SAND2013-8255P

# Update to the Salt R&D Reference Case

## Fuel Cycle Research & Development

*Prepared for*
*U.S. Department of Energy*
*Used Fuel Disposition*

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# APPENDIX E
# FCT DOCUMENT COVER SHEET[1]

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This deliverable was prepared in accordance with Sandia National Laboratories
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QA program which meets the requirements of
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# ACRONYMS

| | |
|---|---|
| DOE | U.S. Department of Energy |
| DSA | Disposal System Analysis |
| DRZ | Disturbed Rock Zone |
| EBS | Engineered Barrier System |
| FEP | Feature, Event, and Process |
| FY | Fiscal Year |
| GDSA | Generic Disposal System Analysis |
| GWd | Gigawatt-days (units of energy) |
| HLW | High-Level Radioactive Waste |
| MTHM | Metric Tons of Heavy Metal |
| MTIHM | Metric Tons of Initial Heavy Metal |
| MTU | Metric Tons of Uranium |
| NBS | Natural Barrier System |
| NE | Office of Nuclear Energy |
| OoR | (Age) Out of Reactor |
| PA | Performance Assessment |
| R&D | Research and Development |
| UNF | Used Nuclear Fuel |

# 1. INTRODUCTION

Within the scope of the U.S. Department of Energy's generic approach to RD&D for geological disposal of high activity nuclear waste (DOE 2012a), the Offices of Nuclear Energy (DOE-NE) and Environmental Management (DOE-EM) agreed upon a specific workscope related to geologic disposal of heat-generating waste in salt. This workscope was documented in a "Salt R&D Study Plan," dated March 23, 2012 and documented in Sevougian et al. (2013a, App. C). Part of this Salt R&D effort was the development of a performance assessment (PA) model methodology for a bedded salt repository, first described by Sevougian et al. (2012). The initial focus of the PA model methodology was on the following five steps (Sevougian et al. 2013b):

(1) FEPs identification specific to salt host rock,
(2) definition of a salt repository "reference case,"
(3) preliminary FEPs screening based on past salt R&D and safety assessments,
(4) specification of quantitative sensitivity analyses and/or reasoned arguments necessary to support FEPs screening, and
(5) implications of FEPs screening for PA model construction.

The second step, the salt repository reference case was initially described in detail by Sevougian et al. (2012) and later expanded upon in Vaughn et al. (2013) with the specification of additional parameter values, especially for features of the natural barrier system (NBS). Since that time, it has been further refined, as described here, to support its primary purpose as the first reference case for testing the Generic Disposal System Analysis (GDSA) Model framework, which will be reported on in further detail in a Level 2 milestone, due in November 2013: *Generic Disposal System Modeling Report* (M2FT-13SN0808043). A preliminary description of the role of the Salt R&D Reference case within the context of the GDSA Model was presented in a recent Level 4 Milestone (Freeze et al. 2013a).

Regarding the significance and purpose of the reference case for a generic repository in bedded salt, Vaughn et al. (2013) have stated:

> "The emphasis on generic repositories creates some unique challenges for safety case development and subsequent modeling of a geologic disposal system. Normally, a safety case and associated safety assessment address a specific site, a well-defined inventory, waste form, and waste package, a specific repository design, specific concept of operations, and an established regulatory environment. This level of specificity does not exist for a 'generic' repository, so it is important to establish a reference case, to act as a surrogate for site/design specific information upon which a safety case can be developed….(and to provide) enough information to support the initial screening of Features, Events, Processes (FEPs) and the design of models for preliminary safety assessments for HLW/SNF repositories in bedded salt."

The initial focus of the bedded salt disposal reference case is on the undisturbed repository performance (performance in the absence of external events). This focus is appropriate at this time because disturbed scenarios, e.g. inadvertent human intrusion, igneous intrusion, and seismic, tend to rely on more site specific information than the undisturbed scenario.

# 2. UPDATED SALT DISPOSAL REFERENCE CASE

The salt disposal reference case, as originally described by Sevougian et al. (2012; 2013) and later updated in Vaughn et al. (2013), consisted of five major elements: (a) waste inventory, (b) geologic disposal system (the engineered and natural barrier systems), (c) concept of operations, (d) biosphere, and (e) regulatory environment. These five elements are simplified to four elements in this update to the salt reference case, as shown in Figure 1:

- Waste inventory
- Geologic disposal system (the engineered and natural barrier systems)
- Biosphere
- Regulatory environment

The repository "concept of operations," which is part of the engineering design used to ensure preclosure and postclosure safety, through mechanical, thermal, and criticality design constraints, is now described under the EBS element of the reference case. (Criticality design constraints are not part of the initial reference case described below; they will be considered later.)

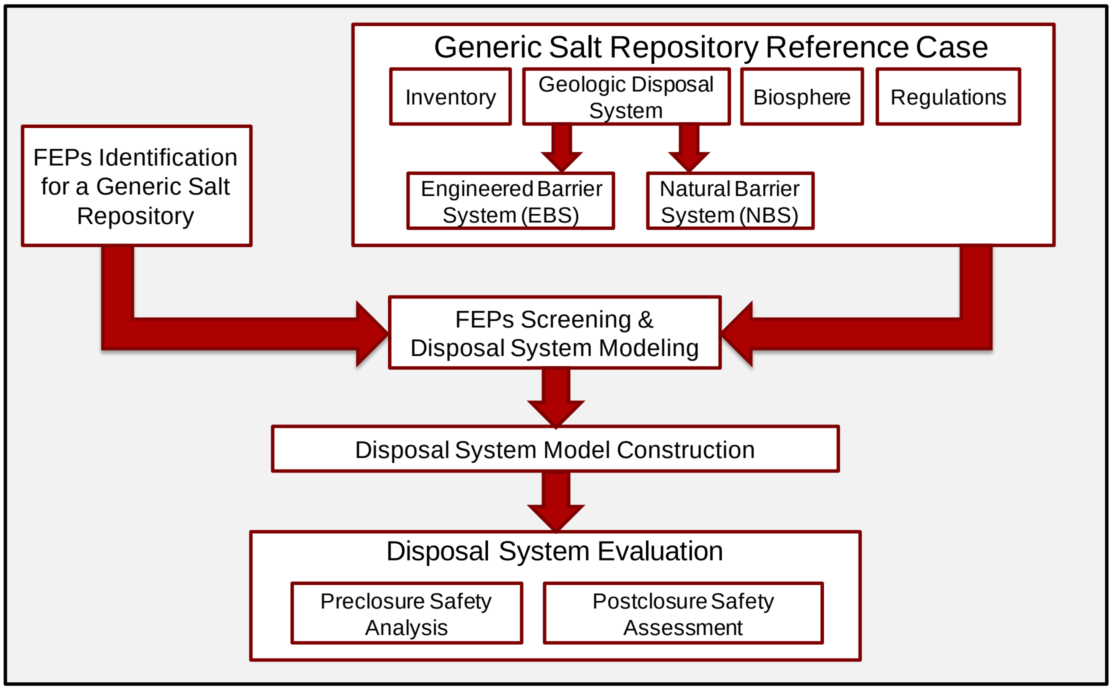

Figure 1. Major components of the bedded salt disposal reference case and its place in the disposal system model development methodology (after Vaughn et al. 2013).

