary condition is applied as a unit gradient boundary condition where the water flux across the boundary is equal to the flux due to gravity at the water content of the material. HYDRUS calculates and reports surface runoff, evaporation, and infiltration fluxes for the atmospheric boundary and fluxes for the seepage face and free drainage boundaries.

The boundary conditions for the models for designs 1 and 2 are shown in Figure 13. An atmospheric boundary condition was assigned to a portion of the upper surface of the model. The development of a 100-year record of daily inputs for this boundary was described in Section 5.3.1 above. Precipitation, evaporation, and root water uptake were allowed to occur only on the surface of the upper 23 ft on the upslope side of the model in order to observe any lateral movement into layers downslope. The remaining 7 ft of the upper surface was set to a no-flow boundary. The vertical sides of the model were set to no-flow boundaries with two exceptions. These are the downslope edge of the frost protection layer in design 1 and the filter zone in design 2 which were assigned a seepage face boundary condition to record lateral flows out of the cover system from these layers. The location of these seepage face boundary conditions are shown in Figure 13. A free-drainage boundary condition was applied to the bottom of the lower radon barrier for both designs.

An observation point where water content will be calculated and reported was placed between the surface and evaporative zone layers below the atmospheric boundary condition to record the input of precipitation to the top layer of the cover for both models. Another point was placed in the frost protection layer for design 1 and in the filter layer for design 2 at a point 18 ft further down slope to record the migration of water pulses from infiltration upslope in these layers. The locations of these points are shown in Figure 13. The frost protection layer of design 1 and the filter layer of design 2 were chosen for the observation points because they are included in the designs as the lateral transport layers, and are thus most likely to have lateral flow occur. Since the down slope points are located below a no-flow boundary condition on the surface, water can only reach these points as a result of lateral drainage.

5.3.6 Initial Conditions

An initial pressure head condition of -100 cm was applied to the entire model domain. This pressure head corresponds to a slightly unsaturated condition for the fine-grained materials. The model is deliberately run for a long period of time to in order reach a near-steady state net infiltration rate that is not influenced by the initial conditions.

5.3.7 Root Water Uptake

Root water uptake was modeled assuming the roots extended to the bottom of the evaporative zone layer and a rooting density that decreased with depth. Root water uptake was modeled only under the part of the domain with atmospheric boundary conditions.

5.3.8 Results

The models were run with daily atmospheric boundary conditions for 100 years. After 100 years the models were stopped and the recording interval for the water contents at the observation points was changed to a daily time period. The models were then restarted and run for an additional 10 years with daily atmospheric boundary conditions for each design.

HYDRUS modeled atmospheric flux along the atmospheric boundary condition on the cover surface over the 100-year simulation period is shown in Figure 14. This flux represents the net balance between infiltration and evaporation. Positive values indicate water leaving the cover system due to evaporation while negative values indicate downward movement of water into the cover. The significant temporal variability of this boundary is evident with additions of water to the upper layer occurring in pulses followed by periods of drying. No surface runoff was recorded over the simulation period. This is due to the fact that laboratory measured hydraulic properties for the Unit 4 soil were used for the simulations. These measurements do not account for some processes that can occur in the field. Under actual field conditions, low conductivity crusts can form in the upper few millimeters of the soil surface due to raindrop impact. Dispersed clay particles fill the soil pores and create a thin layer with a greatly reduced hydraulic conductivity (Radcliffe and Šimůnek 2010). The result of this process is a reduction in infiltration and an increase in runoff. Not including the effect of soil crusts on infiltration will overestimate the actual net infiltration rate at the site.

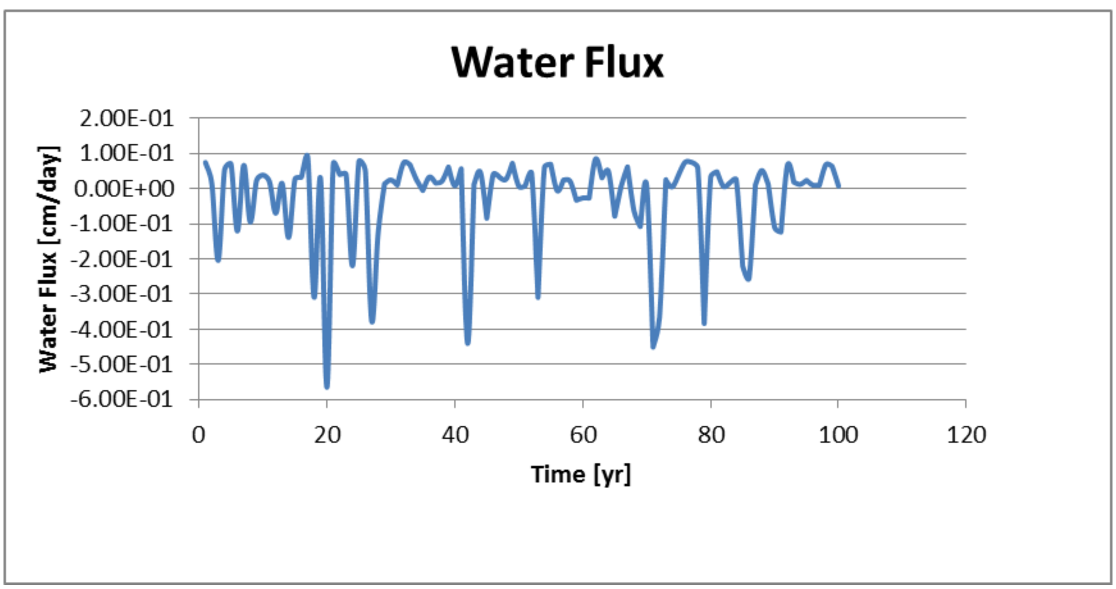


Figure 14: HYDRUS modeled flux of water through the surface over the 100-year simulation period. Negative values indicate flow into the upper layer of the cover and positive values flow out of the upper layer of the cover to the atmosphere.

Water content with time at the observation point in the surface layer for design 1 is shown in Figure 15. Responses to the HYDRUS modeled water flux (Figure 14) are evident in the variations in water content with time due to infiltration, evaporation, and root water uptake in the upper layer at the upslope observation node. No response, however, is seen in water content in the frost protection layer downslope in Figure 15 meaning that over the 100-year period water has not migrated laterally in the frost protection layer.

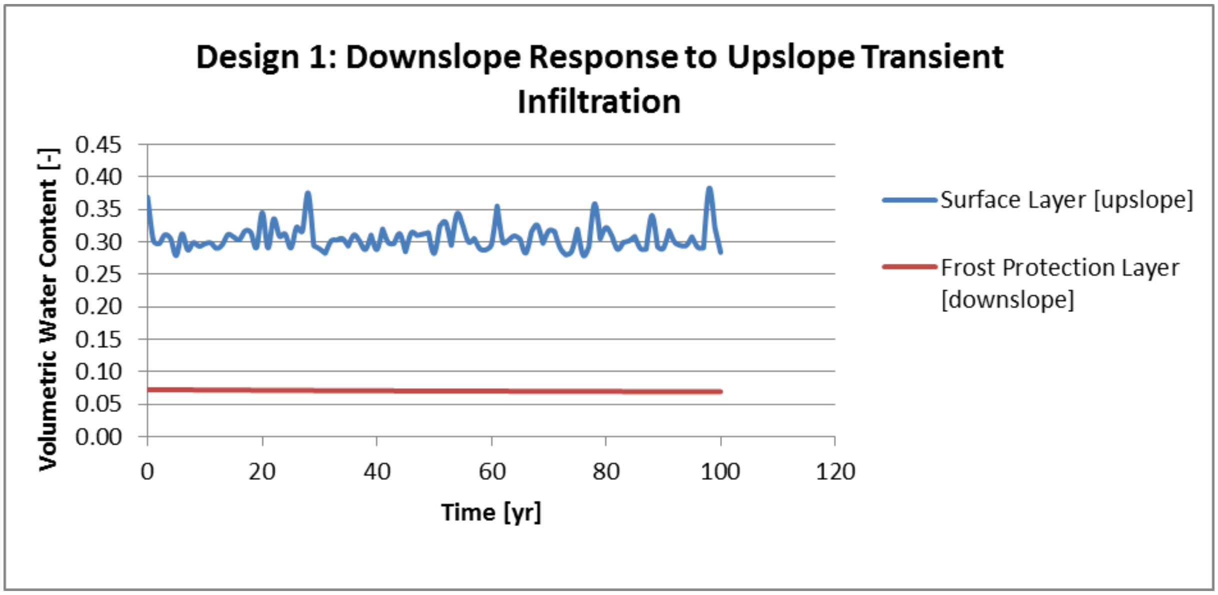


Figure 15: Annual water content response in the Surface layer and the Frost Protection layer to atmospheric boundary conditions for design 1 for a 100-year simulation.

Similar results are seen for design 2 in Figure 16 with no evidence of changing water contents in the filter zone indicating no lateral flow in the filter zone. These plots of water content on an annual scale show no accumulation of water in cover layers due to lateral flow. Zero water flux was recorded through the seepage faces (Figure 13) for both designs for the entire 100-year simulation period meaning that no water is expected to be transported via the horizontal transport layer to the side trenches for either design.

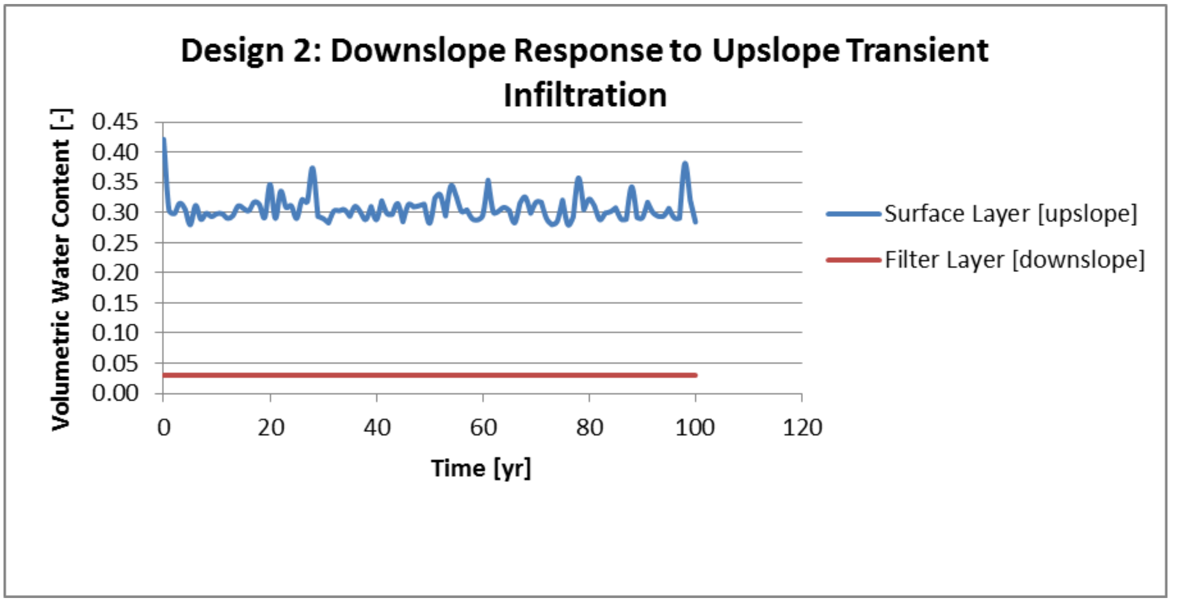


Figure 16: Annual water content response in the Surface layer and the Filter layer to atmospheric boundary conditions for Design 2 for a 100-year simulation.

Simulations were extended for an additional 10 years recording water content at the observation nodes on a daily basis. Figure 17 and Figure 18 show no downslope response to upslope infiltration for either design.

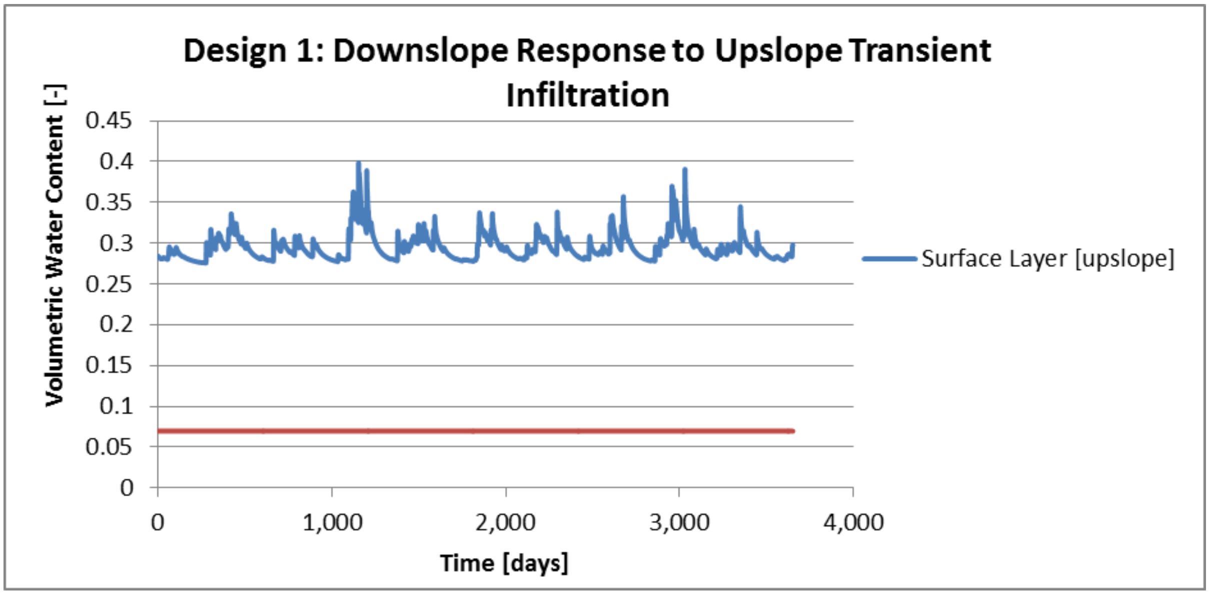


Figure 17: Daily water content response in the Surface layer and the Frost Protection layer to atmospheric boundary conditions for design 1 for the additional 10-year extended simulation.

The results of these 2-D simulations demonstrate that water flow in the cover system for both designs is predominantly vertical with no significant horizontal component. The demonstration of 1-D flow for the 20 percent side slope means that flow will also be 1-D with no lateral flow in the less sloped top slope sections and the crest of the cover. Thus, the top slope of the two ET cover designs cannot provide an additional source of water to the side slope as is seen in traditional rock armor design embankments. In addition, the magnitude of the water flux to the top of the waste for any particular design will not depend on the position on the cover and thus will not have different values for the top slope and the side slope. These results demonstrate that 1-D models can be used to provide a defensible analysis of cover performance for these two evapotranspiration cover designs.

The 2-D HYDRUS models and associated input and output files are provided in the attached electronic files.

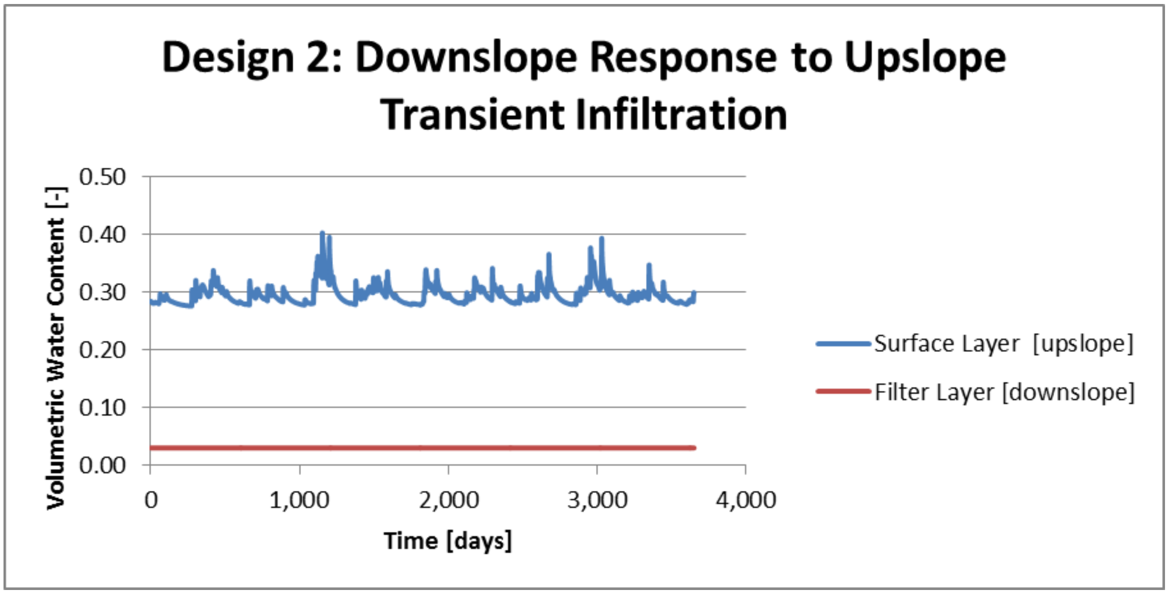


Figure 18: Daily water content response in the Surface layer and the Filter zone to atmospheric boundary conditions for Design 2 for the additional 10-year extended simulation.

5.4 1-D Models

1-D HYDRUS models of the evapotranspiration cover designs were developed and run for 500 years to estimate long-term net infiltration required as input to the RESRAD transport model. In addition, the models were developed to assess the effect of the thickness of the Evaporative Zone layer and the sensitivity of estimated fluxes to soil and vegetation influences.

