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Abstract

Preliminary evaluation of deep borehole disposal of high-level radioactive waste and spent nuclear fuel indicates the potential for excellent long-term safety performance at costs competitive with mined repositories. Significant fluid flow through basement rock is prevented, in part, by low permeabilities, poorly connected transport pathways, and overburden self-sealing. Deep fluids also resist vertical movement because they are density stratified. Thermal hydrologic calculations estimate the thermal pulse from emplaced waste to be small (less than 20 ^{o}C at 10 meters from the borehole, for less than a few hundred years), and to result in maximum total vertical fluid movement of ~100 m. Reducing conditions will sharply limit solubilities of most dose-critical radionuclides at depth, and high ionic strengths of deep fluids will prevent colloidal transport.

For the bounding analysis of this report, waste is envisioned to be emplaced as fuel assemblies stacked inside drill casing that are lowered, and emplaced using off-the-shelf oilfield and geothermal drilling techniques, into the lower 1-2 km portion of a vertical borehole ~ 45 cm in diameter and 3-5 km deep, followed by borehole sealing.

Deep borehole disposal of radioactive waste in the United States would require modifications to the Nuclear Waste Policy Act and to applicable regulatory standards for long-term performance set by the US Environmental Protection Agency (40 CFR part 191) and US Nuclear Regulatory Commission (10 CFR part 60). The performance analysis described here is based on the assumption that long-term standards for deep borehole disposal would be identical in the key regards to those prescribed for existing repositories (40 CFR part 197 and 10 CFR part 63).

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NOMENCLATURE

BTC	Buttress threaded casing
BWR	Boiling water reactor
CSNF	Commercial spent nuclear fuel
DB	Deep boreholes
DB-PA	Deep borehole performance assessment
DSNF	Defense spent nuclear fuel
EIS	Environmental impact statement
EPA	Environmental Protection Agency
FEP	Features, events, and processes
HLW	High-level waste
HLWG	High-level waste glass
ID	Inner diameter
MTHM	Metric tons of heavy metal
NEPA	National Environmental Policy Act (1970)
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act (1984, 1987)
ppf	pounds per foot
OD	Outer diameter
PA	Performance assessment
PWR	Pressurized water reactor
RMEI	Reasonably maximally exposed individual
SKB	Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co.)
SNF	Spent nuclear fuel
TRU	Transuranic (waste)

1. INTRODUCTION

The purpose of this report is to document an evaluation and analysis of several factors (technical, regulatory, safety and performance) concerning the potential for a deep borehole disposal program, particularly with regard to the US, but also relevant to any agency or institution considering the potential for a borehole disposal program.

In 1957 the US National Academy of Sciences Committee on Waste Disposal considered both deep borehole disposal of radioactive waste (in liquid form) and mined storage of radioactive waste in a positive light (National Academy of Sciences 1957). The intervening half-century has seen high-level waste (HLW) and spent nuclear fuel (SNF) disposal efforts in the US and other nations focus primarily on mined repositories, yet over the same time, the potential technical and cost advantages of deep borehole disposal have become more apparent. Radioactive waste emplaced in solid form (spent fuel or glass) at the bottom of deep (3-5 km) boreholes in crystalline basement rocks – typically granites (see schematic in Figure 1) - with off-the-shelf oilfield technology would be more effectively isolated from the biosphere than waste emplaced in shallower, mined repositories. The physical transport of radionuclides away from HLW and SNF at multi-kilometer depths would be limited by: low water content, low porosity and low permeability of crystalline basement rock, high overburden pressures that contribute to the sealing of transport pathways; and the presence of convectively stable saline fluids. Deep borehole disposal of radioactive waste has the added advantage of not producing as large a "thermal footprint" as a mined geologic repository, because boreholes placed more than ~200 m apart are unlikely to thermally affect one another.

DOE estimates that 109,300 metric tons heavy metal (MTHM) of high-level waste and spent nuclear fuel – primarily commercial spent nuclear fuel (CSNF), but also DOE spent nuclear fuel (DSNF), and high-level waste glass (HLWG) – will need to be disposed of in the US (the projected US HLW and SNF inventory is summarized in Appendix A).

Deep borehole disposal, characterization and excavation costs should scale linearly with waste inventory: small inventories require fewer boreholes; large inventories require more boreholes. Not needing a specially engineered waste package would also lower overall borehole disposal costs. Both aspects might make borehole disposal attractive for smaller national nuclear power efforts (having an inventory of 10,000 MTHM or less). In the US, the 70,000 MTHM of waste currently proposed for Yucca Mountain could be accommodated in about 600 deep boreholes (assuming each deep borehole had a 2 km long waste disposal zone that contained approximately 400 vertically stacked fuel assemblies). The remainder of the projected inventory of 109,300 MTHM could be fit into an additional 350 or so boreholes.