The primary updates to the reference case are (1) the specification or modification of some parameter values and (2) refinements to the concept of operations (thermal management). These updates of the reference case in Fiscal Year 2013 have been directed toward its specific application for testing of the GDSA Model—see Figure 2 (Freeze et al. 2013a). A description of these updates in the context of the four major elements of the reference case is given in the following sections (with much of the text being derived from Vaughn et al. 2013).

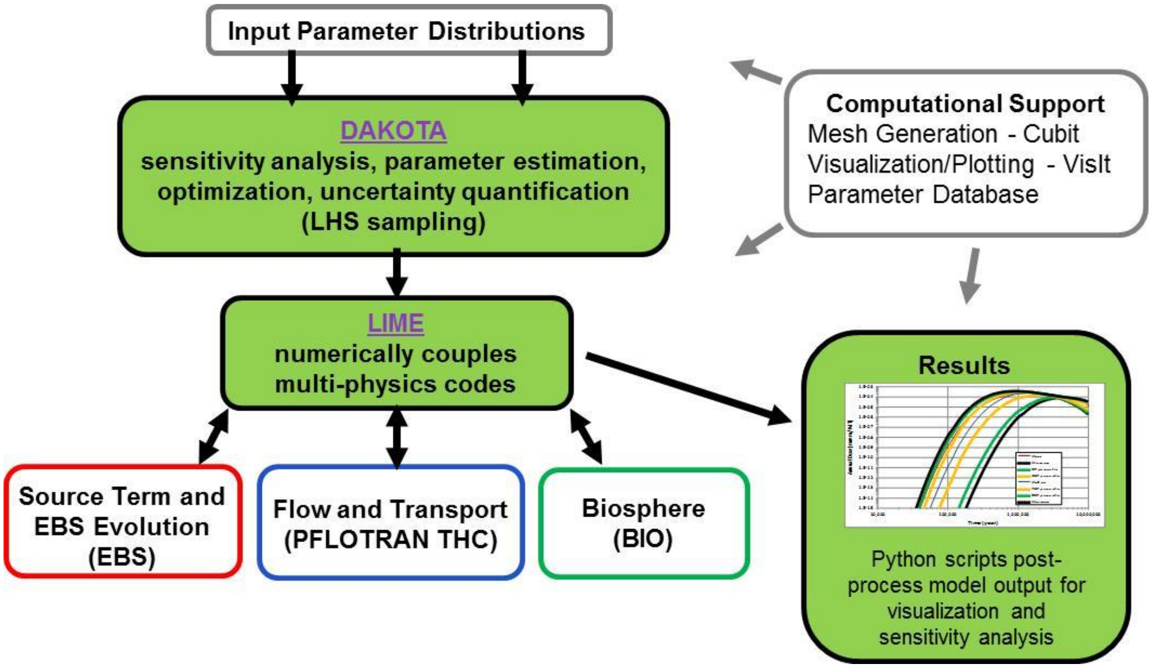

Figure 2. GDSA Model Framework (after Freeze et al. 2013a).

## 2.1 Waste Inventory

The nominal waste inventory for the salt reference case includes:

a. The current U.S. inventory of spent nuclear fuel from commercial reactors;
b. UNF discharged in the future from the current reactor fleet through final shutdown in about 2055, i.e., the “no replacement nuclear generation” scenario of Sec. 3.2.1 in Carter et al. (2012);
c. HLW and SNF currently owned and managed by DOE, see Sections 2.1 and 2.3 in Carter et al. (2012); and
d. Naval SNF.

Projections show that, if all operating commercial reactors in the U.S. receive license amendments that extend operating life to 60 years, the total inventory of commercial UNF will reach approximately 140,000 MTHM in the year 2055 (Carter et al. 2012, Table 3-7). However, for the purposes of testing the GDSA Model, a smaller inventory will be assumed, according to the maximum inventory allowed in the Nuclear Waste Policy Act (NWPA 1983, Sec. 114(d)). Furthermore, a bounding fuel burnup will be assumed that gives a conservative heat load in the reference repository. In particular, 70,000 MTHM of PWR UNF with a burnup of 60 GWd/MTHM will be assumed for the salt reference case. As shown in Appendix B of Carter et al. (2012), the average discharged PWR UNF burnup is about 54.2 GWd/MTHM in 2055, so the assumption of 60 GWd/MTHM for the reference repository will produce a conservative heat loading for the repository.

Regarding the radioisotope composition of the reference waste inventory, the 30-year decay inventory (60 GWd/MTHM) in Appendix C of Carter et al. 2012 will initially be assumed in the salt reference case, even though this is slightly inconsistent with assumed decay storage times of either 50 or 70 years, discussed below. This PWR radioisotope inventory will later be augmented with the inventories of DOE HLW and DOE SNF, if and when these are added to the GDSA reference case analyses.

For initial testing of the GDSA Model, a limited suite of radionuclides is simulated, including two major alpha-decay chains, the neptunium series ($^{241}$Am → $^{237}$Np → $^{233}$Pa → $^{233}$U → $^{229}$Th), which includes $^{237}$Np, known to be an important radionuclide for long-term dose calculations (e.g., see DOE 2008, Sec. 2.4.2.2.1), and the uranium series ($^{242}$Pu → $^{238}$U → $^{234}$U → $^{230}$Th → $^{226}$Ra → $^{222}$Rn), which includes $^{226}$Ra, a potentially important species for groundwater protection requirements (e.g., see 10 CFR 63.331). Also, included in the simulations is $^{129}$I, which is a nonsorbing radionuclide with a long half-life that frequently is another key contributor to potential long-term dose. Based on the inventory in Carter et al. (2012, App. C), the mole fractions of these radionuclides in a PWR fuel with 60 GWd/MTHM burnup and 30 years age OoR is given in Table 1, assuming a molecular weight of 100 g/mol for the UNF waste form.

Table 1. Mole Fractions of Select Radioisotopes in the UNF Inventory.

| Isotope | Waste inventory mass (g/MTIHM)[1] | Molecular weight (g/mol) | Mass fraction (g/gUNF) | Mole fraction (mol/molUNF) |
|---|---|---|---|---|
| U238 | 9.10E+05 | 238.05 | 6.32E-01 | 2.66E-01 |
| Np237 | 1.24E+03 | 237.05 | 8.61E-04 | 3.63E-04 |
| Am241 | 1.25E+03 | 241.06 | 8.68E-04 | 3.60E-04 |
| Pu242 | 8.17E+02 | 242.06 | 5.68E-04 | 2.34E-04 |
| I129 | 3.13E+02 | 129 | 2.17E-04 | 1.69E-04 |
| U234 | 3.06E+02 | 234.04 | 2.13E-04 | 9.08E-05 |
| Th230 | 2.28E-02 | 230.03 | 1.58E-08 | 6.89E-09 |
| U233 | 1.40E-02 | 233.04 | 9.73E-09 | 4.17E-09 |
| Pa233 | 4.20E-05 | 233.04 | 2.92E-11 | 1.25E-11 |
| Th229 | 6.37E-06 | 229.03 | 4.43E-12 | 1.93E-12 |
| Ra226 | 3.18E-06 | 226.03 | 2.21E-12 | 9.77E-13 |
| Rn222 | 2.04E-11 | 222.02 | 1.42E-17 | 6.38E-18 |

[1] from Carter et al. (2012, Table C-1)

## 2.2 Geologic Disposal System: Engineered Barrier System

The Engineered Barrier System (EBS) includes everything within the physical excavations. The physical components of the EBS in the reference bedded salt repository are (see Figure 3): (1) the waste form; (2) the waste package; (3) crushed-salt backfill; (4) tunnels/drifts/alcoves, and (5) seals (panel closures and shaft seals). The bedded salt disposal reference case is based on the generic salt repository design concept described in Hardin et al. (2013, Sec. 4.2)—originally based on the design in Carter et al. (2011)—which requires no tunnel liners or special waste package buffers, so those generic components shown in Figure 3 are not applicable in this case.