5.4.1 Evaporative Zone Thickness

The thickness of the evaporative zone layer needed to reduce seepage into the waste zone to an acceptable level was investigated by developing a series of 1-D HYDRUS models for each design with varying thicknesses of the evaporative zone layer. Cases considered were thicknesses of 6 inches (15.2 cm), 12 inches (30.5 cm) and 18 inches (45.7 cm). The thickness and arrangement of the other layers were kept the same as in the 2-D models. A finite element mesh was generated using HYDRUS for each of the models. Relatively small elements were required especially near the surface due to the large hydraulic gradients. Material properties described in Table 4 were assigned to each layer.

The 100-year daily atmospheric boundary conditions described in Section 5.3.1 were applied to the surface. This 100-year record was repeated 5 times to provide time-varying boundary conditions for a 500-year simulation period. A free drainage boundary condition was assigned to the bottom of the Lower Radon Barrier.

Rooting depth varied for each case with roots extending to the bottom of the Evaporative Zone layer. Rooting depths considered were 12 inches (30.5 cm), 18 inches (45.7 cm), and 24 inches (45.7cm), all less than the maximum depth of 31 inches (80 cm) measured in excavations at the site (SWCA 2011). Root density was modeled as varying linearly from 1 at the surface to 0 at the bottom of the Evaporative Zone layer. The root water uptake model used was the same used for the 2-D models described in Section 5.3.2.

An initial pressure head condition of -100 cm of water was set for the entire model domain.

The models were run for 500 years to reach a near-steady state condition that was minimally influenced by the initial conditions. The net infiltration at the top of the waste with time is shown in Figure 19 for design 1 with an Evaporative Zone layer thickness of 18 inches. All other model cases showed similar behavior. This curve represents the change of flow in the cover system with time as the system adjusts from initial conditions to near-steady state conditions representative of the surface boundary conditions imposed by the climate and vegetation. The vertical axis shows net infiltration with a logarithmic axis. Average annual fluxes through the bottom of the Lower Radon Barrier at 500 years are shown in Table 5 and below for the three evaporative zone thicknesses for each design.

Average annual fluxes are small even for the case of the 6 inch thick Evaporative Zone layer. A small reduction in flux is achieved with the increase of thickness by another 6 inches of Unit 4 material, however further increase in thickness provides no additional decrease in net infiltration. The small reduction in flux as the layers become thicker is due to an increase in the capacity of the layer to store water in the near surface until it can return to the atmosphere through evaporation or root water uptake.

For comparison with other designs, the net infiltration calculated for the traditional rock armor design for the same cell was 3.5E-02 in/yr for the top slope and 6.6E-02 in/yr for the side slope (Whetstone 2011).

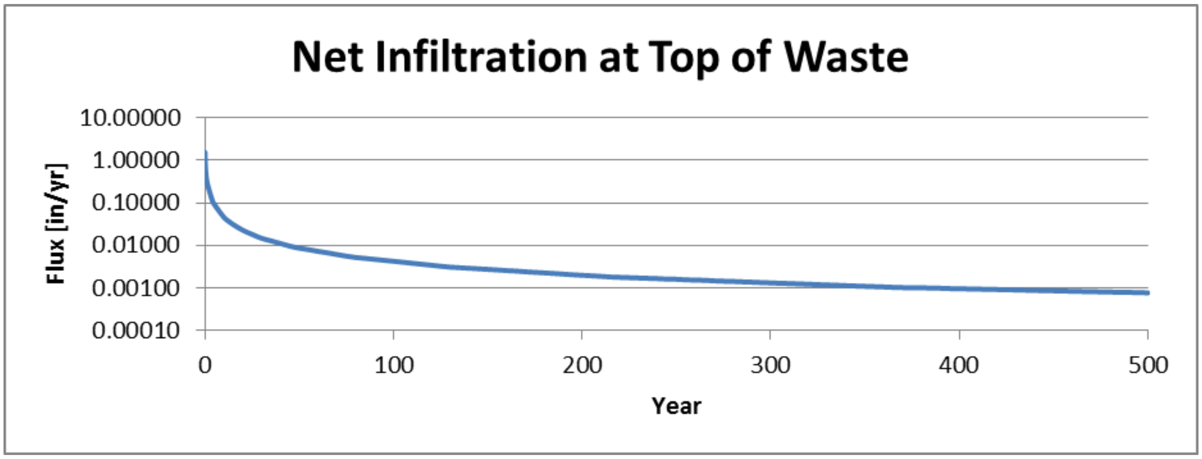


Figure 19: Net infiltration with time at the top of waste for design 1 with an Evaporative zone thickness of 18 inches.

Table 5: Average annual net infiltration through the bottom of the Lower Radon Barrier at 500 years for design 1.

Evaporative Zone Thickness		Net Infiltration Flux	
[in]	[cm]	[in/yr]	[mm/yr]
6	15.2	9.86E-04	2.51E-02
12	30.5	7.77E-04	1.97E-02
18	45.7	7.66E-04	1.95E-02

Table 6: Average annual net infiltration through the bottom of the Lower Radon Barrier at 500 years for design 2.

Evaporative Zone Thickness		Net Infiltration Flux	
[in]	[cm]	[in/yr]	[mm/yr]
6	15.2	7.55E-04	1.92E-02
12	30.5	7.45E-04	1.89E-02
18	45.7	7.43E-04	1.89E-02

5.4.2 Model Sensitivity

The Unit 4 soil used for the Surface and Evaporative Zone layers is classified as a silty clay based on grain size distributions according to the Unified Soil Classification System (Bingham, 1991). The four cores tested had on average slightly less than 50 percent clay and 50 percent silt and a small percentage of clay. The influence of soil properties of the Surface and Evaporative Zone layers was examined by modeling net infiltration for design 1 with a 6 inch thick Evaporative Zone layer using soil hydraulic properties of a coarser-grained material. Soil hydraulic parameters for a hypothetical soil consisting of 35 percent clay, 35 percent silt and 30 percent sand were determined from the database of Carsel and Parrish (1988). The parameters used are listed in Table 7 below.

Table 7: Parameters used for van Genuchten–Mualem hydraulic model for coarse-grained cover layer simulation.

Parameter	θ_r	θ_s	α [1/cm]	n	K_s [cm/day]
Value	0.095	0.41	0.019	1.31	6.24

The long-term annual net infiltration rate into the waste is shown in Table 8. A comparison with the results for Unit 4 soil used in design 1 with a 6 inch Evaporative Zone thickness shown in Table 5 indicates a nearly 3-fold increase in long-term net infiltration using a coarser-grained material in the upper cover layers.

Separation of potential soil evaporation and potential transpiration described in Section 5.3.1 was done using a soil cover fraction (SCF) of 0.18 estimated from vegetation surveys. This value corresponds to a leaf area index of 0.4 which is low when compared with literature values of 1 for sparse vegetation cover (Varado et al. 2006).

The influence of plant transpiration on the long-term annual net infiltration into the waste was examined by modeling net infiltration for design 1 with a 6 inch thick Evaporative Zone with no root water uptake. The long-term annual net infiltration rate into the waste for the cover system without vegetation is shown in Table 8. A comparison with the results for design 1 with a 6 inch Evaporative Zone thickness shown in Table 5 indicates only a 3.5 percent increase in long-term net infiltration when the cover is not vegetated. The 1-D HYDRUS models and the associated input and output files are provided in the attached electronic files.

Table 8: Sensitivity to Vegetation Cover and Cover Material Properties

	Evaporative Zone Thickness		**Net Infiltration Flux**	
Case	[in]	[cm]	[in/yr]	[mm/yr]
No Vegetation	6	15.2	1.02E-03	2.59E-02
Coarse-grained Surface Layers	6	15.2	4.13E-03	1.05E-01

6.0 RESRAD-OFFSITE Transport Modeling for Radionuclide Groundwater Concentrations: Inputs and Results

This section of the report describes the basis of the RESRAD-OFFSITE input parameter values used to evaluate radionuclide groundwater concentrations at the point of compliance and the results of the analysis. The objectives of the radionuclide transport modeling are estimation of radionuclide groundwater concentrations in the period of time up to 500 years following facility closure, and identification of the peak concentrations up to 10,000 years following facility closure. The concentrations through 500 years post-closure are compared to groundwater protection limits described in UAC R317-006. The input and output files for the RESRAD-OFFSITE transport modeling are provided in an electronic attachment to this modeling report.

6.1 Input Parameter Values for the RESRAD-OFFSITE Groundwater Transport Model

RESRAD-OFFSITE input parameter values related to leaching of radionuclides from the contaminated zone and transport through unsaturated and saturated zones to the point of compliance are described in Table 9. The RESRAD-OFFSITE parameter values related to the IHI dose assessment are described in Section 7.

As described in Section 4.1, the RESRAD-OFFSITE groundwater modeling is conducted in a phased manner, with the first objective being to determine whether any radionuclide that may potentially be disposed in the embankment could reach the hypothetical well at the point of compliance within the 10,000-year modeling period. Because of the very low infiltration rates associated with the disposal system, as described in the results of the HYDRUS modeling, it is possible that no water that infiltrates through the cover at the beginning of the modeling period will reach the point of compliance within 10,000 years.

To determine whether any radionuclide could reach the point of compliance within 10,000 years, a source concentration of 10,000 pCi/g of iodine-129 was used in RESRAD-OFFSITE and assigned to the entire potential waste volume in the CAW embankment. Iodine-129 was assigned a K_D of zero in the contaminated zone, and in the unsaturated and saturated zones, which indicates that no adsorption onto soil particles is modeled during leaching and for unsaturated or saturated zone transport. Because no adsorption occurs, there is no retardation of iodine-129 during transport and hence the transport time of iodine-129 is identical to that of water molecules. Due to its very long half-life of approximately 16-million years, no appreciable decay of iodine-129 occurs within 10,000 years. With a K_D of zero and an effectively infinite half-life relative to the 10,000 year modeling period, iodine-129 represents a bounding case for determining whether any radionuclide disposed in the CAW embankment could reach the point of compliance within 10,000 years.

The interface between the HYDRUS and RESRAD-OFFSITE modeling relates to infiltration rate through the cover. The HYDRUS modeling conducted for the CAW embankment established the infiltration rate into the disposed waste at the base of the cover system. The limiting case (highest steady-state net infiltration rate) of the cover alternatives evaluated in

HYDRUS occurs with Design 1 and an evaporation zone thickness of 6 inches (see Tables 5 and 6). The associated infiltration rate at the base of the cover is 0.0251 mm/yr (2.51E-05 m/yr).

RESRAD-OFFSITE accepts user inputs to internally calculate an infiltration rate based on boundary conditions at the ground surface. The infiltration rate (m/yr) is calculated in RESRAD-OFFSITE as:

$$I = (1 - C_e)[(1 - C_r)P_r + I_{rr}]$$

where,

C_e	=	evapotranspiration coefficient (unitless)
C_r	=	runoff coefficient (unitless)
P_r	=	precipitation rate (m/yr)
I_{rr}	=	irrigation rate (m/yr)

Input parameter values for the evapotranspiration coefficient and runoff coefficient have been adjusted such that the infiltration rate calculated within RESRAD-OFFSITE matches the steady-state value of 0.0251 mm/yr developed in HYDRUS. Note that the particular values of the individual parameters in the infiltration equation are not important as long as the set of values returns a calculated infiltration rate to match the value from HYDRUS at the base of the cover system. In other words, the definition and role of these parameters within RESRAD is unimportant in this application because the value of the infiltration rate is defined externally to RESRAD-OFFSITE. As described in Table 9, the irrigation rate was set to 0 m/yr and the average annual precipitation rate for the area was defined as 0.2138 m/yr. The runoff coefficient was set at a value of 0.99. Solving for the remaining term a value of 0.9883 was defined for the evapotranspiration coefficient in order to establish an infiltration rate of 0.0251 mm/yr.

The format of Table 9 includes columns to document the references for parameter values as well as notes to discuss important attributes of the parameter when necessary. In a few cases, these notes describe the results of sensitivity analyses conducted to determine whether model results were affected by the parameter value selected. This was primarily done to confirm that model results were insensitive to the value of a parameter.

Table 9: RESRAD-OFFSITE Groundwater Transport Model Parameter Values and References.

Parameter Description[a]	Units	Value	Reference	Notes
Preliminary Inputs				
Exposure duration	yr	30		This input only affects cancer risk results.
Number of unsaturated zones	unitless	1		
Site Layout				
Bearing of x-axis (clockwise from N)	degrees	90	CAW Final Drawing 10014, C01, Rev. 2	Orientation of Class A West embankment is approximately in line with N-S axis.
X dimension of primary contamination	m	685	CAW Final Drawing 10014, C01, Rev. 2	2246.7 ft; E-W axis, limit of waste disposal
Y dimension of primary contamination	m	780	CAW Final Drawing 10014, C01, Rev. 2	2558.9 ft; N-S axis, limit of waste disposal
X,Y coordinates: fruit, grain, non-leafy vegetables plot	m			Not applicable. Exposure is limited to the groundwater ingestion pathway.
X,Y coordinates: leafy vegetables plot	m			Not applicable. Exposure is limited to the groundwater ingestion pathway.
X,Y coordinates: pasture / silage growing area	m			Not applicable. Exposure is limited to the groundwater ingestion pathway.
X,Y coordinates: grain fields	m			Not applicable. Exposure is limited to the groundwater ingestion pathway.
X,Y coordinates: dwelling site	m			Not applicable. Exposure is limited to the groundwater ingestion pathway.
X,Y coordinates: surface water body	m			Not applicable. Exposure is limited to the groundwater ingestion pathway.
Site Properties				
Precipitation	m/yr	0.2138		See Section 5.3.1 of this report.

Parameter Description[a]	Units	Value	Reference	Notes
Wind Speed	m/s			Not applicable. Transport of contamination to an offsite location and inhalation exposure pathways are not modeled.
Contaminated Zone Physical/Hydrological Parameters				
Length parallel to aquifer	m	780	CAW Final Drawing 10014, C01, Rev. 2	Appdx 10.5, Saturated Zone Modeling; mean value. The length of the N-S axis was selected because groundwater flow direction is generally to the north.
Depth of soil mixing layer	m	0.15	RESRAD default	Value is far below cover zone thickness of 1.8 m. Soil mixing cannot dilute the contaminated zone source term.
Deposition velocity of dust	m/s	0.001	RESRAD default	Not applicable. Transport of contamination to an offsite location is not modeled.
Irrigation	m/yr	0		No irrigation on the embankment is assumed.
Evapotranspiration coefficient	unitless	0.9883		Modified to match the HYDRUS infiltration rate (see text). Sensitivity analysis: Adjusted value of the evapotranspiration coefficient to explore model results using Whetstone (2011) infiltration rates. Changed to 0.2237 to match side slope infiltration rate of 0.066 in/yr (1.7 mm/yr) in Whetstone (2011), Tables 10 and 11. RESRAD mass balance error occurs (Recharge is 908 m^3/yr and GW flow is only 708 m^3/yr). Using the Whetstone top slope infiltration rate of 0.036 in/yr (0.91 mm/yr), breakthrough at the well occurs between 500 and 1000 yr.

Parameter Description[a]	Units	Value	Reference	Notes
Runoff coefficient	unitless	0.99		The runoff coefficient is the fraction of precipitation leaving the cover as runoff. This variable is defined in conjunction with evapotranspiration to match the HYDRUS infiltration rate (see text).
Rainfall and runoff factor	unitless	0.01		A measure of the energy of the rainfall; used to calculate erosion rate and surface soil concentrations. Default is 160. Set to 0.01 to produce a negligible erosion rate; erosion rate is a linear function of this value. (RESRAD-OFFSITE internally-calculated erosion rate is 6.9E-10 m/yr)
Slope-length-steepness factor	unitless	0.4	RESRAD default	Accounts for the effect of terrain on erosion; used to calculate erosion rate and surface soil concentrations.
Cover and management factor	unitless	0.003	RESRAD default	Accounts for the effects of land use (forest, pasture), vegetation (type and height), and management practices (mulching, crop rotation) to calculate erosion rate and surface soil concentrations.
Support practice factor	unitless	1	RESRAD default	Accounts for conservation practices to manage erosion; used to calculate erosion rate and surface soil concentrations.
Thickness of contaminated zone	m	23		76 ft maximum thickness. This thickness is protectively assigned to the entire footprint of the waste, although in actuality the waste thickness decreases with distance from the center of the embankment in proportion to the slope of the cover.
Thickness of clean cover	m	1.8		Approximate CAW Embankment cover thickness.
Total porosity of contaminated zone	unitless	0.437	Whetstone 2011	Table 8 of Whetstone 2011

Parameter Description[a]	Units	Value	Reference	Notes
Total porosity of cover material	unitless	0.428		Value is the higher of Unit 3 and Unit 4 porosity estimates of mean porosity. Estimates calculated with Monte Carlo methods using data from two Unit 4 borehole cores.
Dry bulk density of contaminated zone	g/cm^3	1.8	Envirocare 1998	
Dry bulk density of cover material	g/cm^3	1.56	Bingham Environmental 1991; Appendix B	Based on the lower of Unit 3 bulk density values from two borehole cores. Bulk density calculated from water retention experiments performed by Colorado State University Porous Media Laboratory.
Contaminated zone soil erodibility factor	tons/acre	0.001		Not applicable; cover erosion does not expose waste within the modeling period. Arbitrarily low value used.
Cover soil erodibility factor	tons/acre	0.4	RESRAD default	Rainfall and runoff factor modified to result in a very low cover erosion rate of 6.9E-10 m/yr.
Contaminated zone field capacity	unitless	0.062	Whetstone 2011	Θ_{fc} in Table 8 of Whetstone 2011
Contaminated zone b parameter	unitless	5.3	RESRAD default	Associated with silty loam soil texture (Yu et al 2001; Table E.2) <u>Sensitivity analysis</u>: Changing to 4.0 (lowest value in Table E.2 of Yu et al, 2001) in both waste and unsat zones does not change breakthrough time (between 12.5 and 15K yrs) but increases dose at 15K yr by ~30%. Changing to 11 (upper end of range in Table E.2 of Yu et al, 2001) similar; dose at 15K yr decreases by ~30 %.
Contaminated zone hydraulic conductivity	m/yr	160	Whetstone 2011	K_s in Table 8 of Whetstone 2011 (5E-04 cm/s)
Unsaturated Zone Hydrology				

Parameter Description[a]	Units	Value	Reference	Notes
Number of unsaturated zone strata	unitless	1		Unsaturated zone is primarily Unit 3 materials. Modeled as a single stratum following Whetstone (2011).
Unsaturated zone thickness	m	4.23		Calculated from CAS embankment measurements as the mean value of Zone 3 thickness + the 1-ft clay liner underlying the waste. Mean Zone 3 thickness computed by interpolating data from the 4 corners of the embankment. Thickness at each corner calculated as the elevation of the bottom of the clay liner minus the water table elevation.
Unsaturated zone dry bulk soil density	g/cm^3	1.61	Bingham Environmental 1991; Appendix B	Calculated as particle density × (1 - total porosity). A particle density of 2.65 g/cm3 was assumed based on the higher of values calculated by Colorado State University Porous Media Laboratory from two Unit 3 borehole cores.
Unsaturated zone total porosity	unitless	0.393		Based on the saturated moisture content of Zone 3. Estimate calculated with Monte Carlo methods using data from two Unit 3 borehole cores.
Unsaturated zone effective porosity	unitless	0.393		Effective and total porosity assumed to be identical.
Unsaturated zone field capacity	unitless	0.232		Based on Unit 3 soil texture of 45% sand, 39% silt, and 15% clay (Appdx 10.5, Unsaturated Zone Modeling). Field capacity from Table 4 of Schroeder et al, (1994a); HELP soil class 8 (loam).
Unsaturated zone hydraulic conductivity	m/yr	227		Associated with silty loam soil texture (Yu et al 2001; Table E.2). Sensitivity analysis: Changing this value to 0.001 m/yr or 1000 m/yr does not alter the result of no breakthrough at the well in the 10,000-year modeling period.

Parameter Description[a]	Units	Value	Reference	Notes
Unsaturated zone b parameter	unitless	5.3	RESRAD default	Associated with silty loam soil texture (Yu et al 2001; Table E.2) Sensitivity analysis: Changing to 4.0 (lowest value in Table E.2 of Yu et al, 2001) in both waste and unsat zones does not change breakthrough time (between 12.5 and 15K yrs) but increases dose at 15K yr by ~30%. Changing to 11 (upper end of range in Table E.2 of Yu et al, 2001) similar; dose at 15K yr decreases by ~30 %.
Unsaturated zone longitudinal dispersivity	m	0.15		Higher values of longitudinal dispersivity result in shorter radionuclide transport times. Longitudinal dispersivity is a function of the length of the flow path (Gelhar et al, 1992). The ratio of dispersivity to unsaturated zone thickness for the RESRAD-OFFSITE default values is 0.025. This is less than a value of 0.036 based on linear regression of the data shown in Figure 1 of Gelhar et al (1992). The higher ratio of 0.036 was protectively applied to calculate dispersivity as 0.036 × 4.23 m.
Saturated Zone Hydrology				
Thickness of the saturated zone	m	4.94	Envirocare 2000; Envirocare 2004	Calculated as the mean of a normal distribution from measurements at wells GW-19B, GW-27D, GW-25, and GW-1.
Dry bulk density of saturated zone	g/cm^3	1.57	Whetstone 2000; Section 7.1.2	
Saturated zone total porosity	unitless	0.29	Whetstone 2000; Section 7.1.3	
Saturated zone effective porosity	unitless	0.29		Effective and total porosity assumed to be identical.

Parameter Description[a]	Units	Value	Reference	Notes
Saturated zone hydraulic conductivity	m/yr	237.5	Whetstone 2011	
Saturated zone hydraulic gradient	unitless	0.001	Whetstone 2011	
Depth of aquifer contributing to well	m	4.94		Corresponds to the screened interval of the well. Assumed to be equal to the aquifer thickness.
Saturated zone longitudinal dispersivity	m	0.99		Higher values of longitudinal dispersivity result in shorter radionuclide transport times. Longitudinal dispersivity is a function of the length of the flow path (Gelhar et al, 1992). The ratio of dispersivity to groundwater flow path length (distance to the well) for the RESRAD default values is 0.030. This is less than a value of 0.036 based on linear regression of the data shown in Figure 1 of Gelhar et al (1992). The higher ratio of 0.036 was protectively applied to calculate dispersivity as 0.036 × 27.4 m (90 ft).
Saturated zone horizontal lateral dispersivity	m	0.001		RESRAD default is 0.4, smaller values of lateral dispersivity are conservative because dilution in the aquifer is minimized.
Select: 1) disperse vertically 2) do not disperse vertically	unitless	Do Not		Lack of vertical dispersion reduces dilution along the groundwater path to the well.
IF 1) vertical lateral dispersivity	m			
IF 2) averaged over sat zone length to well:				
Irrigation rate	m/yr	0		No irrigation assumed to exist in the area.
Evapotranspiration coefficient	unitless	0.99		This value applies to the ground above the GW transport pathway. High ET results in minimal dilution of GW with clean infiltration outside the bounds of the embankment.

Parameter Description[a]	Units	Value	Reference	Notes
Runoff coefficient	unitless	0.99		This value applies to the ground above the GW transport pathway. High runoff results in minimal dilution of GW with clean infiltration outside the bounds of the embankment.
Water Use				
Human consumption rate	L/yr	730		2 L/day. UAC R317-6-2.
Number of humans consuming	unitless	2		RESRAD default is 4; lower water use corresponds to minimal required pumping rate and less dilution of contamination in well water (Yu et al 2007).
Use indoors of dwelling	L/day	100		RESRAD default is 225; lower water use corresponds to minimal required pumping rate and less dilution of contamination in well water (Yu et al 2007).
Beef cattle consumption rate	L/day			Not applicable. Exposure is limited to the groundwater ingestion pathway.
Number of cattle consuming	unitless			Not applicable. Exposure is limited to the groundwater ingestion pathway.
Dairy cow consumption rate	L/day			Not applicable. Exposure is limited to the groundwater ingestion pathway.
Number of cows consuming	unitless			Not applicable. Exposure is limited to the groundwater ingestion pathway.
Irrigation applied to fruit, grain, and non-leafy vegetables	m/yr			Not applicable. Exposure is limited to the groundwater ingestion pathway.
Irrigation applied to leafy vegetables	m/yr			Not applicable. Exposure is limited to the groundwater ingestion pathway.
Irrigation applied to pasture or silage	m/yr			Not applicable. Exposure is limited to the groundwater ingestion pathway.
Irrigation applied to livestock feed grain	m/yr			Not applicable. Exposure is limited to the groundwater ingestion pathway.

Parameter Description[a]	Units	Value	Reference	Notes
Well pumping rate	m^3/yr	100		RESRAD default is 5100. Minimum water need calculated in RESRAD-OFFSITE is 74.5 m^3/yr. Smaller values minimize radionuclide dilution and are more protective (Yu et al 2007).
Groundwater Transport				
Distance parallel to aquifer flow from downgradient edge of contamination to well	m	27.4		A 90 ft distance is defined in the license application.
Distance perpendicular to aquifer flow from center of contamination to well	m	0		The well is assumed to be located in the center of the groundwater flow path from the embankment.
Convergence criterion	unitless	0.0001		RESRAD default is 0.001. Lower value improves precision as long as the model converges.
Number of saturated zone sub zones (to model dispersion of progeny)	unitless	1	RESRAD default	
Number of partially saturated zone sub zones (to model dispersion of progeny)	unitless	1	RESRAD default	Includes selection among 3 variations of longitudinal dispersion and retardation characteristics: "nuclide specific retardation in all subzones, longitudinal dispersion in all but the sub zone of transformation". Sensitivity analysis: selection among the 3 alternatives does not affect results.

[a] RESRAD parameter values related to surface exposure pathways for the IHI scenarios assessment are described in Section 7.

6.2 Results of the RESRAD-OFFSITE Groundwater Modeling

Concentrations in well water and drinking water doses were identified at 10 points in time between model year zero and model year 10,000. Iodine-129 did not reach the groundwater well within the 10,000-year time frame. Groundwater concentrations were 0 pCi/g and annual radiation dose was 0 mrem/yr at all model calculation times. Because iodine-129 does not even reach the groundwater point of compliance within the model timeframe of 10,000 years, other radionuclides are not evaluated. Iodine-129 represents a bounding condition for potential breakthrough at the point of compliance due to the use of a K_D of zero and very long half-life of approximately 16-million years. The RESRAD-OFFSITE results indicate that no radionuclides have the potential to reach the groundwater point of compliance within 10,000 years. In simulations extending beyond the 10,000-year modeling period, breakthrough of iodine-129 at the point of compliance was between approximately 12,500 and 15,000 years. The input and output files for the RESRAD-OFFSITE transport modeling are provided in an electronic attachment to this modeling report.

As described in the notes field of Table 9, several protective assumptions were made to ensure that groundwater transport times to the point of compliance were not underestimated. For example, the thickness of the entire footprint of the contaminated zone was protectively set as the maximum waste thickness at the center of the CAW embankment. In actuality the waste thickness decreases with distance from the center of the embankment in proportion to the slope of the cover and reaches zero at the edges of the embankment. RESRAD does not support a pyramidal contaminated zone geometry. Also, longitudinal dispersivity in the unsaturated and saturated zones was set at a larger value than that suggested by RESRAD default values, as described in Table 9. Larger values of longitudinal dispersivity reduce the potential breakthrough time. Lateral dispersivity was set to a very low value to effectively shut down this mechanism of contaminant dilution in the saturated zone.

The results of this groundwater transport modeling differ from those described in Whetstone (2011), where breakthrough of some radionuclides was observed at the same point of compliance near 500 years. The difference appears to be attributable primarily to the difference in steady-state infiltration rates used. Using the Whetstone (2011) top slope infiltration rate of 0.036 in/yr (0.93 mm/yr) in place of the HYDRUS value of 0.025 mm/yr, and adjusting the evapotranspiration rate accordingly as described in Section 6.1, iodine-129 was modeled to break through at the point of compliance at a time between model year 500 and model year 1000.

7.0 IHI Dose Assessment Modeling: Inputs and Results

This section of the report describes the basis of the RESRAD input parameter values used to evaluate radionuclide dose under the Intruder-Driller scenario for the period of time up to 1000 years following facility closure identified in the license application. A parallel evaluation of external dose from radionuclides in an open “mud pit” using the MicroShield® program is also provided.

In principle, annual doses for IHI scenarios are compared to an annual dose limit of 500 mrem/yr, as described in Section 5.1.1 of NRC (1981). In this assessment, unit concentrations of radionuclides are employed to produce ratios of dose per unit waste concentration (mrem/yr per pCi/g), referred to as “dose / source ratios” (DSRs) in output files of the RESRAD program. Because dose is a linear function of radionuclide concentration, these DSRs may be employed with any proposed or actual radionuclide waste concentration to calculate Intruder-Driller doses as the product of the DSR and the waste concentration. A discussion to support interpretation of the dose assessment results is also presented in this section. The input and output files for RESRAD, as well as Excel® files documenting the compilation of DSRs, are provided in an electronic attachment to this modeling report.

7.1 Input Parameter Values for the IHI Dose Assessment

Input parameter values related to the on-site IHI Intruder-Driller scenario are described in this section. The RESRAD input parameters for the Intruder-Driller are summarized in Table 10. The format of Table 10 includes columns to document the references for parameter values as well as notes to discuss important attributes of the parameter when necessary. In a few cases, these notes describe the results of sensitivity analyses conducted to determine whether model results were affected by the parameter value selected. This was primarily done to confirm that model results were insensitive to the value of a parameter.

The RESRAD program requires as an input an estimate of the annual average absolute humidity in air (mass of water per volume of air). This value is employed in the tritium exposure pathway calculations. However, only information for relative humidity (Whetstone 2011; Table 2) was available for use. Therefore, the relative humidity value was converted to absolute humidity, as described here. The method and equations for the conversion were obtained from an organization that promotes the application of physics to the preservation of materials (http://www.conservationphysics.org/atmcalc/atmoclc2.pdf). In the first step of the conversion, a saturation water vapor pressure was calculated for the mean annual temperature of 10.8 C at Clive, UT (Whetstone 2011; Table 7) according to:

$$VP_{sat} = 610.78 \times \mathrm{EXP}(\ T / (T + 283.3)\ ) \times 17.2694$$

where,

VP_{sat} = saturation water vapor pressure (Pa)

T = mean annual temperature (ºC)

The concentration of water in air at VP_{sat} was then calculated according to:

$$C_{sat} = \{(VP_{sat} \times 0.002166) / (T + 273.16)\} \times 1000 \text{ g/kg}$$

where,

C_{sat} = concentration of water in air at VP_{sat} (g/m^3)

Absolute humidity is then calculated as the product of the relative humidity and C_{sat}.

The treatment of parameter values related to the infiltration rate (precipitation, irrigation, evapotranspiration, and runoff) has been described in relation to the groundwater transport model in Section 6.1. The infiltration rate is defined identically in RESRAD and RESRAD-OFFSITE, and the parameter values described in Section 6.1 are also applied in the IHI calculations. With respect to leaching of contamination from the buried waste over time, the condition established using the HYDRUS model is equally applicable to the IHI calculations in RESRAD. The cover system is assumed to remain intact up to the point in time where an IHI event may occur. At that time, the dimensions of the contaminated zone for human exposure are defined in a scenario-specific manner as discussed in Section 3.3 and defined in Table 10.

Table 10: RESRAD Parameter Values and References for the Intruder-Driller Scenario.

Parameter Description[a]	Units	Value	Reference	Notes
Soil Concentration Data				
Distribution coefficients (K_d's)	cm^3/g	Default values	RESRAD defaults	Due to the very low infiltration rate, leaching of radionuclides from the contaminated zone is negligible. Identification of site-specific K_ds for surface exposure pathways is unnecessary.
Radiation dose limit	mrem/yr	25	UAC R313-15-402 and Title 10 CFR §61.41	Applies to calculation of single radionuclide soil guidelines within the RESRAD program.
Calculation Times				
Times for reporting results	yr	1, 10, 50, 100, 250, 500, 750, 1000		Modeling period for radiological decay and ingrowth is 1000 yr. The very low infiltration rate and effectively zero erosion rate results in a static contaminated zone with respect to radionuclide migration.
Contaminated Zone Parameters				
Area of contaminated zone	m^2	6.7	NRC 1986; Section 4.2.1 and 4.2.4.4	Exposure source term is the open drilling mud pit containing drill cuttings covered by water. Assumed dimensions of the mud pit are 8 ft (2.43 m) × 9 ft (2.74 m).
Thickness of contaminated zone	m	0.3048	NRC 1986; Section 4.2.1	Assumed thickness of drill cuttings in the mud pit is 1 ft.
Length parallel to aquifer flow	m	2.7		Set a 9 ft; this parameter does not affect dose assessment results because groundwater pathways are inactive.
Does the initial contamination penetrate the water table ?	unitless	no		
Cover and Contaminated Zone (CZ) Hydrological Data				The thickness of the waste in the CAW embankment (23 m) greatly exceeds the thickness of the unsaturated zone (4.23 m). The values related to waste material (see Table 9) were assigned to the drill cuttings.
Cover depth	m	0.61	NRC 1986; Section 4.2.1	Depth of drill fluid in the open mud pit is assumed to be 2 ft (0.61 m).

Parameter Description[a]	Units	Value	Reference	Notes
Density of cover material	g/cm^3	1.0		The density of water is applied for this calculation, where the RESRAD cover material (soil) is used as a surrogate for water-based drilling fluid.
Cover erosion rate	m/yr	6.9E-10	See Table 9	An effectively zero cover erosion rate is used corresponding to static cover conditions.
Density of CZ	g/cm^3	1.8	Envirocare 1998	
CZ erosion rate	m/yr	6.9E-10		Effective erosion rate applied in the RESRAD-OFFSITE modeling; see Table 9.
CZ Total porosity	unitless	0.437	Whetstone 2011	Table 8 of Whetstone 2011
CZ Field capacity	unitless	0.062	Whetstone 2011	Θ_{fc} in Table 8 of Whetstone 2011
CZ Hydraulic conductivity	m/yr	160	Whetstone 2011	K_s in Table 8 of Whetstone 2011 (5E-04 cm/s)
CZ “b” parameter	unitless	5.3	RESRAD default	Associated with silty loam soil texture (Yu et al 2001; Table E.2). See discussion of sensitivity in Table 9.
Humidity in air	g/m^3	3.3		Based on the mean of quarterly average relative humidity (37.4%) for a 20-yr period (Whetstone 2011; Table 2) and mean annual temperature of 10.8 C at Clive, UT (Whetstone 2011; Table 7). Employed in tritium pathway calculations. See text for details.
Evapotranspiration coefficient	unitless	0.9883		This value, in conjunction with a runoff coefficient of 0.99 and precipitation of 0.2138 m/yr, yields an infiltration rate of 0.0251 mm/yr (see text of Section 6).
Wind speed	m/s	3.14		Mean value based on 5 years of meteorological records at Clive, UT.
Precipitation	m/yr	0.2138		See Section 5.3.1 of this report.
Irrigation	m/yr	0		No irrigation on the embankment is assumed.
Runoff coefficient	unitless	0.99		See note for evapotranspiration coefficient.
Watershed area for nearby stream or pond	m^2			Not applicable; surface water exposure pathways are inactivated.
Accuracy for water/soil computations	unitless			Not applicable; water-dependent exposure pathways are inactivated.