In addition to the design of the individual physical components listed above, the repository itself must be arranged geometrically to observe certain thermal and mechanical design constraints to ensure safe preclosure and postclosure performance. For example, mechanical design guidelines regarding the "extraction ratio" (defined as the mined volume to the original volume) and the pillar width-to-height ratio must be observed to ensure safe preclosure operations, i.e., to prevent drift collapse (Zipf 2001; Poulsen 2010). Similarly, the waste package and drift loading is generally designed so that highest salt temperature from decay heat is kept to 200°C or less (Hardin et al. 2012; Freeze et al. 2013b), to prevent thermal degradation of either the salt backfill or the native host rock. These thermal and mechanical design and operational considerations are often referred to as the "concept of operations."

The following paragraphs describe, at a high level, the repository concept of operations, as well as the configuration and characteristics of each of the five physical components/features in the salt reference EBS.

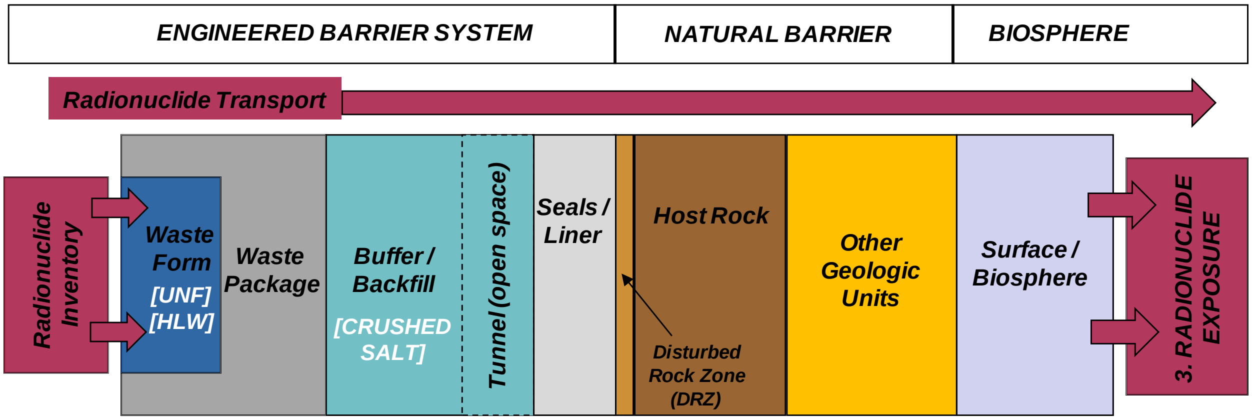

Figure 3. Features and Components of the Generic Salt Disposal System [after Sevougian et al. (2012)].

### 2.2.1 Concept of Operations

The engineering concept of operations takes into account the characteristics of the EBS and the NBS to define the excavation, emplacement, and closure operations for the repository disposal system. The salt reference case considers these aspects at a high level, as appropriate for generic safety assessments and for testing the GDSA Model. Although previous conceptual designs for repositories in bedded salt called for disposal of waste canisters in vertical or horizontal boreholes (ONWI 1987), the reference case uses a simpler disposal scheme with disposal of waste packages on the floor of the drifts, using the in-drift emplacement design chosen by Hardin et al. (2013, Sec. 4.2.1 and Figure 4-3).

#### *2.2.1.1 Thermal Design Constraint*

For the reference case the temperature constraint is taken to be a peak temperature of 200°C at the waste package surface in order to limit thermal degradation of the the salt backfill or the native host rock. This has implications for both repository layout and waste package decay storage time, size, content, and spacing, e.g., see Sections 1.4.2 and 1.4.5.2 of Hardin et al. (2012). Prior studies have also considered a peak temperature limit of 250°C (Hardin et al. 2012, Sec. 1.4.1), which may be adopted by this reference case as the PA model matures. For preliminary analyses with the salt reference case, the alcove herringbone arrangement described in Carter et al. (2011, Figure 14), and also described in Section 4.2 of Hardin et al. (2012), was originally proposed by Sevougian et al. (2012) and Vaughn et al. (2013) to ensure temperatures below 200°C. However, an in-drift emplacement mode with waste packages emplaced either in semi-cylindrical drift floor cavities or directly on the drift floor may have advantages from a heat dissipation perspective as well as transportation perspective (Hardin et al. 2013, Section 4.2.1). Also, the original alcove emplacement concept is more complex than required to test the GDSA Model (Figure 2). Thus, this update to the bedded salt reference case implements the in-drift arrangement.

#### *2.2.1.2 Drift Design*

For the reference case the height and width of the access drifts and emplacement drifts are selected to provide clearance for the waste package emplacement operations. As proposed in Hardin et al. (2013, Fig. 4-3), emplacement drifts might be 4 meters high and 6 meters wide (providing clearance for emplacement of 5-meter-long waste packages—see Section 2.2.3—with a wheeled transporter). Drifts containing waste packages are backfilled with crushed salt either during or just after waste emplacement.

#### *2.2.1.3 Repository Layout*

The reference case will eventually include UNF that varies with respect to initial enrichment, burnup, and age out-of-reactor. However, for initial testing of the GDSA Model, a more homogeneous waste stream is desired. As described in Section 2.1, an assumption of 60 GWd/MTHM PWR fuel is bounding with respect to UNF burnup for the current reactor fleet. This assumption, as well as the amount of UNF per waste package controls heat loading in the repository. For the current update to the salt reference case, each waste package will be assumed to contain 12 fuel-rod assemblies of PWR UNF. This is based on a set of thermal calculations investigating sensitivity of peak waste-package wall temperature to waste package size (loading), decay storage time (age out of reactor or OoR), repository ventilation rate, burnup, and initial waste package heat output, described in Table C-4 of Hardin et al. (2012)—also see Hardin et al. (2013, Table 4-2). With these two assumptions (60 GWd/MTHM and 12-PWR waste packages), the waste package wall temperature remains below 200°C for reasonable OoR values (generally 50 years or less), if the waste package spacing is 20 m by 20 m. However, a more compact repository design is desirable for testing of the GDSA Model, so for the salt reference case the drift spacing will be taken as 20 m, with a 10-m spacing between waste packages in each drift. This design creates a hotter repository than modeled by Hardin et al. (2012, App. C). However, simple thermal analyses with MathCad®, using an analytical superposition line-source solution, show that a storage time of 70 years OoR will maintain a waste package surface temperature below 200°C for this assumed repository design of a 20 m by 10 m spacing for 60 GWd/MTHM UNF. Figure 4 is a plot of these calculations.