Parameter Description[a]	Units	Value	Reference	Notes
Saturated Zone Hydrologic Data				Values of all parameters set to RESRAD defaults: the drinking water exposure pathway is inactive and use of irrigation water is not specified. Therefore, model characteristics related to aquifer transport do not affect the intruder dose calculations.
Unsaturated Zone Data				Values of all parameters set to RESRAD defaults: the drinking water exposure pathway is inactive and use of irrigation water is not specified. Therefore, model characteristics related to vertical migration of radionuclides to the aquifer do not affect the intruder dose calculations. Verification: Dose assessment results were compared with CAW-specific values for unsaturated zone hydrology and RESRAD default values. Results over the 10,000-yr modeling period were identical to four significant figures.
Occupancy Data				
Inhalation rate	m^3/yr			The inhalation exposure pathway is inactive in the intruder-drilling scenario.
Mass loading for inhalation	g/m^3	0.00741	NRC 1986; Section 4.2.2	The inhalation exposure pathway is inactive in the intruder-drilling scenario.
Exposure duration	yr	1		This input only affects cancer risk results.
Indoor dust filtration factor	unitless			The inhalation exposure pathway is inactive in this scenario.
External gamma shielding factor	unitless	0.7	RESRAD default	This value does not affect intruder-drilling calculations because no indoor exposure exists for this scenario.
Indoor time fraction	unitless	0.0		
Outdoor time fraction	unitless	0.000685	NRC 1986; Section 4.2.1	Based on a 6-hr exposure event, with 4 hr drilling and 2 hr for casing and well development.
Shape factor	unitless	circular		A circular area maximizes potential external radiation dose.
Ingestion Pathway: Dietary Data				Values of all parameters set to RESRAD defaults: ingestion exposure pathways are inactive in the intruder-drilling scenario.

Parameter Description[a]	Units	Value	Reference	Notes
Ingestion Pathway: Nondietary Data				Values of all parameters set to RESRAD defaults: ingestion exposure pathways are inactive in the intruder-drilling scenario.
Radon				Values of all parameters set to RESRAD defaults: radon inhalation is inactive in the intruder-drilling scenario.
Storage Times Before Use				Values of all parameters set to RESRAD defaults: ingestion exposure pathways are inactive in the intruder-drilling scenario.
Carbon-14 Data				Values of all parameters set to RESRAD defaults. Applies to inhalation and food ingestion exposure pathways, not external radiation.

[a] RESRAD parameter values related to the groundwater pathway are described in Section 6.

7.2 Results of the IHI Dose Assessment

The IHI dose assessment calculations using RESRAD are performed with a modeling period of 1,000 years. Institutional control is assumed to exist during the 100 years following facility closure (NRC 1981; Section 5.1.1). During this period, decay of radionuclides and ingrowth of progeny are occurring but doses to inadvertent intruders are not assessed because active control of the facility will prohibit such exposures. After the institutional control period, it is assumed that inadvertent intrusion may occur at any time. Therefore, the modeling results of interest pertain to a model time period of 100 through 1,000 years.

For the majority of radionuclides, the time of highest potential radiation dose related to a radionuclide and its progeny (if any) occurs before 100 years. For a small subset of radionuclides, the time of highest potential radiation dose occurs at the end of the modeling period due to ingrowth of progeny. Therefore, DSRs at the modeling times of 100 and 1,000 years are always evaluated. There are also a relatively few radionuclides for which the time of maximum dose occurs between 100 and 1,000 years. DSRs at these times are also of interest because they represent a potential point in time where radiation dose may be limiting if the radionuclide in question represents a significant component of a radionuclide inventory being evaluated for disposal. The time within the modeling period where dose is limiting is reported as t_{min} in RESRAD summary report output files in the table labeled *Summed Dose/Source Ratios and Single Radionuclide Soil Guidelines*.

Summed DSRs are available in RESRAD output files only at the model year where total dose for all radionuclides is highest, and for the model year associated with the time of maximum dose for a particular radionuclide. A summed DSR includes the contribution of the parent and all progeny. DSRs that are output from RESRAD for all model calculation times are the individual DSRs for each parent and progeny. As described above, DSRs are required for multiple model years in order to support evaluation of potential dose from varied inventories of disposed radionuclides. Therefore, DSRs for the individual parent and progeny were summed externally. This was accomplished by importing a .txt file with the individual parent and progeny DSRs from the RESRAD summary report file into Excel® software. RESRAD provides DSRs for the parent and each progeny, as well as the sum. When only a single decay branch for a radionuclide exists, it is only necessary to remove all records excepting the DSR sum to establish a single row of summed DSRs for each model calculation time. Where one or more decay branches exist, the DSRs for each branch were first summed with a function within Excel®. Additionally, as described below, DSRs calculated in RESRAD were multiplied by a correction factor to account for dilution of waste with other material as defined in the scenario. The input and output files for RESRAD, as well as Excel® files documenting the compilation of DSRs, are provided in an electronic attachment to this modeling report.

7.2.1 RESRAD Results for the Intruder-Driller Scenario

Dose-source ratios for the Intruder-Driller scenario are provided in Table 11. A single RESRAD simulation was performed for the Intruder-Driller scenario to evaluate external radiation dose to a water well driller from drill cuttings in an open “mud pit”. The DSRs reported in the output of the RESRAD program are based on a unit concentration of 1 pCi/g.

The RESRAD results calculated using a unit concentration of 1 pCi/g must be multiplied by a cuttings dilution factor to account for the proportion of cuttings, cover material, unsaturated zone material, and saturated zone material comprising the cuttings. The thickness of each of these layers, as described in the tables in Sections 6.1 and 7.1, is:

- Cover (1.8 m);
- Waste (23 m);
- Unsaturated Zone (4.23); and.
- Saturated Zone (4.94).

The RESRAD DSRs are modified to account for dilution of the waste by other borehole material according to:

Drill Cuttings DSR = *RESRAD DSR* × cuttings dilution factor

where,

cuttings dilution factor = the ratio of waste thickness : borehole depth

The cuttings dilution factor for a well drilled to the base of the saturated zone is therefore equivalent to the waste thickness (23 m) divided by the borehole length (34 m), or 0.68.

In addition to DSRs at model times of 100 and 1,000 years, DSRs are reported at the time of highest potential dose for Cm-244 (150 yr), Pa-231 (220 yr), and Np-236 (770 yr).

Table 11: Intruder-Driller: Dose / Source Ratios[1] Summed for All Progeny and Branching Fractions.

Nuclide	Year 100	Year 150	Year 220	Year 710	Year 1000
Ac-227+D	3.01E-08	6.12E-09	6.59E-10	1.64E-17	1.08E-20
Ag-108m+D	4.99E-06	3.69E-06	2.42E-06	8.70E-08	2.17E-08
Al-26	5.26E-05	5.10E-05	4.90E-05	3.55E-05	3.10E-05
Am-241	8.40E-12	1.21E-11	1.67E-11	3.97E-11	4.47E-11
Am-242m+D	2.08E-08	1.65E-08	1.20E-08	9.85E-10	3.56E-10
Am-243+D	5.72E-08	5.69E-08	5.65E-08	5.36E-08	5.24E-08
Ar-39	1.02E-11	8.72E-12	6.99E-12	1.23E-12	5.93E-13
Ba-133	1.11E-09	4.39E-11	4.79E-13	1.84E-28	6.57E-35
Be-10	1.66E-11	1.66E-11	1.66E-11	1.66E-11	1.66E-11
Bi-207	2.33E-06	9.07E-07	2.43E-07	7.74E-12	1.02E-13
Bi-210m+D	4.51E-07	4.38E-07	4.21E-07	3.05E-07	2.67E-07
Bk-247	3.52E-08	3.46E-08	3.38E-08	2.81E-08	2.61E-08
C-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca-41	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Cd-113	9.75E-14	9.47E-14	9.09E-14	6.59E-14	5.76E-14
Cd-113m	4.42E-14	3.36E-15	9.10E-17	4.42E-29	3.13E-34
Cf-249	8.51E-07	7.70E-07	6.71E-07	2.26E-07	1.44E-07
Cf-250	1.91E-20	3.11E-20	4.84E-20	2.01E-19	2.73E-19
Cf-251	3.35E-08	3.23E-08	3.06E-08	2.00E-08	1.68E-08
CF-252	1.55E-17	2.35E-17	3.47E-17	1.23E-16	1.59E-16
Cl-36	2.46E-10	2.43E-10	2.38E-10	2.07E-10	1.95E-10
Cm-243	4.95E-09	1.47E-09	2.68E-10	5.28E-13	5.16E-13
Cm-244	8.16E-17	8.27E-17	8.23E-17	7.78E-17	7.60E-17
Cm-245	5.44E-09	5.42E-09	5.39E-09	5.18E-09	5.10E-09
Cm-246	8.53E-18	1.29E-17	1.92E-17	7.48E-17	1.01E-16
Cm-247+D	1.06E-06	1.06E-06	1.06E-06	1.07E-06	1.07E-06
Cm-248	2.13E-12	3.20E-12	4.68E-12	1.63E-11	2.12E-11
Cm-250+D	4.15E-06	4.13E-06	4.10E-06	3.88E-06	3.79E-06
Co-60	8.32E-11	1.16E-13	1.17E-17	0.00E+00	0.00E+00
Cs-135	2.90E-15	2.90E-15	2.90E-15	2.90E-15	2.90E-15
Cs-137+D	3.54E-07	1.11E-07	2.21E-08	6.70E-14	3.30E-16
Eu-150	1.06E-06	3.86E-07	9.35E-08	1.35E-12	1.27E-14
Eu-152	7.30E-08	5.43E-09	1.42E-10	5.41E-23	3.46E-28
Eu-154	5.75E-09	1.12E-10	4.51E-13	6.92E-32	9.38E-40
Eu-155	4.60E-16	4.25E-19	2.40E-23	0.00E+00	0.00E+00
Fe-55	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fe-60+D	4.56E-05	4.56E-05	4.55E-05	4.54E-05	4.53E-05
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hg-194+D	9.79E-06	8.57E-06	7.11E-06	1.64E-06	8.88E-07
Ho-166m	1.15E-05	1.12E-05	1.07E-05	7.80E-06	6.83E-06
I-129	3.11E-25	3.07E-25	3.02E-25	2.62E-25	2.47E-25
In-115	4.21E-12	4.21E-12	4.21E-12	4.21E-12	4.21E-12
Mn-53	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mo-93	1.43E-34	1.41E-34	1.39E-34	1.25E-34	1.19E-34
Na-22	5.38E-17	8.84E-23	7.04E-31	0.00E+00	0.00E+00
Nb-93m	1.23E-37	9.34E-39	2.53E-40	0.00E+00	0.00E+00
Nb-94	1.21E-05	1.17E-05	1.12E-05	7.98E-06	6.92E-06
Ni-59	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-63	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Np-236	2.82E-06	3.56E-06	4.14E-06	4.73E-06	4.73E-06
Np-237+D	2.77E-07	2.77E-07	2.77E-07	2.77E-07	2.77E-07
Os-194+D	4.59E-12	1.42E-14	4.37E-18	9.53E-46	0.00E+00
Pa-231	7.64E-07	7.87E-07	7.92E-07	7.83E-07	7.79E-07
Pb-202+D	1.74E-06	1.74E-06	1.74E-06	1.73E-06	1.73E-06
Pb-205	5.33E-43	5.33E-43	5.33E-43	5.33E-43	5.33E-43
Pb-210+D	1.94E-11	4.10E-12	4.66E-13	1.75E-20	1.38E-23
Pd-107	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-145	3.98E-18	5.62E-19	3.63E-20	1.60E-29	1.97E-33
Pm-147	1.39E-25	2.55E-31	2.37E-39	0.00E+00	0.00E+00
Pt-193	1.06E-43	5.34E-44	2.00E-44	0.00E+00	0.00E+00
Pu-236	8.59E-07	5.31E-07	2.71E-07	1.36E-09	1.48E-10
Pu-238	1.10E-13	1.91E-13	4.42E-13	8.70E-12	1.53E-11
Pu-239	2.46E-11	2.46E-11	2.45E-11	2.42E-11	2.40E-11
Pu-240	3.00E-14	2.99E-14	2.96E-14	2.80E-14	2.73E-14
Pu-241+D	2.31E-13	3.52E-13	5.13E-13	1.30E-12	1.48E-12
Pu-242	4.78E-14	4.92E-14	5.11E-14	6.60E-14	7.22E-14

Pu-244+D	2.76E-06	2.76E-06	2.76E-06	2.76E-06	2.76E-06
Ra-226+D	3.05E-05	2.99E-05	2.90E-05	2.28E-05	2.07E-05
Ra-228+D	5.06E-10	1.22E-12	2.64E-16	4.76E-45	0.00E+00
Rb-87	9.24E-14	9.24E-14	9.24E-14	9.24E-14	9.24E-14
Re-187	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Se-79	1.43E-16	1.39E-16	1.33E-16	9.61E-17	8.38E-17
Si-32+D	1.39E-09	1.29E-09	1.16E-09	4.95E-10	3.47E-10
Sm-146	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	8.61E-34	5.86E-34	3.42E-34	4.94E-36	8.40E-37
Sn-121m+D	1.49E-13	7.70E-14	3.06E-14	2.17E-17	1.04E-18
Sn-126+D	1.15E-05	1.12E-05	1.07E-05	7.75E-06	6.76E-06
Sr-90+D	5.45E-10	1.66E-10	3.13E-11	6.45E-17	2.70E-19
Tb-157	1.13E-20	8.93E-21	6.46E-21	5.09E-22	1.76E-22
Tb-158	4.92E-06	3.91E-06	2.83E-06	2.23E-07	7.69E-08
Tc-98	9.66E-06	9.38E-06	9.00E-06	6.52E-06	5.70E-06
Tc-99	9.91E-14	9.62E-14	9.23E-14	6.68E-14	5.83E-14
Te-123	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Th-229+D	1.36E-06	1.36E-06	1.35E-06	1.28E-06	1.25E-06
Th-230	1.36E-06	2.01E-06	2.90E-06	9.02E-06	1.12E-05
Th-232	6.57E-05	6.57E-05	6.57E-05	6.57E-05	6.57E-05
Ti-44+D	5.01E-06	2.41E-06	8.63E-07	2.73E-10	9.37E-12
Tl-204	4.29E-20	4.34E-24	1.11E-29	0.00E+00	0.00E+00
U-232	2.08E-05	1.29E-05	6.56E-06	3.29E-08	3.59E-09
U-233	1.31E-08	1.95E-08	2.84E-08	9.65E-08	1.24E-07
U-234	6.20E-10	1.38E-09	2.93E-09	3.30E-08	5.39E-08
U-235+D	6.12E-08	6.20E-08	6.32E-08	7.24E-08	7.61E-08
U-236	5.91E-13	7.53E-13	9.80E-13	2.76E-12	3.51E-12
U-238+D	1.76E-07	1.76E-07	1.76E-07	1.76E-07	1.76E-07
Zr-93	2.15E-35	2.16E-35	2.16E-35	2.16E-35	2.16E-35

[1] mrem/yr per pCi/g. DSRs incorporate a borehole dilution factor of 68%, as described in the text.

+D: Includes contribution of daughters (progeny).

7.2.2 Comparison of RESRAD and Microshield® Results for the Intruder-Driller Scenario

The results of calculations of external dose for the Intruder-Driller scenario in RESRAD were compared to analogous calculations performed using Microshield® software, Version 9.05. The Microshield® calculations employed the same dimensions and other attributes of the open mud pit evaluated in RESRAD and described in Section 7.1, but with the orientation of the driller receptor to the side of the pit. In RESRAD, this pathway was evaluated with the receptor located directly above the mud pit source and with soil as a surrogate cover material. As described below, the differences in external dose for three cases were within a range of +/- 20 to 60%. The comparison indicates that RESRAD and Microshield® may be used interchangeably to develop DSRs for the Intruder-Driller scenario. The input and output files for the Microshield® modeling are provided in an electronic attachment to this modeling report.

A schematic representation of the Microshield® case geometry is shown in Figure 20. The shielding (in blue) has been extended above the cuttings source (in green) towards the receptor to emulate the presence of soil cover beneath the receptor, and the height of the exposure point reflects the orientation of a receptors torso standing to the side of the mud pit. As described in Table 10 and consistent with NRC (1986), the assumed mud pit dimensions are 2.43 m by 2.74 m, with a 2-ft (0.61 m) layer of water above a 1-ft (0.3048 m) layer of cuttings.

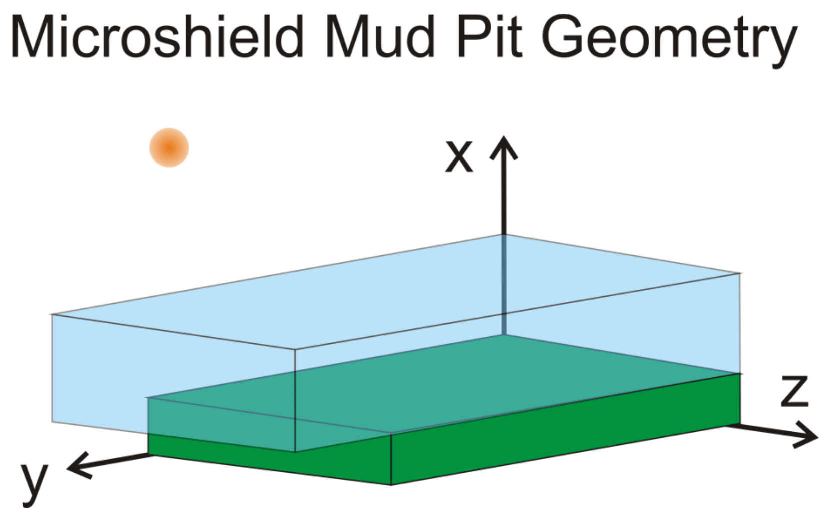


Figure 20: Microshield mud pit geometry.