Based on the layout of 20 meters between drift centers and 10 meters between waste package centers within each drift, an overall repository size can be calculated. This calculation is based on assuming the emplacement of 70,000 MTHM UNF with 12 PWR fuel rod assemblies per waste package. From Table 3-7 in Carter et al. (2012), each PWR assembly represents ~435.4 kg of initial MTU (91,000 MTU/209,000 assemblies) in the year 2055 for the no-replacement nuclear power generation scenario. With 12 PWR assemblies per waste package, there is about ~5.225 kg initial MTU represented in each waste package.[1] Based on the 20-m by 10-m repository layout, the waste package loading (5.225 kg MTU/WP), and the total amount of UNF in the repository (70,000 MTU), Table 2 gives the repository and drift dimensions for the repository layout shown schematically in Figure 5. The actual weight of UNF associated with this amount of initial MTU (or MTIHM) is given in Table C-1 of Carter et al. (2012), which sums up the UNF on an isotopic basis (including the oxygen content in the $UO_2$ and the zirconium content in the fuel rods, as well as iron activitation products). This total amount of UNF is 1.44 MT of UNF per MTIHM.

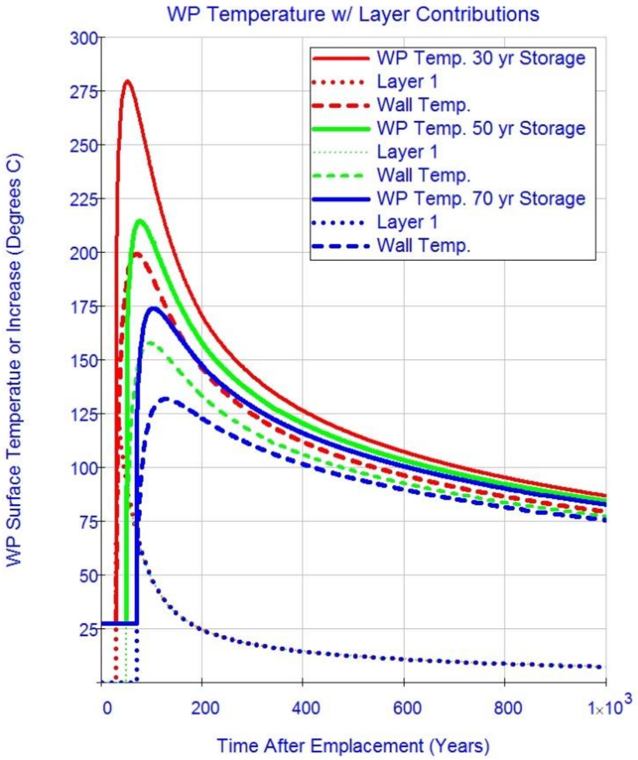

Figure 4. Waste package surface and drift wall temperatures for 60 GWd/MTHM UNF in 12-PWR packages for various decay storage times—MathCad superposition solution.

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[1] As stated by Carter et al. (2012, Sec. 1.7): "This report uses initial, also known as beginning of life (BOL), uranium mass (i.e., MTU) values when reporting inventory for commercial UNF. This is the value typically reported by utilities and the units in which the data were collected. Initial MTU and Metric Tons Initial Heavy Metal (MTIHM) are the same for commercial UNF since uranium is the only heavy metal present."

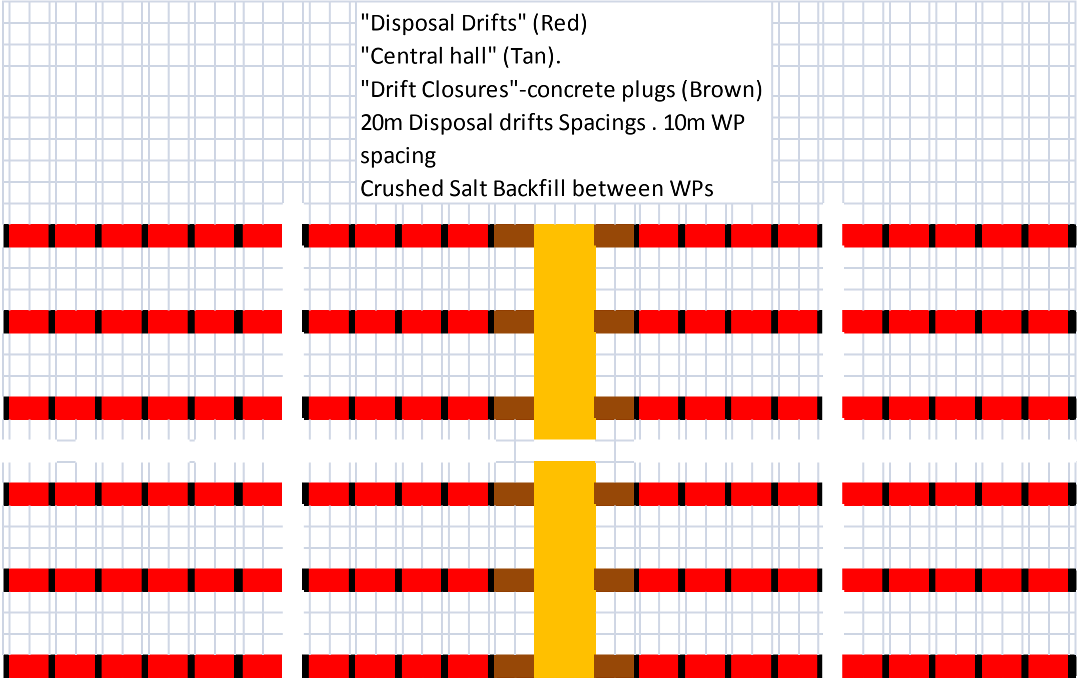

Figure 5. Schematic representation of repository geometry used in GDSA Model testing (not all drifts or waste packages are shown; WPs shown in black).

Table 2. Repository Layout Parameters.

| | |
|---|---|
| **Input** | |
| Inventory (kgHM) | 7.00E+07 |
| **WP Info** | |
| WP Length (m) | 5 |
| WP OD (m) | 1.29 |
| Overpack Thickness (m) | 0.05 |
| WP spacing (m), center-to-center | 10 |
| Number of PWR assemblies per WP | 12 |
| Inventory per PWR (kgHM) | 435.4067 |
| **Drift Info** | |
| Drift width (m) | 6 |
| Drift height (m) | 4 |
| Number of WPs per drift (≡ tunnel to left or right of center hall) | 80 |
| Drift spacing (m), center-to-center | 20 |
| Center Hall width (m) | 8 |
| **Other Info** | |
| Drift closure Length (m) | 10 |
| **Output** | |
| Number of PWR assemblies | 1.61E+05 |
| Number of WPs | 13397.44 |
| Number of drifts needed | 167.47 |
| Number of drift pairs, rounded up in pairs | 84.00 |
| Drift length (m), includes closures | 805.00 |
| Repository Width (m) | 1618.00 |
| Repository Length (m) | 1666.00 |
| Length of drift required (m), includes round-up | 136080 |
| Actual amount of waste contained (kgHM), includes round-up | 7.02E+07 |
| Actual number of waste packages contained, includes round-up | 13440.00 |

### 2.2.2 Waste Form

The disposed waste forms for the bedded salt reference case assume HLW borosilicate glass and uranium oxide UNF and contain the reference inventory of radionuclides described in Section 2.1. The specific geometry and the degradation rates in typical bedded salt environments will be specified as needed to test the GDSA Model (to be described in the Generic Disposal System Modeling Report, M2FT-13SN0808043, November 2013, if appropriate).