Although a density of 1.0 g/cm^3 was applied to soil shielding in RESRAD (see Table 10), other differences in the characteristics of the shielding medium (soil in RESRAD and water in Microshield®) may contribute to differences between the external doses. For example, the "buildup" factors for these media, which relate to the photon scattering interactions in the shielding material, will differ for soil and water. RESRAD dose calculations employed external DCFs published in EPA (1993), which differ from those described in ICRP 51 (ICRP, 1987), which is the reference employed in Microshield®. There are a number of differences in the EPA (1993) and ICRP (1978) methods, most obviously that the DCFs in ICRP (1987) are gender-specific, whereas those developed in EPA (1993) are based on a hermaphrodite body phantom. Another potential source of differences between RESRAD and Microshield® is the reference library for radionuclide photon energies and yields. RESRAD employs ICRP 38 for this information. Therefore, this reference was also selected for the nuclide library in Microshield® rather than the default "Groves software" library.

Cesium-137, Co-60, and uranium-235 were selected for comparing RESRAD and Microshield® open mud pit dose calculation results. Unlike RESRAD, Microshield® does not account for the ingrowth of progeny because the calculations are not time-dependent. Therefore, identical source concentrations were defined in Microshield® for Cs-137 and its progeny Ba-137m (where Ba-137m has a half-life of 2.5 min and quickly reaches secular equilibrium) and for U-235 and its progeny Th-231 (where Th-231 has a half-life of 1.06 day). Microshield® accepts source input values with units of µCi/cm^3. A concentration in the source material of 1.8E-6 µCi/cm^3, corresponding to the 1 pCi/g unit concentration used in RESRAD and waste density of 1.8 g/cm^3, was calculated as:

$$1 \text{ pCi/g} \times 1.8 \text{ g/cm}^3 \times 1\text{E-6 } \mu\text{Ci/pCi} = 1.8\text{E-6 } \mu\text{Ci/cm}^3$$

Because soil is not available as a generic source material in Microshield®, the source material was alternatively defined as either concrete or silicon dioxide (sand) to explore the sensitivity of results to this input. With an equivalent density of 1.8 g/cm^3 assigned to these materials, the results were identical. Microshield® effective dose equivalent results for an isotropic geometry, with dimensions of dose / hr, were used for comparison with RESRAD results. Because the exposure time for the Intruder-Driller scenario in RESRAD is 6 hr, the Microshield® results were multiplied by 6 hr/yr to yield an annual dose. A comparison of RESRAD and Microshield® annual dose results for the three nuclide cases is presented in Table 12.

Table 12: Comparison of RESRAD and Microshield® Intruder-Driller Dose Calculations.

	Microshield®	RESRAD	Microshield® / RESRAD
	Annual dose[1] (mrem/yr)	Annual dose[1] (mrem/yr)	
Cobalt-60	4.4E-5	6.3E-5	0.70
Cesium-137	4.1E-6	5.2E-6	0.79
Uranium-235	1.4E-7	8.8E-8	1.6

[1] Based on a unit concentration of 1 pCi/g in drill cuttings.

The variability in the open mud pit external dose rates using RESRAD and Microshield® are relatively small in relation to the broader uncertainties underlying the exposure model for this scenario. The most obvious example is that the lack of potable water at the location of the CAW embankment does not support this exposure scenario. But even internal to the scenario, uncertainty exists related to the selection of drilling method, the location of a worker during the rotary drilling process with respect to the mud pit, the dimensions of the mud pit, the depth of water, and the length of time required to complete a well. Each of these factors likely contribute more to uncertainty in the Intruder-Driller dose calculation than does the selection of RESRAD and Microshield® as the modeling software.

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APPENDIX C

Inadvertent Intruder Scenario

Dose-To-Source Ratio and Dose Tables

LIST OF TABLES

Table C-1

Radionuclides Unanalyzed In Prior Performance Assessments

Isotope	Disposed Activity (mCi) [1]
Ar-39	0.04
Ba-137	0.00
Bi-208	3.30
Cm-250	0.00
Co-59	0.01
Eu-150	0.38
In-113	0.10
In-115	0.00
Mo-93	0.63
Np-236	0.00
Pb-205	0.10
Rb-87	0.01
Sm-146	0.16
Sm-147	0.01
Sm-148	0.00
Sm-149	0.00
Sn-117	0.04
Tc-98	0.04
Te-123	0.43
Zr-93	0.05

[1] In addition to those listed, a single curie of Gd-152 was reported in a single shipment (e.g., manifest number 0868-01-0030). Upon further evaluation, the generator determined that this manifested valued was a typographical error and the activity should have been assigned to Gd-153, which has a half-life of 241.6 days. Because Gd-153 is addressed within prior site-specific Performance Assessments, it is not included in this table. The generator requested that Energy*Solutions* correct the shipping manifest.

Table C-2

List of Radionuclide Inventories Classified as Class A According to UAC R313-15-1009

ELEMENT	NUCLIDE	CLASS A CONCENTRATION LIMIT (pCi/g)	HALF-LIFE (years)
Actinium	Ac-225	440,000,000	2.74E-02
Silver	Ag-105	440,000,000	1.13E-01
Silver	Ag-108	440,000,000	4.51E-06
Silver	Ag-110m	440,000,000	6.84E-01
Silver	Ag-111	440,000,000	2.04E-02
Americium	Am-241	10,000	4.32E+02
Americium	Am-242	440,000,000	1.83E-03
Americium	Am-242m	10,000	1.41E+02
Americium	Am-243	10,000	7.37E+03
Americium	Am-244	440,000,000	1.15E-03
Americium	Am-245	440,000,000	2.34E-04
Arsenic	As-73	440,000,000	2.20E-01
Arsenic	As-74	440,000,000	4.87E-02
Gold	Au-195	440,000,000	5.10E-01
Gold	Au-198	440,000,000	7.38E-03
Gold	Au-199	440,000,000	8.60E-03
Barium	Ba-140	440,000,000	3.49E-02
Beryllium	Be-7	440,000,000	1.46E-01
Bismuth	Bi-205	440,000,000	4.19E-02
Bismuth	Bi-206	440,000,000	1.71E-02
Bismuth	Bi-214	440,000,000	3.79E-05
Berkelium	Bk-247	10,000	1.40E+03
Berkelium	Bk-249	440,000,000	8.77E-01
Berkelium	Bk-250	440,000,000	3.68E-04
Carbon	C-14	7,207,207	5.73E+03
Calcium	Ca-41	440,000,000	1.03E+05
Calcium	Ca-45	440,000,000	4.46E-01
Calcium	Ca-47	440,000,000	1.24E-02
Cadmium	Cd-105	440,000,000	1.06E-04
Cadmium	Cd-107	440,000,000	7.42E-04
Cadmium	Cd-109	440,000,000	1.27E+00
Cerium	Ce-129	440,000,000	6.66E-06
Cerium	Ce-133	440,000,000	1.85E-04

ELEMENT	NUCLIDE	CLASS A CONCENTRATION LIMIT (pCi/g)	HALF-LIFE (years)
Cerium	Ce-137	440,000,000	1.03E-03
Cerium	Ce-139	440,000,000	3.77E-01
Cerium	Ce-141	440,000,000	8.90E-02
Cerium	Ce-143	440,000,000	3.77E-03
Cerium	Ce-144	440,000,000	7.81E-01
Cerium	Ce-147	440,000,000	1.79E-06
Californium	Cf-248	440,000,000	9.14E-01
Californium	Cf-249	10,000	3.51E+02
Californium	Cf-250	10,000	1.31E+01
Californium	Cf-251	10,000	2.46E+00
Californium	Cf-252	440,000,000	2.65E+00
Chlorine	Cl-36	33,522,654,030	3.01E+05
Curium	Cm-241	440,000,000	8.99E-02
Curium	Cm-242	2,000,000	4.46E-01
Curium	Cm-243	10,000	2.91E+01
Curium	Cm-244	10,000	1.81E+01
Curium	Cm-245	10,000	8.50E+03
Curium	Cm-246	10,000	4.73E+03
Curium	Cm-247	10,000	1.56E+07
Curium	Cm-248	10,000	3.40E+05
Curium	Cm-249	440,000,000	1.22E-04
Cobalt	Co-56	440,000,000	2.12E-01
Cobalt	Co-57	440,000,000	7.45E-01
Cobalt	Co-58	440,000,000	1.94E-01
Cobalt	Co-60	440,000,000	5.27E+00
Cobalt	Co-63	440,000,000	8.69E-07
Chromium	Cr-51	440,000,000	7.59E-02
Cesium	Cs-134	440,000,000	2.07E+00
Cesium	Cs-136	440,000,000	3.61E-02
Cesium	Cs-137	630,000	3.01E+01
Copper	Cu-67	440,000,000	1.69E-01
Dysprosium	Dy-166	440,000,000	9.32E-03
Einsteinium	Es-253	440,000,000	5.61E-02
Einsteinium	Es-254	440,000,000	7.55E-01
Europium	Eu-155	440,000,000	4.76E+00
Europium	Eu-156	440,000,000	4.16E-02
Iron	Fe-52	440,000,000	9.45E-04
Iron	Fe-53	440,000,000	1.62E-05

ELEMENT	NUCLIDE	CLASS A CONCENTRATION LIMIT (pCi/g)	HALF-LIFE (years)
Iron	Fe-55	440,000,000	2.73E+00
Iron	Fe-59	440,000,000	1.22E-01
Fermium	Fm-252	440,000,000	2.90E-03
Gallium	Ga-67	440,000,000	8.93E-03
Gadolinium	Gd-151	440,000,000	3.40E-01
Gadolinium	Gd-153	440,000,000	6.62E-01
Germanium	Ge-68	440,000,000	7.42E-01
Hydrogen	H-3	25,000,000	1.23E+01
Hafnium	Hf-172	440,000,000	1.87E+00
Hafnium	Hf-175	440,000,000	1.92E-01
Hafnium	Hf-181	440,000,000	1.16E-01
Mercury	Hg-203	440,000,000	1.28E-01
Holmium	Ho-166	440,000,000	3.05E-03
Iodine	I-123	440,000,000	1.52E-03
Iodine	I-125	440,000,000	1.63E-01
Iodine	I-126	440,000,000	3.59E-02
Iodine	I-129	5,000	1.57E+07
Iodine	I-131	440,000,000	2.20E-02
Iodine	I-133	440,000,000	2.37E-03
Iodine	I-135	440,000,000	7.50E-04
Iodine	I-137	440,000,000	7.77E-07
Indium	In-111	440,000,000	7.68E-03
Indium	In-113m	440,000,000	1.89E-04
Indium	In-114	440,000,000	2.28E-06
Indium	In-114m	440,000,000	1.36E-01
Iridium	Ir-192	440,000,000	2.02E-01
Lanthanum	La-140	440,000,000	4.60E-03
Manganese	Mn-52	440,000,000	1.53E-02
Manganese	Mn-52m	440,000,000	4.01E-05
Manganese	Mn-54	440,000,000	8.56E-01
Molybdenum	Mo-99	440,000,000	7.53E-03
Sodium	Na-22	440,000,000	2.60E+00
Niobium	Nb-94	13,000	2.03E+04
Neodymium	Nd-147	440,000,000	3.01E-02
Nickel	Ni-59	14,000,000	7.60E+04
Nickel	Ni-63	2,200,000	1.00E+02
Neptunium	Np-235	440,000,000	1.09E+00
Neptunium	Np-237	10,000	2.14E+06

ELEMENT	NUCLIDE	CLASS A CONCENTRATION LIMIT (pCi/g)	HALF-LIFE (years)
Osmium	Os-191	440,000,000	4.22E-02
Osmium	Os-191m	440,000,000	1.50E-03
Phosphorous	P-32	440,000,000	3.91E-02
Phosphorous	P-33	440,000,000	6.93E-02
Protactinium	Pa-233	440,000,000	7.39E-02
Protactinium	Pa-234	440,000,000	7.65E-04
Protactinium	Pa-234m	440,000,000	2.23E-06
Lead	Pb-203	440,000,000	5.92E-03
Lead	Pb-214	440,000,000	5.10E-05
Palladium	Pd-103	440,000,000	4.66E-02
Promethium	Pm-143	440,000,000	7.26E-01
Promethium	Pm-147	440,000,000	2.62E+00
Polonium	Po-208	440,000,000	2.90E+00
Polonium	Po-210	440,000,000	3.79E-01
Polonium	Po-214	440,000,000	5.21E-12
Plutonium	Pu-236	500	2.86E+00
Plutonium	Pu-238	10,000	8.77E+01
Plutonium	Pu-239	10,000	2.41E+04
Plutonium	Pu-240	10,000	6.56E+03
Plutonium	Pu-241	350,000	1.44E+01
Plutonium	Pu-242	10,000	3.73E+05
Plutonium	Pu-243	500	5.66E-04
Plutonium	Pu-244	500	8.08E+07
Radium	Ra-225	440,000,000	4.08E-02
Radium	Ra-226	10,000	1.60E+03
Rubidium	Rb-82	440,000,000	2.38E-06
Rubidium	Rb-83	440,000,000	2.36E-01
Rubidium	Rb-84	440,000,000	8.99E-02
Rubidium	Rb-86	440,000,000	5.10E-02
Rhenium	Re-183	440,000,000	1.92E-01
Rhenium	Re-184	440,000,000	1.04E-01
Rhenium	Re-184m	440,000,000	4.63E-01
Rhenium	Re-186	440,000,000	1.02E-02
Rhenium	Re-187	38,000	4.35E+10
Rhenium	Re-188	440,000,000	1.94E-03
Rhodium	Rh-103m	440,000,000	1.07E-04
Ruthenium	Ru-103	440,000,000	1.08E-01
Ruthenium	Ru-106	440,000,000	1.02E+00

ELEMENT	NUCLIDE	CLASS A CONCENTRATION LIMIT (pCi/g)	HALF-LIFE (years)
Sulfur	S-35	440,000,000	2.40E-01
Antimony	Sb-122	440,000,000	7.40E-03
Antimony	Sb-124	440,000,000	1.65E-01
Antimony	Sb-125	440,000,000	2.76E+00
Antimony	Sb-126	440,000,000	3.42E-02
Antimony	Sb-126m	440,000,000	3.61E-05
Antimony	Sb-129	440,000,000	5.02E-04
Scandium	Sc-41	440,000,000	1.89E-08
Scandium	Sc-44	440,000,000	4.48E-04
Scandium	Sc-46	440,000,000	2.30E-01
Scandium	Sc-47	440,000,000	9.18E-03
Selenium	Se-75	440,000,000	3.28E-01
Selenium	Se-85	440,000,000	1.01E-06
Samarium	Sm-145	440,000,000	9.32E-01
Samarium	Sm-153	440,000,000	5.28E-03
Tin	Sn-113	440,000,000	3.15E-01
Tin	Sn-117m	440,000,000	3.73E-02
Tin	Sn-119m	440,000,000	8.03E-01
Tin	Sn-121	440,000,000	3.09E-03
Strontium	Sr-81	440,000,000	4.24E-05
Strontium	Sr-82	440,000,000	7.00E-02
Strontium	Sr-85	440,000,000	1.78E-01
Strontium	Sr-87m	440,000,000	3.20E-04
Strontium	Sr-89	440,000,000	1.38E-01
Strontium	Sr-90	25,000	2.88E+01
Tantalum	Ta-182	440,000,000	3.14E-01
Terbium	Tb-160	440,000,000	1.98E-01
Technetium	Tc-95	440,000,000	2.28E-03
Technetium	Tc-95m	440,000,000	1.67E-01
Technetium	Tc-99	187,500	2.11E+05
Technetium	Tc-99m	440,000,000	6.86E-04
Tellurium	Te-123m	440,000,000	3.28E-01
Tellurium	Te-125m	440,000,000	1.57E-01
Tellurium	Te-129	440,000,000	1.32E-04
Tellurium	Te-129m	440,000,000	9.21E-02
Thorium	Th-231	440,000,000	2.91E-03
Thorium	Th-234	440,000,000	6.60E-02
Thallium	Tl-201	440,000,000	8.32E-03

ELEMENT	NUCLIDE	CLASS A CONCENTRATION LIMIT (pCi/g)	HALF-LIFE (years)
Thallium	Tl-202	440,000,000	3.35E-02
Thallium	Tl-204	440,000,000	3.78E+00
Thallium	Tl-210	440,000,000	2.47E-06
Thulium	Tm-170	440,000,000	3.52E-01
Thulium	Tm-171	440,000,000	1.92E+00
Uranium	U-228	440,000,000	1.73E-05
Uranium	U-230	440,000,000	5.70E-02
Uranium	U-233	75,000	1.59E+05
Uranium	U-235	15,500	7.04E+08
Uranium	U-depleted	370,000	
Vanadium	V-48	440,000,000	4.38E-02
Tungsten	W-181	440,000,000	3.32E-01
Tungsten	W-185	440,000,000	2.06E-01
Tungsten	W-187	440,000,000	2.71E-03
Tungsten	W-188	440,000,000	1.90E-01
Xenon	Xe-127	440,000,000	9.97E-02
Xenon	Xe-131m	440,000,000	3.27E-02
Xenon	Xe-133	440,000,000	1.44E-02
Xenon	Xe-133m	440,000,000	6.00E-03
Yttrium	Y-88	440,000,000	2.92E-01
Yttrium	Y-91	440,000,000	1.60E-01
Yttrium	Y-99	440,000,000	4.66E-08
Ytterbium	Yb-169	440,000,000	8.78E-02
Zinc	Zn-65	440,000,000	6.69E-01
Zirconium	Zr-88	440,000,000	2.28E-01
Zirconium	Zr-95	440,000,000	1.75E-01

Table C-3

List of Specific Activity Limits for Radionuclides Not Included in UAC R313-15-1009

ELEMENT	NUCLIDE	SPECIFIC ACTIVITY CONCENTRATION LIMIT (pCi/g)	HALF-LIFE (years)
Actinium	Ac-227	72,300,000,000,000	2.18E+01
Silver	Ag-108m	26,081,000,000,000	4.18E+02
Aluminum	Al-26	18,600,000,000	7.40E+05
Barium	Ba-133	256,160,000,000,000	1.05E+01
Beryllium	Be-10	22,000,000,000	1.51E+06
Bismuth	Bi-207	53,670,000,000,000	3.16E+01
Bismuth	Bi-210m	567,820,000	3.04E+06
Cadmium	Cd-113	0.4303	9.30E+15
Cadmium	Cd-113m	224,520,000,000,000	1.41E+01
Cesium	Cs-135	1,152,100,000	2.30E+06
Europium	Eu-152	173,050,000,000,000	1.35E+01
Europium	Eu-154	270,420,000,000,000	8.59E+00
Iron	Fe-60	3,974,800,000	1.50E+06
Gadolinium	Gd-148	32,228,000,000,000	7.46E+01
Mercury	Hg-194	3,546,100,000,000	4.44E+02
Holmium	Ho-166m	1,800,000,000,000	1.20E+03
Manganese	Mn-53	1,800,000,000	3.74E+06
Niobium	Nb-91	5,780,000,000,000	6.80E+02
Niobium	Nb-92	112,000,000	3.47E+07
Niobium	Nb-93m	263,460,000,000,000	1.61E+01
Neodymium	Nd-144	4.27	2.29E+15
Osmium	Os-194	307,330,000,000,000	6.00E+00
Protactinium	Pa-231	47,000,000,000	3.28E+04
Lead	Pb-202	3,400,000,000	5.25E+04
Lead	Pb-210	76,000,000,000,000	2.23E+01
Palladium	Pd-107	510,000,000	6.50E+06
Promethium	Pm-145	140,000,000,000,000	1.77E+01
Polonium	Po-209	16,781,000,000,000	1.02E+02
Platinum	Pt-193	37,000,000,000,000	5.00E+01
Radium	Ra-228	272,396,000,000,000	5.75E+00
Selenium	Se-79	69,700,000,000	6.50E+04
Silicon	Si-32	65,000,000,000,000	1.72E+02
Samarium	Sm-151	26,320,000,000,000	9.00E+01

ELEMENT	NUCLIDE	SPECIFIC ACTIVITY CONCENTRATION LIMIT (pCi/g)	HALF-LIFE (years)
Tin	Sn-121m	53,754,000,000,000	5.50E+01
Tin	Sn-126	28,391,000,000	1.00E+05
Terbium	Tb-157	15,000,000,000,000	7.10E+01
Terbium	Tb-158	15,000,000,000,000	1.80E+02
Tellurium	Te-123	291	1.00E+13
Thorium	Th-229	212,830,000,000	7.88E+03
Thorium	Th-230	20,628,000,000	7.54E+04
Thorium	Th-232	110,000	1.41E+10
Titanium	Ti-44	156,350,000,000,000	6.30E+01
Uranium	U-232	22,028,000,000,000	6.89E+01
Uranium	U-234	6,210,000,000	2.46E+05
Uranium	U-236	64,720,000	2.34E+07
Uranium	U-238	336,260	4.47E+09
Uranium	U-natural	680,000	
Vanadium	V-50	0.0511	1.40E+17
Zirconium	Zr-93	2,514,100,000	1.53E+06

Table C-4

Nuclide Distribution Coefficients

NUCLIDE	DISTRIBUTION COEFFICIENT (K_d) (L/Kg)
Ac-225	4.5
Ac-227	4.5
Ag-105	2.7
Ag-108	2.7
Ag-108m	2.7
Ag-110m	2.7
Ag-111	2.7
Al-26	15
Am-241	1
Am-242	1
Am-242m	1
Am-243	1
Am-244	1
Am-245	1
As-73	1
As-74	1
Au-195	0.25
Au-198	0.25
Au-199	0.25
Ba-133	10
Ba-140	10
Be-10	2.5
Be-7	2.5
Bi-205	1
Bi-206	1
Bi-207	1
Bi-210m	1
Bi-214	1
Bk-247	0.001
Bk-249	0.001
Bk-250	0.001
C-14	8.52
Ca-41	0.05
Ca-45	0.05
Ca-47	0.05

NUCLIDE	DISTRIBUTION COEFFICIENT (K_d) (L/Kg)
Cd-105	1
Cd-107	1
Cd-109	1
Cd-113	1
Cd-113m	1
Ce-129	1
Ce-133	1
Ce-137	1
Ce-139	1
Ce-141	1
Ce-143	1
Ce-144	1
Ce-147	1
Cf-248	2
Cf-249	2
Cf-250	2
Cf-251	2
Cf-252	2
Cl-36	0.0025
Cm-241	93.3
Cm-242	93.3
Cm-243	93.3
Cm-244	93.3
Cm-245	93.3
Cm-246	93.3
Cm-247	93.3
Cm-248	93.3
Cm-249	93.3
Co-56	370
Co-57	370
Co-58	370
Co-60	370
Co-63	370
Cr-51	1
Cs-134	133
Cs-135	133
Cs-136	133
Cs-137	133
Cu-67	1

NUCLIDE	DISTRIBUTION COEFFICIENT (K_d) (L/Kg)
Dy-166	6.5
Es-253	0.001
Es-254	0.001
Eu-152	6.5
Eu-154	6.5
Eu-155	6.5
Eu-156	6.5
Fe-52	1.4
Fe-53	1.4
Fe-55	1.4
Fe-59	1.4
Fe-60	1.4
Fm-252	0.001
Ga-67	15
Gd-148	6.5
Gd-151	6.5
Gd-153	6.5
Ge-68	0.25
H-3	0.04
Hf-172	4.5
Hf-175	4.5
Hf-181	4.5
Hg-194	10
Hg-203	10
Ho-166	2.5
Ho-166m	2.5
I-123	0.12
I-125	0.12
I-126	0.12
I-129	0.12
I-131	0.12
I-133	0.12
I-135	0.12
I-137	0.12
In-111	15
In-113m	15
In-114	15
In-114m	15
Ir-192	1.5

NUCLIDE	DISTRIBUTION COEFFICIENT (K_d) (L/Kg)
La-140	6.5
Mn-52	6.4
Mn-52m	6.4
Mn-53	6.4
Mn-54	6.4
Mo-99	1
Na-22	1
Nb-91	1.6
Nb-92	1.6
Nb-93m	1.6
Nb-94	1.6
Nd-144	6.5
Nd-147	6.5
Ni-59	10
Ni-63	10
Np-235	3
Np-237	3
Os-191	4.5
Os-191m	4.5
Os-194	4.5
P-32	0.035
P-33	0.035
Pa-231	5.5
Pa-233	5.5
Pa-234	5.5
Pa-234m	5.5
Pb-202	19
Pb-203	19
Pb-210	19
Pb-214	19
Pd-103	0.55
Pd-107	0.55
Pm-143	6.5
Pm-145	6.5
Pm-147	6.5
Po-208	9
Po-209	9
Po-210	9
Po-214	9

NUCLIDE	DISTRIBUTION COEFFICIENT (K_d) (L/Kg)
Pt-193	0.9
Pu-236	10
Pu-238	10
Pu-239	10
Pu-240	10
Pu-241	10
Pu-242	10
Pu-243	10
Pu-244	10
Ra-225	10
Ra-226	10
Ra-228	10
Rb-82	0.55
Rb-83	0.55
Rb-84	0.55
Rb-86	0.55
Re-183	0.075
Re-184	0.075
Re-184m	0.075
Re-186	0.075
Re-187	0.075
Re-188	0.075
Rh-103m	0.001
Ru-103	5
Ru-106	5
S-35	0.075
Sb-122	100
Sb-124	100
Sb-125	100
Sb-126	100
Sb-126m	100
Sb-129	100
Sc-41	10
Sc-44	10
Sc-46	10
Sc-47	10
Se-75	1
Se-79	1
Se-85	1

NUCLIDE	DISTRIBUTION COEFFICIENT (K_d) (L/Kg)
Si-32	0.35
Sm-145	2.45
Sm-151	2.45
Sm-153	2.45
Sn-113	50
Sn-117m	50
Sn-119m	50
Sn-121	50
Sn-121m	50
Sn-126	50
Sr-81	0.05
Sr-82	0.05
Sr-85	0.05
Sr-87m	0.05
Sr-89	0.05
Sr-90	0.05
Ta-182	2.2
Tb-157	6.5
Tb-158	6.5
Tb-160	6.5
Tc-95	0.11
Tc-95m	0.11
Tc-99	0.11
Tc-99m	0.11
Te-123	1.25
Te-123m	1.25
Te-125m	1.25
Te-129	1.25
Te-129m	1.25
Th-229	10
Th-230	10
Th-231	10
Th-232	10
Th-234	10
Ti-44	10
Tl-201	0.15
Tl-202	0.15
Tl-204	0.15
Tl-210	0.15

NUCLIDE	DISTRIBUTION COEFFICIENT (K_d) (L/Kg)
Tm-170	6.5
Tm-171	6.5
U-228	6
U-230	6
U-232	6
U-233	6
U-234	6
U-235	6
U-236	6
U-238	6
U-depleted	6
U-natural	6
V-48	10
V-50	10
W-181	1.5
W-185	1.5
W-187	1.5
W-188	1.5
Xe-127	0.001
Xe-131m	0.001
Xe-133	0.001
Xe-133m	0.001
Y-88	1.7
Y-91	1.7
Y-99	1.7
Yb-169	6.5
Zn-65	0.1
Zr-88	10
Zr-93	10
Zr-95	10

Table C-5

Disposed Class A Waste Inventory*

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m³)	Mass Concentration (pCi/g)
Ac-224	6.10E-02	2.06E-08	1.14E-05
Ac-225	2.61E+01	8.80E-06	4.89E-03
Ac-227	1.08E+04	3.64E-03	2.02E+00
Ac-228	1.64E+03	5.53E-04	3.07E-01
Ag-105	8.91E-03	3.01E-09	1.67E-06
Ag-108	8.16E-01	2.75E-07	1.53E-04
Ag-108m	2.46E+03	8.30E-04	4.61E-01
Ag-109m	1.35E-02	4.55E-09	2.53E-06
Ag-110	5.23E+01	1.76E-05	9.80E-03
Ag-110m	6.76E+04	2.28E-02	1.27E+01
Ag-111	7.65E-10	2.58E-16	1.43E-13
Al-26	4.07E+01	1.37E-05	7.63E-03
Am-241	2.55E+04	8.60E-03	4.78E+00
Am-242	2.48E+00	8.36E-07	4.65E-04
Am-242m	1.83E-01	6.16E-08	3.42E-05
Am-243	1.56E+02	5.25E-05	2.92E-02
Am-244	6.71E-04	2.26E-10	1.26E-07
Am-245	8.95E-04	3.02E-10	1.68E-07
Am-246	2.24E-07	7.56E-14	4.20E-11
Ar-37	5.30E-01	1.79E-07	9.94E-05
Ar-39	4.00E-02	1.35E-08	7.50E-06
Ar-41	1.69E-12	5.70E-19	3.17E-16
Ar-42	2.11E-02	7.12E-09	3.95E-06
As-73	1.24E+00	4.19E-07	2.33E-04
As-74	2.98E-05	1.01E-11	5.58E-09
As-76	1.00E+00	3.37E-07	1.87E-04
At-211	6.89E-01	2.32E-07	1.29E-04
At-217	4.77E+00	1.61E-06	8.94E-04
Au-194	3.68E-03	1.24E-09	6.90E-07
Au-195	5.95E+00	2.01E-06	1.11E-03
Au-198	2.98E-01	1.00E-07	5.58E-05
Au-199	4.77E-01	1.61E-07	8.94E-05
Ba-131	4.28E+00	1.44E-06	8.02E-04
Ba-133	1.05E+03	3.53E-04	1.96E-01
Ba-133m	8.25E+00	2.78E-06	1.55E-03

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m^3)	Mass Concentration (pCi/g)
Ba-137	4.80E-03	1.62E-09	8.99E-07
Ba-137m	2.67E+02	9.02E-05	5.01E-02
Ba-140	4.96E+04	1.67E-02	9.30E+00
Be-7	6.19E+03	2.09E-03	1.16E+00
Be-10	1.02E-02	3.44E-09	1.91E-06
Bi-205	2.74E+00	9.24E-07	5.13E-04
Bi-206	1.08E-03	3.64E-10	2.02E-07
Bi-207	1.99E+02	6.73E-05	3.74E-02
Bi-208	3.30E+00	1.11E-06	6.18E-04
Bi-210	5.17E+00	1.74E-06	9.68E-04
Bi-211	2.54E-05	8.57E-12	4.76E-09
Bi-212	3.13E+01	1.06E-05	5.86E-03
Bi-213	4.77E+00	1.61E-06	8.94E-04
Bi-214	2.25E+01	7.58E-06	4.21E-03
Bk-247	1.50E-03	5.06E-10	2.81E-07
Bk-249	7.19E-01	2.43E-07	1.35E-04
C-14	3.86E+05	1.30E-01	7.23E+01
Ca-41	1.49E-01	5.03E-08	2.79E-05
Ca-45	3.07E+03	1.03E-03	5.75E-01
Ca-47	2.11E-03	7.12E-10	3.95E-07
Cd-109	2.19E+04	7.39E-03	4.11E+00
Cd-113	8.12E-05	2.74E-11	1.52E-08
Cd-113m	1.80E+03	6.07E-04	3.37E-01
Cd-115m	1.29E+00	4.35E-07	2.42E-04
Ce-137	4.39E+01	1.48E-05	8.23E-03
Ce-139	2.46E+01	8.30E-06	4.61E-03
Ce-141	1.01E+04	3.40E-03	1.89E+00
Ce-143	9.19E-02	3.10E-08	1.72E-05
Ce-144	8.09E+04	2.73E-02	1.52E+01
Cf-249	6.86E+00	2.31E-06	1.29E-03
Cf-250	1.84E-01	6.19E-08	3.44E-05
Cf-251	8.55E-04	2.88E-10	1.60E-07
Cf-252	2.27E+02	7.65E-05	4.25E-02
Cl-36	1.37E+02	4.61E-05	2.56E-02
Cm-241	9.78E-04	3.30E-10	1.83E-07
Cm-242	1.12E+03	3.78E-04	2.10E-01
Cm-243	8.35E+02	2.82E-04	1.56E-01
Cm-244	8.99E+02	3.03E-04	1.68E-01
Cm-245	2.63E+01	8.87E-06	4.93E-03

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m³)	Mass Concentration (pCi/g)
Cm-246	3.94E+00	1.33E-06	7.38E-04
Cm-247	2.88E-01	9.72E-08	5.40E-05
Cm-248	3.82E-01	1.29E-07	7.17E-05
Cm-250	7.51E-04	2.53E-10	1.41E-07
Co-56	8.13E+02	2.74E-04	1.52E-01
Co-57	1.57E+05	5.31E-02	2.95E+01
Co-58	9.24E+05	3.12E-01	1.73E+02
Co-58m	3.31E+01	1.12E-05	6.20E-03
Co-59	6.41E-03	2.16E-09	1.20E-06
Co-60	1.36E+07	4.59E+00	2.55E+03
Co-61	2.69E-05	9.07E-12	5.04E-09
Cr-51	2.93E+05	9.88E-02	5.49E+01
Cr-57	2.15E-01	7.25E-08	4.03E-05
Cs-134	1.46E+05	4.93E-02	2.74E+01
Cs-134m	5.50E-01	1.86E-07	1.03E-04
Cs-135	1.18E+02	3.98E-05	2.21E-02
Cs-136	6.31E+00	2.13E-06	1.18E-03
Cs-137	1.45E+06	4.89E-01	2.72E+02
Cu-64	4.49E+01	1.52E-05	8.42E-03
Cu-67	1.80E+00	6.07E-07	3.37E-04
Dy-159	9.01E-03	3.04E-09	1.69E-06
Es-254	5.04E-07	1.70E-13	9.44E-11
Eu-146	1.30E-03	4.38E-10	2.44E-07
Eu-147	3.24E-04	1.09E-10	6.07E-08
Eu-148	2.70E-04	9.11E-11	5.06E-08
Eu-149	3.45E-03	1.16E-09	6.46E-07
Eu-150	3.84E-01	1.30E-07	7.20E-05
Eu-152	2.50E+04	8.43E-03	4.68E+00
Eu-152m	9.39E-02	3.17E-08	1.76E-05
Eu-154	3.92E+03	1.32E-03	7.35E-01
Eu-155	1.51E+03	5.11E-04	2.84E-01
Eu-156	3.67E+00	1.24E-06	6.88E-04
F-18	4.53E-03	1.53E-09	8.49E-07
Fe-55	2.88E+07	9.71E+00	5.40E+03
Fe-59	1.32E+05	4.46E-02	2.48E+01
Fr-221	4.77E+00	1.61E-06	8.94E-04
Ga-67	4.75E+01	1.60E-05	8.90E-03
Ga-68	1.78E+01	6.01E-06	3.34E-03
Gd-146	1.18E-03	3.98E-10	2.21E-07