### 2.2.3 Waste Package

The bedded salt reference case assumes the emplaced waste forms will be sealed in stainless steel canisters that are contained in disposal overpacks made of carbon steel with welded closures. As stated by Hardin et al. (2013, Sec. 4.2): "Waste package overpacks could consist of low-alloy steel (or nodular cast iron, etc.) to maintain integrity throughout repository operations, and for a period of time after emplacement. The minimum time could be on the order of 50 years to facilitate retrieval as required by current regulation (10 CFR 60.111(b)). The overpack could be made of corrosion-allowance material, and robust to withstand mechanical loading by salt creep during this period. Because moisture is scarce in the salt disposal environment, corrosion of such an overpack may be limited so that containment integrity is maintained for hundreds or thousands of years."

Although carbon steel is susceptible to general (uniform) corrosion, available data indicate that carbon steel is not susceptible to localized corrosion in typical repository applications (Kursten et al. 2004), which eliminates the uncertainty associated with penetration rates for various localized corrosion mechanisms, such as pitting corrosion, crevice corrosion, and stress-corrosion cracking. Based on conservative general corrosion rates, an overpack wall thickness of 7.5 cm was initially selected in Sevougian et al. (2012) to ensure a 300-year recovery period for the reference case (Vaughn et al. 2013). In the present update to the salt reference case the retrievability period of 50 years at 10 CFR 60.111(b) is considered a more appropriate design standard. Thus, if corrosion is the only design consideration, the 5.0 cm overpack suggested by Hardin et al. (2012, Sec. 4.2) is adequate for this update.[2] Furthermore, at this stage of GDSA Model testing, assumptions about package corrosion or penetration rates are not critical to the analyses, so the exact overpack thickness mentioned here is subject to change.

Waste package outer dimensions will be based on Table 1.4-1 of Hardin et al. (2012), which are 1.29 m in diameter and 5 m in length for the reference 12-PWR waste package.

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[2] Structural calculations have yet to be conducted to support a choice of either 5.0 or 7.5 cm for the waste package wall thickness. As described in Sevougian et al. (2012), a thicker-walled waste package design was selected by the DOE Salt Repository Project during preliminary site selection work that targeted the bedded salt formations in Deaf Smith County, Texas (Westinghouse Electric Corporation 1986). Based on estimated corrosion rates at that time, 2.3 cm of waste package thickness was calculated to be degraded during 1000 years of general corrosion after emplacement (a retrievability period of 1000 years was assumed based on 10 CFR 60.113). Using this corrosion estimate and estimates of structural strength for A216 carbon steel, waste packages containing 12-PWR intact SNF assemblies were designed with a wall thickness of 12.8 cm, assuming a host rock lithostatic pressure of 18 MPa at the repository horizon (ONWI 1987, Sec. 4.4.4.2 and Appendices C and D). (As a comparison, the lithostatic pressure at the WIPP repository horizon is about 15 MPa.) This type of structural design constraint for waste package thickness would only be necessary if closure and reconsolidation (approaching lithostatic pressure) of some portion of the initial emplacement drifts were expected during the assumed 50-year retrieval period.

### 2.2.4 Backfill

The bedded salt disposal reference case assumes that waste packages will be emplaced on the drift floor and covered with crushed salt backfill after waste packages are emplaced. The backfill will begin consolidating as drifts and entries close due to creep of the host salt formation. Past field experience (DOE 2012b) supplemented by simulations shows that backfill reconsolidates rather quickly. For example, simulations using the multi-mechanism model for creep deformation of the intact host rock (Munson et al. 1989) and a model for creep behavior of crushed salt (Callahan 1999) indicate that the reconsolidation of backfill will be mostly complete in approximately 200 years (Clayton et al. 2012). Permeability of the consolidated backfill is expected to evolve to a condition of similar to the original intact host rock (Hansen and Leigh 2011, Sec. 2.4.1.7). A number of literature sources are available for the porosity and permeability of crushed salt backfill, as compiled in Jove-Colon et al. (2012, Part VI, Sec. 1.5.1); however, this is still an active area of research (Hansen et al. 2012), so any values used for this update to the reference case are subject to change.

In order to assign values to the consolidated backfill, it is assumed for the reference case that the backfill will likely evolve similarly to a crushed-salt shaft seal (although decay heat could enhance its consolidation—or at least its rate of consolidation). With this assumption, porosity and permeability values can be drawn from the WIPP parameter database (Fox 2008) for the 2009 Compliance Recertification Application (DOE 2009). This database lists two distributions for the porosity and permeability of the shaft seal component in the Salado host rock ("the lower portion of the simplified shaft seal"), one distribution for the first 200 years after emplacement (given below in Table 3) and one for 200 to 10,000 years after emplacement (given below in Table 4).[3] The permeability is higher during the initial period, prior to consolidation. For the purposes of the reference case, the values for the initial 200-year period will be used because the shaft seal consolidation is enhanced at WIPP with the addition of 1 wt. % water (Hansen et al. 2012, Sec. 4.1.1) that might not be used in run-of-mine backfill. The porosity is 0.113 (Fox 2008, Table 19), while the $\log_{10}$ of the intrinsic permeability ($m^2$) is taken to be the cumulative distribution shown in Table 3. Its mean value is −18 (Fox 2008, Table 4), which is the value to be used initially in the reference case.

Table 3. Cumulative distribution of the log of intrinsic permeability for the lower portion of the simplified shaft seal from 0 to 200 years (Fox 2008, Table 4 and Parameter Sheet 69).

| **Value** | –20.0 | –19.5 | –19.0 | –18.5 | –18.0 | –17.5 | –17.0 | –16.5 |
|---|---|---|---|---|---|---|---|---|
| **Percentiles** | 0 | 0.01 | 0.10 | 0.31 | 0.64 | 0.87 | 0.99 | 1 |

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[3] It should be noted that the WIPP shaft seal system is a multicomponent system and that values of permeability and porosity in Fox (2008) have been averaged over these components (James and Stein 2002). Since the permeability average is taken to be a harmonic mean, it will be most strongly influenced by the lowest permeability component, i.e., the consolidated crushed salt component. Porosity on the other hand is taken to be a volume-weighted arithmetic mean. The value of $10^{-18}$ $m^2$ assumed here also falls within the range of permeability for the crushed salt component alone in the 1996 WIPP CCA, which was $10^{-23}$ $m^2$ to $10^{-16}$ $m^2$, with a 50th percentile value of about $10^{-19}$ (DOE 1996, Appendix SEAL A, Fig. A-8).

Table 4. Cumulative distribution of the log of intrinsic permeability for the lower portion of the WIPP simplified shaft seal from 200 to 10,000 years (Fox 2008, Table 4 and Parameter Sheet 70).

| **Value** | –22.5 | –22.0 | –21.5 | –21.0 | –20.5 | –20.0 | –19.5 | –19.0 | –18.5 | –18.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Percentiles** | 0 | 0.02 | 0.08 | 0.17 | 0.31 | 0.53 | 0.70 | 0.87 | 0.97 | 1 |

### 2.2.5 Seals

Plugs, seals, and other closures (collectively referred to here as seals) will be used to isolate emplacement panels and to limit water or radionuclide migration along the shafts. The reference shaft seal is based on the WIPP design, which has received regulatory acceptance as part of the repository system for disposal of negligible heat generating TRU waste (Hansen and Knowles 2000). The WIPP shaft seal system is a multi-component barrier (James and Stein 2002, Fig. 1; DOE 2009, Sec. PA-4.2.7), consisting of clay, asphalt, concrete, and crushed salt components. As stated in DOE (2009, Sec. PA-2.1.3): "Concrete, clay, and asphalt components of the shaft seal system will provide an immediate and effective barrier to fluid flow through the shafts, isolating the repository until salt creep has consolidated the compacted crushed salt components and permanently sealed the shafts." The crushed salt component is expected to consolidate to a state close to that of the surrounding intact rock within approximately 200 years (DOE 2009, Sec. PA-2.1.3; Fox 2008, Table 4). For the reference shaft seal (see Figure 6) the permeability and porosity values are based on those values for the lower portion (the portion in the Salado formation above the repository horizon) of the WIPP "simplified" shaft seal system after 200 years (Fox 2008, Table 4 and Parameter Sheet 70), with a porosity of 0.113 (Fox 2008, Table 19) and a permeability distribution given above in Table 4. Its mean value is –19.8 (Fox 2008, Table 4), which is the value to be used initially in the reference case.

## 2.3 Geologic Disposal System: Natural Barrier System

The bedded-salt disposal reference case includes high-level specifications of various aspects of the natural barrier system (NBS). The NBS consists of the host rock (bedded salt, the disturbed rock zone (DRZ), and interbeds/seams), as well as other geologic units above or beneath the host rock (repository) horizon that might influence repository performance, and establishes the boundary conditions for performance of engineered barriers. For this update to the reference case many of the NBS parameter specifications have been changed from those presented in Vaughn et al. (2013) and the major features/components of the NBS are organized differently to be consistent with the new FEPs matrix approach reported in Freeze et al. (2013c, Table 2-2). Parameters will be further updated as necessary for testing the GDSA Model, and reported in future deliverables, as appropriate.

### 2.3.1 Characteristics and Geologic Setting

The geologic setting and "characteristic" FEPs (Freeze et al. 2013c) describe the properties of the NBS features that need to be evaluated or specified to perform FEPs screening and design PA models. This includes information about the regional geology and local stratigraphy, including the location of repository within the surrounding geology and the locations of aquifer(s) above or below the repository, as well as the locations of pressurized brine pockets in nearby formations that could interfere with repository performance as a result of human intrusion (DOE 2009).

#### 2.3.1.1 Geologic Setting

This includes the general location of the repository (e.g., Basin and Range Province; Appalachian Region, etc.), which will define hydrogeologic boundary conditions for the NBS, such as regional groundwater characteristics and flow, regional climatic conditions, and regional disruptive event probabilities (e.g., related to seismicity and volcanism). For the salt disposal reference case, the regional geology may remain undefined in some characteristics, such as event probabilities (with the assumption that these will be screened during a site-selection process), but specified in other characteristics, such as general climatic properties (but only to the level of defining a representative biosphere aquifer—see Section 2.4). The reference case considers disposal in bedded salt only.

The reference-case geologic setting draws on information and characteristics representative of the five major bedded salt formations in the United States: Paradox Basin, Permian Salt Basin, Michigan and Appalachian Basins, Williston Basin, and Supai Basin (Sevougian et al. 2012). This information is used to help specify the reference stratigraphy for generic disposal in bedded salt, including depth to the top of the host rock, thickness of the host rock salt deposit, salt areal extent, and regional stratigraphic dip (Sevougian et al. 2012, Table 3-1).

#### 2.3.1.2 Local Stratigraphy

The reference stratigraphy includes formation thicknesses, the position of the repository relative to the features of a vertical stratigraphic cross-section, and the lateral distance to the biosphere. Characteristics such as salt formation thickness, aquifer location(s) relative to repository, thickness of aquifer(s), and the location and properties of other release paths, such as the location and thicknesses of interbeds and the presence of brine pockets, should be included.

Stratigraphic dip is a common feature of bedded salt formations and will influence the flow of brine and gas in and around the repository, particularly when two-phase flow is considered. A dip of 1.0 degrees, consistent with that at WIPP (DOE 2009, App. Mass, Table Mass-5), is assumed for the salt repository reference case.

One of the reference case regulatory assumptions (Section 2.5) is that the distance to the accessible environment will be 5 km from the edges of the underground excavations. A 5-km standoff distance does not pose any significant limitations for geologic disposal in the five major U.S. basins because of their large lateral extent. Both the salt and interbed formations of the reference case will be assumed to be uniform over the lateral extent of the repository and the entire underground area encompassed by the 5-km boundary.

#### 2.3.1.3 Brine Chemistry

The composition of brine in the natural system is important because it establishes the initial chemical conditions from which the chemical environment in the repository evolves. Brine composition is site-specific and varies significantly across the different representative bedded salt formations. The reference brine composition is that of Michigan Basin Devonian Brine because it generally lies within the ranges of the other formation brines obtained from the Permian and Paradox Basins, as well as German Quinare Brine (Sevougian et al. 2012, Table 3-2). Table 5 summarizes important reference brine characteristics.

Table 5. Reference Brine Characteristics, from Wilson and Long (1993).

| Characteristic | Reference Values |
|---|---|
| $Na^+$ | 12400-103000[1] |
| $Mg^{2+}$ | 3540-14600[1] |
| $K^+$ | 440-19300[1] |
| $Ca^{2+}$ | 7390-107000[1] |
| $SO_4^{2-}$ | 0-1130[1] |
| $Cl^-$ | 120000-251000[1] |
| pH | 3.5-6.2 |
| SG | 1.136-1.295 |

[1] Concentration (mg/l)

#### 2.3.1.4 Site-Specific Geologic Features

There are a number of other features that may found in some bedded salt deposits (e.g. folds, anticlines, discontinuities such as faults and fractures, breccias chimneys). These features can potentially create pathways between the repository, interbeds, and aquifers. However, they are site-specific and for generic modeling the reference stratigraphy is assumed to be devoid of them. This is a reasonable approach because repository siting will generally avoid locations with significant folds, anticlines, and discontinuities in close proximity to a repository.

### 2.3.2 Host Rock (Repository Horizon)

#### 2.3.2.1 Bedded Salt (Halite)

The undisturbed host rock is the halite portion of the salt formation that contains the repository but lies outside of the DRZ (see Figure 3). The depths to the top of salt and salt formation thicknesses are based on the five major US bedded salt deposits (Sevougian et al. 2012, Table 3-1). The representative value for the depth to the top of the bedded salt is taken to be 450 m (~1476 feet)—see Figure 6, with a range of 1000 feet[4] to 3500 feet (305 m – 1067 m) for future sensitivity calculations. There are enough regions with significant salt deposits located at these depths such that this range does not significantly limit siting options regionally or nationally (although it does rule out the Supai Basin).

The "thickness of salt" is somewhat subjective because it depends on the purity level of the halite and the tolerance for the presence of interbeds and the thickness of these interbeds. The reference case will assume that the repository horizon is located in relatively pure halite 28 meters thick (= drift height + 2 × DRZ thickness—see next two sections), with only very thin interbeds and seams of impurities less than 0.25 meters thick. Outside of this "repository zone," the salt formation will be assumed to be at least 250 feet (76 m) thick with halite content of at least 50 percent. With the exception of the Supai Basin, there are numerous locations throughout the

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[4] Note that 10 CFR 60.122 lists as a "favorable condition" the siting of a repository at a minimum depth of 300 m from the ground surface.