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m³)	Mass Concentration (pCi/g)
Gd-148	1.15E-02	3.88E-09	2.15E-06
Gd-151	4.01E-03	1.35E-09	7.51E-07
Gd-152	1.00E+03	3.37E-04	1.87E-01
Gd-153	1.22E+05	4.13E-02	2.29E+01
Gd-159	1.00E-03	3.37E-10	1.87E-07
Ge-68	1.04E+04	3.50E-03	1.95E+00
H-3	4.01E+06	1.35E+00	7.52E+02
Hf-172	4.34E-01	1.47E-07	8.14E-05
Hf-175	3.84E+00	1.29E-06	7.19E-04
Hf-181	1.79E+03	6.05E-04	3.36E-01
Hg-194	1.69E+00	5.70E-07	3.17E-04
Hg-197	1.89E-07	6.37E-14	3.54E-11
Hg-203	5.39E+01	1.82E-05	1.01E-02
Hg-207	1.00E-03	3.37E-10	1.87E-07
Ho-166	8.57E-03	2.89E-09	1.61E-06
Ho-166m	7.81E+00	2.63E-06	1.46E-03
I-123	6.01E+01	2.03E-05	1.13E-02
I-124	3.39E-10	1.14E-16	6.35E-14
I-125	1.12E+04	3.76E-03	2.09E+00
I-126	2.37E-05	8.00E-12	4.45E-09
I-129	2.10E+03	7.09E-04	3.94E-01
I-131	6.31E+03	2.13E-03	1.18E+00
I-132	2.00E-04	6.75E-11	3.75E-08
I-133	3.02E+00	1.02E-06	5.66E-04
In-111	2.57E+02	8.67E-05	4.82E-02
In-113	1.00E-01	3.37E-08	1.87E-05
In-113m	1.74E+01	5.87E-06	3.26E-03
In-114	1.31E+00	4.42E-07	2.45E-04
In-114m	1.96E+02	6.61E-05	3.67E-02
In-115	1.00E-03	3.37E-10	1.87E-07
In-133	4.50E-03	1.52E-09	8.43E-07
Ir-189	4.40E-04	1.48E-10	8.24E-08
Ir-192	1.66E+03	5.60E-04	3.11E-01
K-40	1.34E+04	4.51E-03	2.50E+00
K-42	4.21E-08	1.42E-14	7.89E-12
Kr-85	1.33E+04	4.49E-03	2.49E+00
Kr-85m	4.00E-03	1.35E-09	7.50E-07
La-140	1.07E+04	3.61E-03	2.01E+00
Lu-172	4.41E-02	1.49E-08	8.26E-06

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m³)	Mass Concentration (pCi/g)
Lu-173	1.33E+00	4.49E-07	2.50E-04
Lu-174	5.04E-01	1.70E-07	9.44E-05
Lu-177	2.32E+02	7.83E-05	4.35E-02
Lu-177m	5.59E+00	1.89E-06	1.05E-03
Mn-52	1.96E+01	6.60E-06	3.67E-03
Mn-53	1.16E-05	3.93E-12	2.18E-09
Mn-54	2.74E+06	9.24E-01	5.13E+02
Mn-56	3.71E-02	1.25E-08	6.95E-06
Mn-57	1.44E-04	4.86E-11	2.70E-08
Mo-93	6.30E-01	2.12E-07	1.18E-04
Mo-99	9.75E+02	3.29E-04	1.83E-01
Na-22	7.67E+03	2.59E-03	1.44E+00
Na-24	3.01E+00	1.01E-06	5.63E-04
Nb-90	2.42E-03	8.16E-10	4.53E-07
Nb-91	6.30E-01	2.12E-07	1.18E-04
Nb-92	6.30E-01	2.12E-07	1.18E-04
Nb-93m	8.36E+01	2.82E-05	1.57E-02
Nb-94	7.73E+02	2.61E-04	1.45E-01
Nb-95	1.26E+05	4.25E-02	2.36E+01
Nb-95m	2.60E+00	8.78E-07	4.88E-04
Nb-97	1.12E+00	3.78E-07	2.10E-04
Nd-147	7.30E-01	2.46E-07	1.37E-04
Ni-57	4.15E-01	1.40E-07	7.78E-05
Ni-59	2.15E+04	7.26E-03	4.03E+00
Ni-63	2.37E+06	7.98E-01	4.44E+02
Ni-65	2.03E-03	6.85E-10	3.80E-07
Np-236	4.95E-03	1.67E-09	9.28E-07
Np-237	2.57E+03	8.66E-04	4.81E-01
Np-238	1.04E-06	3.51E-13	1.95E-10
Np-239	4.06E+00	1.37E-06	7.60E-04
Os-185	1.84E-01	6.21E-08	3.45E-05
Os-191	4.56E+00	1.54E-06	8.54E-04
Os-194	1.00E-04	3.37E-11	1.87E-08
P-32	4.60E+03	1.55E-03	8.62E-01
P-33	2.88E+03	9.70E-04	5.39E-01
Pa-231	9.44E+03	3.18E-03	1.77E+00
Pa-233	3.12E+00	1.05E-06	5.85E-04
Pa-234	7.18E-01	2.42E-07	1.35E-04
Pa-234m	2.96E+02	9.97E-05	5.54E-02

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m^3)	Mass Concentration (pCi/g)
Pb-202	2.42E-03	8.16E-10	4.53E-07
Pb-203	3.42E-01	1.16E-07	6.42E-05
Pb-209	4.77E+00	1.61E-06	8.94E-04
Pb-210	5.60E+05	1.89E-01	1.05E+02
Pb-211	2.68E-07	9.04E-14	5.02E-11
Pb-212	1.90E+03	6.40E-04	3.56E-01
Pb-214	3.62E+01	1.22E-05	6.79E-03
Pd-103	6.12E-01	2.06E-07	1.15E-04
Pd-107	6.32E-01	2.13E-07	1.18E-04
Pd-109	2.00E-05	6.75E-12	3.75E-09
Pm-143	2.62E-03	8.84E-10	4.91E-07
Pm-144	1.23E-01	4.16E-08	2.31E-05
Pm-145	1.48E+01	4.99E-06	2.77E-03
Pm-146	5.15E-01	1.74E-07	9.65E-05
Pm-147	5.56E+03	1.88E-03	1.04E+00
Po-208	1.00E-01	3.37E-08	1.87E-05
Po-209	1.33E-02	4.50E-09	2.50E-06
Po-210	5.61E+05	1.89E-01	1.05E+02
Po-212	1.61E+01	5.42E-06	3.01E-03
Po-213	4.58E+00	1.55E-06	8.59E-04
Po-214	1.70E+00	5.73E-07	3.19E-04
Po-216	2.50E+01	8.43E-06	4.68E-03
Po-218	1.70E+00	5.73E-07	3.19E-04
Pr-143	2.00E-04	6.75E-11	3.75E-08
Pr-144	2.00E+01	6.73E-06	3.74E-03
Pt-191	2.10E-08	7.08E-15	3.93E-12
Pt-193	1.07E-01	3.61E-08	2.00E-05
Pt-195m	3.58E-01	1.21E-07	6.71E-05
Pu-236	5.76E-02	1.94E-08	1.08E-05
Pu-237	1.76E-03	5.94E-10	3.30E-07
Pu-238	1.07E+05	3.62E-02	2.01E+01
Pu-239	1.03E+05	3.47E-02	1.93E+01
Pu-240	1.54E+04	5.20E-03	2.89E+00
Pu-241	2.13E+05	7.19E-02	4.00E+01
Pu-242	9.17E+01	3.09E-05	1.72E-02
Pu-243	3.52E-02	1.19E-08	6.60E-06
Pu-244	6.28E-01	2.12E-07	1.18E-04
Ra-222	7.73E-05	2.61E-11	1.45E-08
Ra-223	7.79E-02	2.63E-08	1.46E-05

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m³)	Mass Concentration (pCi/g)
Ra-224	3.91E+01	1.32E-05	7.33E-03
Ra-225	6.58E+00	2.22E-06	1.23E-03
Ra-226	6.50E+05	2.19E-01	1.22E+02
Ra-227	5.90E-03	1.99E-09	1.11E-06
Ra-228	4.57E+03	1.54E-03	8.56E-01
Rb-82	1.33E-01	4.49E-08	2.49E-05
Rb-83	1.74E+04	5.85E-03	3.25E+00
Rb-84	5.28E+03	1.78E-03	9.90E-01
Rb-86	6.07E+02	2.05E-04	1.14E-01
Rb-87	1.34E-02	4.52E-09	2.51E-06
Re-183	1.43E-01	4.81E-08	2.67E-05
Re-184	5.81E+01	1.96E-05	1.09E-02
Re-184m	4.96E-02	1.67E-08	9.29E-06
Re-186	5.55E+00	1.87E-06	1.04E-03
Re-187	4.03E-01	1.36E-07	7.55E-05
Re-188	2.79E+04	9.41E-03	5.23E+00
Rh-101	1.24E+01	4.17E-06	2.32E-03
Rh-102	2.86E+01	9.65E-06	5.36E-03
Rh-102m	1.11E+01	3.74E-06	2.08E-03
Rh-103m	6.70E+00	2.26E-06	1.26E-03
Rh-105	3.47E+00	1.17E-06	6.50E-04
Rh-106	1.97E-01	6.64E-08	3.69E-05
Rn-220	2.61E+01	8.81E-06	4.89E-03
Rn-222	1.26E-01	4.25E-08	2.36E-05
Ru-97	4.17E-07	1.41E-13	7.81E-11
Ru-103	5.28E+02	1.78E-04	9.89E-02
Ru-106	5.16E+03	1.74E-03	9.67E-01
S-35	1.82E+04	6.15E-03	3.42E+00
Sb-117	3.52E-07	1.19E-13	6.60E-11
Sb-122	1.24E+02	4.20E-05	2.33E-02
Sb-124	1.27E+04	4.28E-03	2.38E+00
Sb-125	9.53E+04	3.21E-02	1.79E+01
Sb-126	3.69E+00	1.24E-06	6.92E-04
Sb-126m	4.96E-07	1.67E-13	9.29E-11
Sc-44	2.41E-03	8.13E-10	4.52E-07
Sc-46	1.21E+03	4.07E-04	2.26E-01
Sc-47	1.04E-02	3.51E-09	1.95E-06
Sc-48	1.58E-01	5.32E-08	2.95E-05
Se-75	1.75E+03	5.90E-04	3.28E-01

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m³)	Mass Concentration (pCi/g)
Se-79	2.35E+00	7.93E-07	4.40E-04
Si-31	1.00E-06	3.37E-13	1.87E-10
Si-32	1.69E+00	5.70E-07	3.17E-04
Sm-145	1.57E+01	5.30E-06	2.94E-03
Sm-146	1.60E-01	5.40E-08	3.00E-05
Sm-147	1.11E-02	3.74E-09	2.08E-06
Sm-148	1.00E-04	3.37E-11	1.87E-08
Sm-149	1.00E-04	3.37E-11	1.87E-08
Sm-151	4.64E+01	1.56E-05	8.69E-03
Sm-153	2.32E+02	7.82E-05	4.35E-02
Sn-113	4.47E+03	1.51E-03	8.38E-01
Sn-113m	5.80E-02	1.96E-08	1.09E-05
Sn-117	2.40E-04	8.09E-11	4.50E-08
Sn-117m	1.23E+01	4.15E-06	2.30E-03
Sn-119m	8.37E-01	2.82E-07	1.57E-04
Sn-121	3.64E-01	1.23E-07	6.82E-05
Sn-121m	8.22E-05	2.77E-11	1.54E-08
Sn-123	4.30E-01	1.45E-07	8.06E-05
Sn-125	6.25E-02	2.11E-08	1.17E-05
Sn-126	6.32E-02	2.13E-08	1.18E-05
Sn-133	4.50E-03	1.52E-09	8.43E-07
Sr-82	2.01E+02	6.79E-05	3.77E-02
Sr-85	1.07E+03	3.61E-04	2.01E-01
Sr-89	9.01E+03	3.04E-03	1.69E+00
Sr-90	1.17E+05	3.94E-02	2.19E+01
Sr-91	2.01E-01	6.78E-08	3.77E-05
Sr-92	1.27E+00	4.28E-07	2.38E-04
Ta-178	2.00E-03	6.75E-10	3.75E-07
Ta-179	2.53E+00	8.53E-07	4.74E-04
Ta-182	9.17E+02	3.09E-04	1.72E-01
Tb-157	2.50E-03	8.43E-10	4.68E-07
Tb-158	6.98E-02	2.35E-08	1.31E-05
Tb-160	3.60E-03	1.21E-09	6.75E-07
Tc-95	4.37E-01	1.47E-07	8.19E-05
Tc-95m	2.48E+00	8.37E-07	4.65E-04
Tc-98	3.55E-02	1.20E-08	6.65E-06
Tc-99	1.46E+06	4.92E-01	2.73E+02
Tc-99m	7.46E+02	2.52E-04	1.40E-01
Te-121	5.06E-01	1.71E-07	9.48E-05

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m³)	Mass Concentration (pCi/g)
Te-121m	6.05E-02	2.04E-08	1.13E-05
Te-123	4.28E-01	1.44E-07	8.02E-05
Te-123m	2.07E+03	6.98E-04	3.88E-01
Te-125m	7.87E+01	2.65E-05	1.47E-02
Te-127m	1.08E-03	3.64E-10	2.02E-07
Te-129m	5.39E+00	1.82E-06	1.01E-03
Te-132	6.15E+00	2.07E-06	1.15E-03
Th-226	1.67E-03	5.63E-10	3.13E-07
Th-227	1.21E+00	4.09E-07	2.27E-04
Th-228	7.55E+03	2.55E-03	1.41E+00
Th-229	1.28E+02	4.32E-05	2.40E-02
Th-230	1.25E+06	4.22E-01	2.34E+02
Th-231	4.05E+01	1.37E-05	7.59E-03
Th-232	7.40E+04	2.49E-02	1.39E+01
Th-234	1.50E+04	5.05E-03	2.80E+00
Th-Nat	1.13E+04	3.81E-03	2.12E+00
Ti-44	1.10E+02	3.72E-05	2.07E-02
Tl-201	2.17E+01	7.32E-06	4.07E-03
Tl-202	1.56E+02	5.27E-05	2.93E-02
Tl-204	9.03E+02	3.05E-04	1.69E-01
Tl-207	2.26E-07	7.62E-14	4.23E-11
Tl-208	5.82E+02	1.96E-04	1.09E-01
Tl-209	1.93E-01	6.52E-08	3.62E-05
Tm-170	3.46E+01	1.17E-05	6.48E-03
Tm-171	5.10E-01	1.72E-07	9.56E-05
U-230	3.00E-05	1.01E-11	5.62E-09
U-232	3.14E+03	1.06E-03	5.89E-01
U-233	4.16E+03	1.40E-03	7.79E-01
U-234	7.66E+05	2.58E-01	1.44E+02
U-235	1.75E+04	5.92E-03	3.29E+00
U-235m	8.68E-12	2.93E-18	1.63E-15
U-236	1.61E+04	5.43E-03	3.02E+00
U-237	5.28E-07	1.78E-13	9.89E-11
U-238	1.43E+05	4.81E-02	2.67E+01
U-239	8.55E-08	2.88E-14	1.60E-11
U-Dep	1.65E+07	5.57E+00	3.09E+03
U-Nat	1.49E+05	5.02E-02	2.79E+01
V-48	7.89E-02	2.66E-08	1.48E-05
V-49	1.80E+03	6.07E-04	3.37E-01

Isotope	Disposed Activity (mCi)	Volume Concentration (mCi/m³)	Mass Concentration (pCi/g)
W-178	2.70E-03	9.11E-10	5.06E-07
W-181	5.27E+00	1.78E-06	9.88E-04
W-185	1.12E+04	3.77E-03	2.09E+00
W-188	2.86E+04	9.65E-03	5.36E+00
Xe-127	5.36E-03	1.81E-09	1.00E-06
Xe-131m	1.35E+02	4.56E-05	2.53E-02
Xe-133	1.28E+01	4.31E-06	2.39E-03
Xe-133m	1.27E+00	4.28E-07	2.38E-04
Y-86	1.00E-03	3.37E-10	1.87E-07
Y-88	2.39E+02	8.06E-05	4.48E-02
Y-90	9.77E+02	3.30E-04	1.83E-01
Y-91	4.83E-01	1.63E-07	9.05E-05
Yb-169	1.57E+02	5.31E-05	2.95E-02
Yb-175	2.73E-13	9.21E-20	5.12E-17
Zn-65	2.02E+06	6.81E-01	3.78E+02
Zn-69	3.38E-02	1.14E-08	6.33E-06
Zn-69m	2.83E-09	9.54E-16	5.30E-13
Zr-88	2.33E-01	7.86E-08	4.37E-05
Zr-89	4.60E+00	1.55E-06	8.62E-04
Zr-93	5.08E-02	1.71E-08	9.52E-06
Zr-95	7.56E+04	2.55E-02	1.42E+01
Zr-97	4.46E+00	1.50E-06	8.36E-04

* SOURCE: Energy*Solutions*, “2012 Annual Waste Inventory Report”, August 2012.