Paradox, Permian, Michigan, Appalachian, and Williston Basins that have salt of this thickness and content (Sevougian et al. 2012).[5]

The $\log_{10}$ of permeability ($m^2$) of intact halite for the reference case is taken to be a uniform distribution over the range of −24 to −21 (so the mean log value is equal to −22.5) and the porosity is taken to be a cumulative distribution with minimum or zeroth percentile at 0.001, the 50th percentile at 0.01 and the maximum or 100th percentile at 0.0519, which implies a mean value of 0.0182 (Fox 2008, Table 4 and Parameter Sheet 52).

#### *2.3.2.2 Disturbed Rock Zone*

The disturbed rock zone (DRZ) is the interface between the EBS and the undisturbed host rock, and is defined as the portion of the host rock adjacent to the EBS that experiences durable (but not necessarily permanent) changes due to the presence of the repository. Immediately adjacent to the EBS, these repository-induced changes are more likely to be permanent (e.g., mechanical alteration due to excavation), whereas further from the EBS the repository-induced changes are more likely to be time-dependent but not permanent (e.g., thermal effects due to radioactive decay of waste). The porosity of the DRZ is assumed to be 0.013 (Fox 2008, Table 33) and the $\log_{10}$ of the permeability ($m^2$) is assumed to be uniform over a range of −19.4 to −12.5 (Fox 2008, Table 4 and Parameter Sheet 64), which gives a mean value of −15.95. The extent of the DRZ is taken to be 3 drift diameters or about 12 meters and surrounds all sides of the excavation (Sevougian et al. 2012, Section 3.2.3.2).

#### *2.3.2.3 Interbed Thickness and Location*

Interbeds consisting of non-halite stringers (such as anhydrite, clay, or polyhalite) between 0.1 and 20 feet (0.03 to 6.1 m) are commonly observed throughout the major U.S. bedded salt deposits. These interbeds and sedimentary facies are more permeable than the surrounding halite and may become fractured as a result of repository excavation, thereby serving as potential pathways for water seepage and/or radionuclide migration.

For the reference case, an interbed will be located above and below the DRZ and immediately adjacent to the assumed dimensions of the DRZ—see Figure 6. As mentioned above, assuming that the maximum extent of the DRZ is about 3 drift diameters, the closest edge of the assumed interbeds will be taken to be 12 meters vertically from the repository floor and ceiling. The interbeds will be 1 m thick. The $\log_{10}$ of the permeability ($m^2$) of the anhydrite interbeds for the reference case is taken to be −18.9 and the porosity 0.011 (Fox 2008, Tables 30, 31, and 32).

### 2.3.3 Other Geologic Units

Other geologic units are the portions of the NBS outside the DRZ that are not host rock. Their extent, proximity to the repository, and hydrologic and transport properties influence natural barrier capability. Depending on their proximity to the repository or principal release pathways,

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[5] For the GDSA model demonstration problem—see Section 2.6—the salt formation is taken to be at least 244 m thick, i.e., the distance from the far edge of the DRZ beneath the repository to the bottom of the aquifer above the repository—see Figure 6. Also, the original reference case (Sevougian et al. 2012) assumed that the repository horizon need only be 12 m thick, which is probably sufficient for actual siting. The 28 m assumption is used for testing.

their thermal or mechanical properties may also influence barrier capability. Other geologic units in the bedded salt reference case consist of anhydrite interbeds (described above), an aquifer, and underlying formations that may contain over-pressured fluids.

#### 2.3.3.1 Aquifer

The location and characteristics of an aquifer are important considerations because an aquifer provides a potential pathway to the boundary of the controlled area and thus to the biosphere. The generic bedded salt reference case includes an aquifer above the repository, as is the case in the Permian and Williston Basins. The water will be assumed to be potable. The aquifer is taken to be 230 m (~750 feet) above the centerline of the repository—see Figure 6, with a range of 500 feet to 1,500 feet (~152 m – 457 m) for future sensitivity calculations. The effective thickness (water-producing interval) of the aquifer will be taken as 15 m (~50 feet), with a range of 10 feet to 75 feet (~3 m – 23 m) for future sensitivity calculations. The aquifer is assumed to be a saturated, single-porosity sedimentary formation in the regional groundwater basin containing the repository. It is assumed to have a uniform thickness, a constant porosity, and a constant regional Darcy velocity in the portion of the aquifer that might communicate with both the repository horizon and the biosphere location. As a generic approximation, the aquifer is assumed to have the properties of clean sand, with a porosity of 0.4 and a permeability ranging from $2\times10^{-13}$ $m^2$ to $10^{-9}$ $m^2$ or, equivalently, hydraulic conductivity ranging from $2\times10^{-6}$ m/s to $10^{-2}$ m/s (Freeze and Cherry 1979, Table 2.2).

#### 2.3.3.2 Areas of Overpressure

Pressurized brine pockets (i.e., in excess of depth-based hydrostatic pressure) are common in some of the larger bedded salt deposits because of the sealing properties of salt under large lithostatic loads. Because these regions, if they exist, are located well outside of the repository horizon, they are not expected to influence undisturbed performance. They will be considered when the reference case is expanded to included consideration of disturbed scenarios, where such a region could be hydrologically connected to the repository via a human intrusion borehole.

## 2.4 Biosphere

The reference biosphere for the bedded salt disposal reference case is based on the approach utilized by the International Atomic Energy Agency's (IAEA) BIOMASS (BIOsphere Modeling and ASSessment) Example Reference Biosphere 1 (ERB1) dose model (IAEA 2003) to convert radionuclide concentrations in an aquifer into estimates of annual dose to a receptor via drinking water from a hypothetical water well in the aquifer.

In the reference case, vertical shafts provide a potential pathway for radionuclide releases between the repository and the overlying aquifer in an undisturbed scenario. The time dependent individual effective dose rate for each radionuclide is determined from the radionuclide concentration in the drinking well, the water consumption rate of an individual, and the ingestion dose coefficient. A consumption rate of 1.2 $m^3$/yr is used, which is the 95th percentile for young adults and approximately twice the mean adult consumption rate recommended by ICRP (1975) (IAEA 2003, p. 274-275). The dose coefficients for the reference case are based on Table C5 of IAEA (2003). Selected values are shown below in Table 6.

Table 6. Selected Dose Coefficients from Table C5 of IAEA (2003).

| **Radioisotope** | **Dose Coefficient (Sv/Bq)** |
|---|---|
| I-129 | 1.10e-7 |
| Sr-90 | 3.07e-8 |
| Cs-137 | 1.30e-8 |
| Am-241 | 2.0e-7 |
| Np-237 | 1.11e-7 |
| U-233 | 5.10e-8 |
| Th-229 | 6.13e-7 |

## 2.5 Regulatory Environment

The site-specific Environmental Protection Agency and U.S. Nuclear Regulatory Commission regulations for Yucca Mountain, 40 CFR 197 and 10 CFR 63, are not applicable to a generic HLW/SNF bedded salt repository, but existing EPA and U.S. NRC regulations for disposal of high-level radioactive wastes in geologic repositories remain in effect, i.e., 40 CFR 191 and 10 CFR 60. With these guidelines, the following assumptions are appropriate for the reference case:

1. Disposal system models will be based on a screening of FEPs for 10,000 years after repository closure, with the provision that the long-term impacts of seismicity, volcanism, and climate change must be considered for 1,000,000 years (40 CFR 197.20 and 197.35 at 73 FR 61287-61288; 10 CFR 63.311 and 63.342 at 74 FR 10829-10830).
2. SNF and HLW are assumed to be retrievable for a period of 50 years after waste emplacement operations are initiated (10 CFR 60.111(b)).
3. The distance to the accessible environment[6] is assumed to be 5 km (40 CFR 191.12).
4. The safety assessments will be judged on the basis of annual dose, consistent with the approach used in 40 CFR 197.20 and in various international standards (Bailey et al. 2011, Sec. 6.2). The key point here is to use annual dose as a metric for the safety assessments, although the exact numerical limits in the existing regulations will not be the focus of preliminary safety assessments.

## 2.6 Application of the Salt Reference Case in the GDSA Model

This section updates two figures from Section 2.3 of Freeze et al. (2013a), based on the repository dimensions in Table 2 and the descriptions in Section 2.3—also see Figure 5 for the repository layout.

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[6] Here the accessible environment is taken to mean the atmosphere, the land surface, surface water, oceans, and the portion of the lithosphere that is outside the postclosure controlled area, which is an area surrounding the geologic repository where incompatible activities would be restricted following permanent closure.

The model domain for the GDSA demonstration problem, shown in Figure 6, includes an EBS – consisting of waste, disposal tunnels/drifts (shown in red), and a shaft, and a NBS – consisting of a DRZ, host rock halite, anhydrite interbeds (one above the EBS and one below the EBS), and an overlying aquifer. The biosphere (accessible environment) is assumed to be located at the ground surface. The receptor is assumed to be located at the ground surface, at a distance of 5,000 m laterally from the disposal area.

The reference salt repository is assumed to contain approximately 70,000 metric tons heavy metal (MTHM), distributed throughout 84 pairs of disposal tunnels/drifts, where each of the 168 tunnels is 805 m long (includes closure length—see Table 2) and contains 80 waste packages of PWR UNF (Table 2). Figure 7 shows the waste package configuration within a single tunnel.

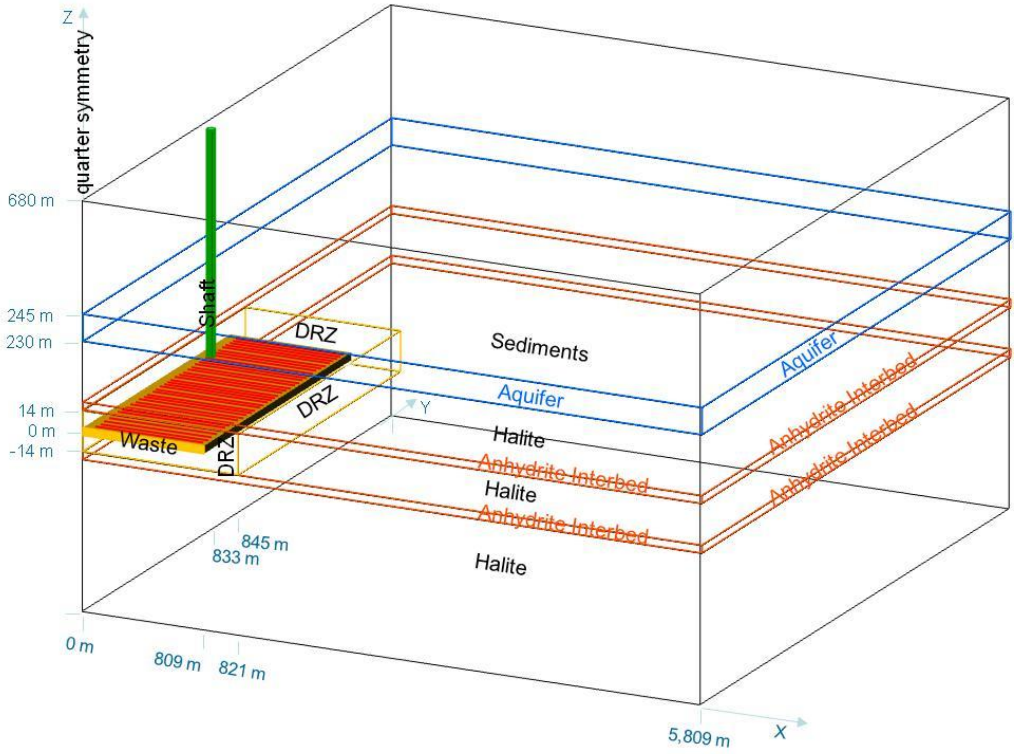

Figure 6. Salt Repository Demonstration Problem Model Domain.

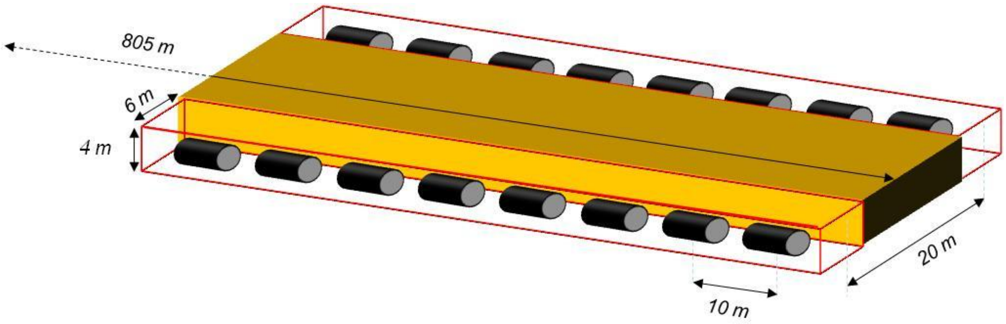

Figure 7. Salt Repository Demonstration Problem Tunnel Configuration.

The model domain in Figure 6 takes advantage of one-quarter horizontal symmetry; it shows 42 disposal tunnels (one-quarter of the total). However, for the demonstration problem model, only the outer 100 m of a single drift was simulated. The properties of the reference case result in two primary radionuclide transport pathways to the biosphere:

- Diffusion out the DRZ and subsequent advection through the interbeds
- Diffusion up the shaft and subsequent advection through the aquifer

Transport in the host rock halite is by diffusion. Transport includes the effects of sorption and decay and ingrowth. $^{129}I$ is the dominant radionuclide because it has unlimited solubility and is non-sorbing.

# 3. SUMMARY AND CONCLUSIONS

The bedded salt repository reference case was initially described in detail by Sevougian et al. (2012) and later expanded upon in Vaughn et al. (2013) with the specification of additional parameter values, especially for features of the natural barrier system (NBS). Since that time, it has been further refined, as described here, to support its primary purpose as the first reference case for testing the Generic Disposal System Analysis (GDSA) Model framework, which will be reported on in further detail in a Level 2 milestone, due in November 2013: *Generic Disposal System Modeling Report* (M2FT-13SN0808043). A preliminary description of the role of the Salt R&D Reference case within the context of the GDSA Model was presented in a recent Level 4 Milestone (Freeze et al. 2013a). The primary updates to the reference case reported here are (1) the specification or modification of some parameter values and (2) refinements to the concept of operations (thermal management).

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