Table C-6

Intruder-Driller Dose-To-Source Ratios

Nuclide	Dose / Source Ratio (mrem/yr per pCi/g)				
	Year 100	Year 150	Year 220	Year 710	Year 1,000
Ac-227+D	3.01E-08	6.12E-09	6.59E-10	1.64E-17	1.08E-20
Ag-108m+D	4.99E-06	3.69E-06	2.42E-06	8.70E-08	2.17E-08
Al-26	5.26E-05	5.10E-05	4.90E-05	3.55E-05	3.10E-05
Am-241	8.40E-12	1.21E-11	1.67E-11	3.97E-11	4.47E-11
Am-242+D	2.08E-08	1.65E-08	1.20E-08	9.85E-10	3.56E-10
Am-243+D	5.72E-08	5.69E-08	5.65E-08	5.36E-08	5.24E-08
Ar-39	1.02E-11	8.72E-12	6.99E-12	1.23E-12	5.93E-13
Ba-133	1.11E-09	4.39E-11	4.79E-13	1.84E-28	6.57E-35
Be-10	1.66E-11	1.66E-11	1.66E-11	1.66E-11	1.66E-11
Bi-207	2.33E-06	9.07E-07	2.43E-07	7.74E-12	1.02E-13
Bi-210m+D	4.51E-07	4.38E-07	4.21E-07	3.05E-07	2.67E-07
Bk-247	3.52E-08	3.46E-08	3.38E-08	2.81E-08	2.61E-08
C-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca-41	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-113	9.75E-14	9.47E-14	9.09E-14	6.59E-14	5.76E-14
Cd-113m	4.42E-14	3.36E-15	9.10E-17	4.42E-29	3.13E-34
Cf-249	8.51E-07	7.70E-07	6.71E-07	2.26E-07	1.44E-07
Cf-250	1.91E-20	3.11E-20	4.84E-20	2.01E-19	2.73E-19
Cf-251	3.35E-08	3.23E-08	3.06E-08	2.00E-08	1.68E-08
Cf-252	1.55E-17	2.35E-17	3.47E-17	1.23E-16	1.59E-16
Cl-36	2.46E-10	2.43E-10	2.38E-10	2.07E-10	1.95E-10
Cm-243	4.95E-09	1.47E-09	2.68E-10	5.28E-13	5.16E-13
Cm-244	8.16E-17	8.27E-17	8.23E-17	7.78E-17	7.60E-17
Cm-245	5.44E-09	5.42E-09	5.39E-09	5.18E-09	5.10E-09
Cm-246	8.53E-18	1.29E-17	1.92E-17	7.48E-17	1.01E-16
Cm-247+D	1.06E-06	1.06E-06	1.06E-06	1.07E-06	1.07E-06
Cm-248	2.13E-12	3.20E-12	4.68E-12	1.63E-11	2.12E-11
Cm-250+D	4.15E-06	4.13E-06	4.10E-06	3.88E-06	3.79E-06
Co-60	8.32E-11	1.16E-13	1.17E-17	0.00E+00	0.00E+00
Cs-135	2.90E-15	2.90E-15	2.90E-15	2.90E-15	2.90E-15
Cs-137+D	3.54E-07	1.11E-07	2.21E-08	6.70E-14	3.30E-16
Eu-150	1.06E-06	3.86E-07	9.35E-08	1.35E-12	1.27E-14
Eu-152	7.30E-08	5.43E-09	1.42E-10	5.41E-23	3.46E-28
Eu-154	5.75E-09	1.12E-10	4.51E-13	6.92E-32	9.38E-40
Eu-155	4.60E-16	4.25E-19	2.40E-23	0.00E+00	0.00E+00

Nuclide	Dose / Source Ratio (mrem/yr per pCi/g)				
	Year 100	Year 150	Year 220	Year 710	Year 1,000
Fe-55	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fe-60+D	4.56E-05	4.56E-05	4.55E-05	4.54E-05	4.53E-05
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hg-194+D	9.79E-06	8.57E-06	7.11E-06	1.64E-06	8.88E-07
Ho-166m	1.15E-05	1.12E-05	1.07E-05	7.80E-06	6.83E-06
I-129	3.11E-25	3.07E-25	3.02E-25	2.62E-25	2.47E-25
In-115	4.21E-12	4.21E-12	4.21E-12	4.21E-12	4.21E-12
Mn-53	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mo-93	1.43E-34	1.41E-34	1.39E-34	1.25E-34	1.19E-34
Na-22	5.38E-17	8.84E-23	7.04E-31	0.00E+00	0.00E+00
Nb-93m	1.23E-37	9.34E-39	2.53E-40	0.00E+00	0.00E+00
Nb-94	1.21E-05	1.17E-05	1.12E-05	7.98E-06	6.92E-06
Ni-59	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-63	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Np-236	2.82E-06	3.56E-06	4.14E-06	4.73E-06	4.73E-06
Np-237+D	2.77E-07	2.77E-07	2.77E-07	2.77E-07	2.77E-07
Os-194+D	4.59E-12	1.42E-14	4.37E-18	9.53E-46	0.00E+00
Pa-231	7.64E-07	7.87E-07	7.92E-07	7.83E-07	7.79E-07
Pb-202+D	1.74E-06	1.74E-06	1.74E-06	1.73E-06	1.73E-06
Pb-205	5.33E-43	5.33E-43	5.33E-43	5.33E-43	5.33E-43
Pb-210+D	1.94E-11	4.10E-12	4.66E-13	1.75E-20	1.38E-23
Pd-107	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-145	3.98E-18	5.62E-19	3.63E-20	1.60E-29	1.97E-33
Pm-147	1.39E-25	2.55E-31	2.37E-39	0.00E+00	0.00E+00
Pt-193	1.06E-43	5.34E-44	2.00E-44	0.00E+00	0.00E+00
Pu-236	8.59E-07	5.31E-07	2.71E-07	1.36E-09	1.48E-10
Pu-238	1.10E-13	1.91E-13	4.42E-13	8.70E-12	1.53E-11
Pu-239	2.46E-11	2.46E-11	2.45E-11	2.42E-11	2.40E-11
Pu-240	3.00E-14	2.99E-14	2.96E-14	2.80E-14	2.73E-14
Pu-241+D	2.31E-13	3.52E-13	5.13E-13	1.30E-12	1.48E-12
Pu-242	4.78E-14	4.92E-14	5.11E-14	6.60E-14	7.22E-14
Pu-244+D	2.76E-06	2.76E-06	2.76E-06	2.76E-06	2.76E-06
Ra-226+D	3.05E-05	2.99E-05	2.90E-05	2.28E-05	2.07E-05
Ra-228+D	5.06E-10	1.22E-12	2.64E-16	4.76E-45	0.00E+00
Rb-87	9.24E-14	9.24E-14	9.24E-14	9.24E-14	9.24E-14
Re-187	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Se-79	1.43E-16	1.39E-16	1.33E-16	9.61E-17	8.38E-17
Si-32+D	1.39E-09	1.29E-09	1.16E-09	4.95E-10	3.47E-10
Sm-146	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Nuclide	Dose / Source Ratio (mrem/yr per pCi/g) Year 100	Year 150	Year 220	Year 710	Year 1,000
Sm-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	8.61E-34	5.86E-34	3.42E-34	4.94E-36	8.40E-37
Sn-121m+D	1.49E-13	7.70E-14	3.06E-14	2.17E-17	1.04E-18
Sn-126+D	1.15E-05	1.12E-05	1.07E-05	7.75E-06	6.76E-06
Sr-90+D	5.45E-10	1.66E-10	3.13E-11	6.45E-17	2.70E-19
Tb-157	1.13E-20	8.93E-21	6.46E-21	5.09E-22	1.76E-22
Tb-158	4.92E-06	3.91E-06	2.83E-06	2.23E-07	7.69E-08
Tc-98	9.66E-06	9.38E-06	9.00E-06	6.52E-06	5.70E-06
Tc-99	9.91E-14	9.62E-14	9.23E-14	6.68E-14	5.83E-14
Te-123	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Th-229+D	1.36E-06	1.36E-06	1.35E-06	1.28E-06	1.25E-06
Th-230	1.36E-06	2.01E-06	2.90E-06	9.02E-06	1.12E-05
Th-232	6.57E-05	6.57E-05	6.57E-05	6.57E-05	6.57E-05
Ti-44+D	5.01E-06	2.41E-06	8.63E-07	2.73E-10	9.37E-12
Tl-204	4.29E-20	4.34E-24	1.11E-29	0.00E+00	0.00E+00
U-232	2.08E-05	1.29E-05	6.56E-06	3.29E-08	3.59E-09
U-233	1.31E-08	1.95E-08	2.84E-08	9.65E-08	1.24E-07
U-234	6.20E-10	1.38E-09	2.93E-09	3.30E-08	5.39E-08
U-235+D	6.12E-08	6.20E-08	6.32E-08	7.24E-08	7.61E-08
U-236	5.91E-13	7.53E-13	9.80E-13	2.76E-12	3.51E-12
U-238+D	1.76E-07	1.76E-07	1.76E-07	1.76E-07	1.76E-07
Zr-93	2.15E-35	2.16E-35	2.16E-35	2.16E-35	2.16E-35

Table C-7

Intruder-Driller Doses (mrem/yr) For The

Current Class A Waste Inventory

Nuclide	Year 100	Year 150	Year 220	Year 710	Year 1,000
Ac-227+D	6.09E-08	1.24E-08	1.33E-09	3.32E-17	2.19E-20
Ag-108m+D	2.30E-06	1.70E-06	1.12E-06	4.01E-08	1.00E-08
Al-26	4.01E-07	3.89E-07	3.74E-07	2.71E-07	2.36E-07
Am-241	4.01E-11	5.78E-11	7.98E-11	1.90E-10	2.14E-10
Am-242+D	9.67E-12	7.67E-12	5.58E-12	4.58E-13	1.65E-13
Am-243+D	1.67E-09	1.66E-09	1.65E-09	1.56E-09	1.53E-09
Ar-39	7.64E-17	6.54E-17	5.24E-17	9.22E-18	4.44E-18
Ba-133	2.18E-10	8.61E-12	9.40E-14	3.61E-29	1.29E-35
Be-10	3.17E-17	3.17E-17	3.17E-17	3.17E-17	3.17E-17
Bi-207	8.71E-08	3.39E-08	9.08E-09	2.89E-13	3.81E-15
Bi-210m+D	4.36E-10	4.24E-10	4.07E-10	2.95E-10	2.58E-10
Bk-247	9.89E-15	9.72E-15	9.50E-15	7.90E-15	7.34E-15
C-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca-41	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd-113	1.48E-21	1.44E-21	1.38E-21	1.00E-21	8.76E-22
Cd-113m	1.49E-14	1.13E-15	3.07E-17	1.49E-29	1.06E-34
Cf-249	1.09E-09	9.90E-10	8.63E-10	2.91E-10	1.85E-10
Cf-250	6.57E-25	1.07E-24	1.66E-24	6.91E-24	9.39E-24
Cf-251	5.37E-15	5.17E-15	4.90E-15	3.20E-15	2.69E-15
Cf-252	6.59E-19	9.99E-19	1.47E-18	5.23E-18	6.76E-18
Cl-36	6.30E-12	6.23E-12	6.10E-12	5.30E-12	5.00E-12
Cm-243	7.74E-10	2.30E-10	4.19E-11	8.26E-14	8.07E-14
Cm-244	1.37E-17	1.39E-17	1.39E-17	1.31E-17	1.28E-17
Cm-245	2.68E-11	2.67E-11	2.66E-11	2.55E-11	2.51E-11
Cm-246	6.30E-21	9.52E-21	1.42E-20	5.52E-20	7.46E-20
Cm-247+D	5.72E-11	5.72E-11	5.72E-11	5.78E-11	5.78E-11
Cm-248	1.53E-16	2.29E-16	3.35E-16	1.17E-15	1.52E-15
Cm-250+D	5.84E-13	5.81E-13	5.77E-13	5.46E-13	5.33E-13
Co-60	2.12E-07	2.96E-10	2.99E-14	0.00E+00	0.00E+00
Cs-135	6.42E-17	6.42E-17	6.42E-17	6.42E-17	6.42E-17
Cs-137+D	9.62E-05	3.02E-05	6.00E-06	1.82E-11	8.97E-14
Eu-150	7.63E-11	2.78E-11	6.73E-12	9.71E-17	9.14E-19
Eu-152	3.42E-07	2.54E-08	6.65E-10	2.53E-22	1.62E-27
Eu-154	4.22E-09	8.23E-11	3.31E-13	5.08E-32	6.89E-40
Eu-155	1.31E-16	1.21E-19	6.81E-24	0.00E+00	0.00E+00

Nuclide	Year 100	Year 150	Year 220	Year 710	Year 1,000
Fe-55	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fe-60+D	1.13E-03	1.13E-03	1.13E-03	1.12E-03	1.12E-03
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hg-194+D	3.10E-09	2.71E-09	2.25E-09	5.19E-10	2.81E-10
Ho-166m	1.68E-08	1.64E-08	1.57E-08	1.14E-08	9.99E-09
I-129	1.22E-25	1.21E-25	1.19E-25	1.03E-25	9.72E-26
In-115	7.89E-19	7.89E-19	7.89E-19	7.89E-19	7.89E-19
Mn-53	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mo-93	1.69E-38	1.66E-38	1.64E-38	1.48E-38	1.40E-38
Na-22	7.74E-17	1.27E-22	1.01E-30	0.00E+00	0.00E+00
Nb-93m	1.93E-39	1.46E-40	3.96E-42	0.00E+00	0.00E+00
Nb-94	1.75E-06	1.69E-06	1.62E-06	1.16E-06	1.00E-06
Ni-59	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-63	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Np-236	2.62E-12	3.30E-12	3.84E-12	4.39E-12	4.39E-12
Np-237+D	1.33E-07	1.33E-07	1.33E-07	1.33E-07	1.33E-07
Os-194+D	8.60E-20	2.66E-22	8.19E-26	1.79E-53	0.00E+00
Pa-231	1.35E-06	1.39E-06	1.40E-06	1.38E-06	1.38E-06
Pb-202+D	7.89E-13	7.89E-13	7.89E-13	7.84E-13	7.84E-13
Pb-205	3.42E-47	3.42E-47	3.42E-47	3.42E-47	3.42E-47
Pb-210+D	2.04E-09	4.30E-10	4.89E-11	1.84E-18	1.45E-21
Pd-107	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-145	1.10E-20	1.56E-21	1.01E-22	4.44E-32	5.46E-36
Pm-147	1.45E-25	2.66E-31	2.47E-39	0.00E+00	0.00E+00
Pt-193	2.13E-48	1.07E-48	4.01E-49	0.00E+00	0.00E+00
Pu-236	9.27E-12	5.73E-12	2.92E-12	1.47E-14	1.60E-15
Pu-238	2.21E-12	3.84E-12	8.88E-12	1.75E-10	3.07E-10
Pu-239	4.75E-10	4.75E-10	4.73E-10	4.67E-10	4.63E-10
Pu-240	8.67E-14	8.64E-14	8.55E-14	8.09E-14	7.89E-14
Pu-241+D	9.23E-12	1.41E-11	2.05E-11	5.20E-11	5.92E-11
Pu-242	8.21E-16	8.45E-16	8.78E-16	1.13E-15	1.24E-15
Pu-244+D	3.25E-10	3.25E-10	3.25E-10	3.25E-10	3.25E-10
Ra-226+D	3.72E-03	3.64E-03	3.53E-03	2.78E-03	2.52E-03
Ra-228+D	4.33E-10	1.04E-12	2.26E-16	4.07E-45	0.00E+00
Rb-87	2.32E-19	2.32E-19	2.32E-19	2.32E-19	2.32E-19
Re-187	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Se-79	6.30E-20	6.12E-20	5.86E-20	4.23E-20	3.69E-20
Si-32+D	4.40E-13	4.09E-13	3.67E-13	1.57E-13	1.10E-13
Sm-146	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Nuclide	Year 100	Year 150	Year 220	Year 710	Year 1,000
Sm-151	7.49E-36	5.09E-36	2.97E-36	4.29E-38	7.30E-39
Sn-121m+D	2.29E-21	1.19E-21	4.71E-22	3.34E-25	1.60E-26
Sn-126+D	1.36E-10	1.33E-10	1.27E-10	9.18E-11	8.01E-11
Sr-90+D	1.19E-08	3.63E-09	6.85E-10	1.41E-15	5.91E-18
Tb-157	5.29E-27	4.18E-27	3.03E-27	2.38E-28	8.24E-29
Tb-158	6.43E-11	5.11E-11	3.70E-11	2.92E-12	1.01E-12
Tc-98	6.43E-11	6.24E-11	5.99E-11	4.34E-11	3.79E-11
Tc-99	2.71E-11	2.63E-11	2.52E-11	1.83E-11	1.59E-11
Te-123	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Th-229+D	3.27E-08	3.27E-08	3.24E-08	3.08E-08	3.00E-08
Th-230	3.19E-04	4.71E-04	6.79E-04	2.11E-03	2.62E-03
Th-232	9.11E-04	9.11E-04	9.11E-04	9.11E-04	9.11E-04
Ti-44+D	1.04E-07	4.99E-08	1.79E-08	5.65E-12	1.94E-13
Tl-204	7.26E-21	7.34E-25	1.88E-30	0.00E+00	0.00E+00
U-232	1.22E-05	7.60E-06	3.86E-06	1.94E-08	2.11E-09
U-233	1.02E-08	1.52E-08	2.21E-08	7.52E-08	9.67E-08
U-234	8.90E-08	1.98E-07	4.21E-07	4.74E-06	7.74E-06
U-235+D	2.01E-07	2.04E-07	2.08E-07	2.38E-07	2.50E-07
U-236	1.78E-12	2.27E-12	2.96E-12	8.33E-12	1.06E-11
U-238+D	4.70E-06	4.70E-06	4.70E-06	4.70E-06	4.70E-06
Zr-93	2.05E-40	2.06E-40	2.06E-40	2.06E-40	2.06E-40
TOTAL	**6.20E-03**	**6.20E-03**	**6.27E-03**	**6.94E-03**	**7.19E-03**

Table C-8

Intruder-Driller Doses For The Embankment

Full of Blended Resins

Isotope	Peak Dose (100 years) (mrem/yr)
C-14	0.00E+00
Co-58	0.00E+00
Co-60	2.27E-04
Cs-137+D	1.11E-01
Fe-55	0.00E+00
H-3	0.00E+00
I-129	1.42E-22
Kr-85	0.00E+00
Mn-54	0.00E+00
Ni-63	0.00E+00
Sr-90+D	3.55E-06
Zn-65	0.00E+00
TOTAL	**1.11E-01**

Table C-9

Net Infiltration Through the Alternate Evapotranspirative Cover Designs

Evaporative Zone Thickness (cm)	Net Infiltration Flux through Cover Design A (cm/yr)	Net Infiltration Flux through Cover Design B (cm/yr)
15.2	2.51E-04	1.92E-04
30.5	1.97E-04	1.89E-04
45.7	1.95E-04	1.89E-04