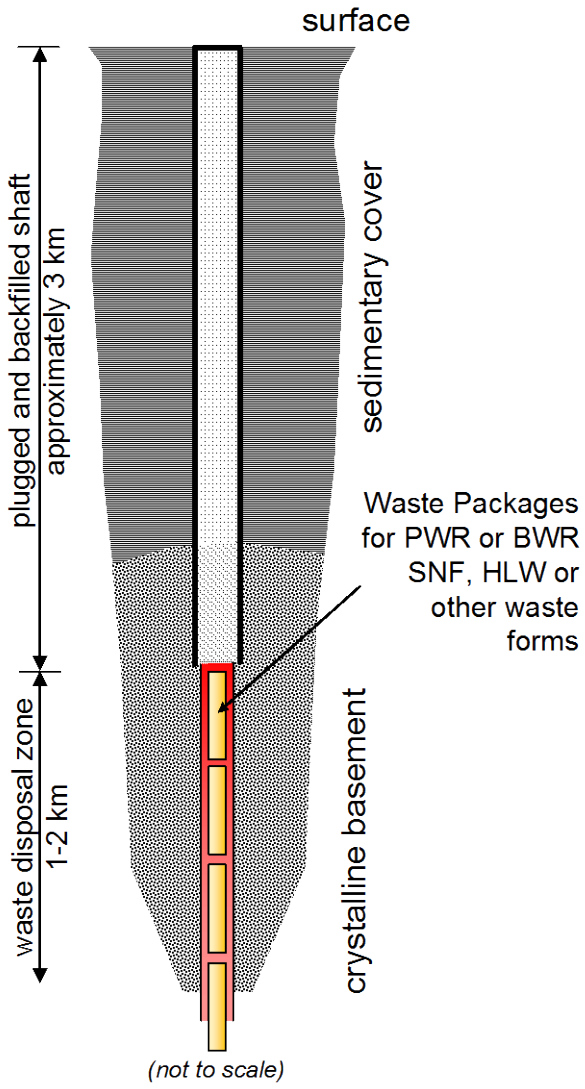


Figure 1. Deep Borehole Disposal Schematic.

Because crystalline basement rocks are relatively common at 2-5 km depth (See Figure 2; also see O'Brien et al. 1979; Heiken et al. 1996), the US waste disposal burden might be shared by shipping waste to regional borehole disposal facilities. If located near existing waste inventories and production, shipping would be minimized. A disposal length of ~2km, and holes spaced 0.2km apart suggests the total projected US inventory could be disposed in several borehole fields totaling ~30 square kilometers.

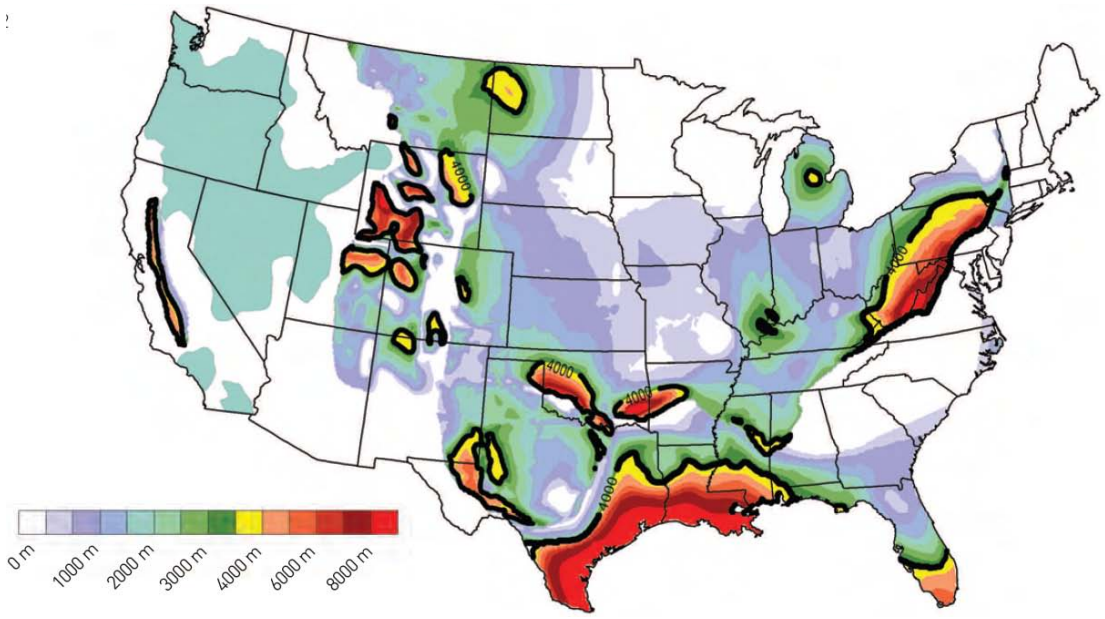


Figure 2. Sediment Thickness Map of the US (MIT, 2006).

Petroleum drilling costs have decreased to the point where boreholes are now routinely drilled to multi-kilometer depths. Research boreholes in Russia and Germany have been drilled to 8-12 km. The drilling costs for 950 deep boreholes to dispose of the entire 109,300 MTHM inventory, assuming a cost of $20 million per borehole (see Section 3.1), would be ~ $19 billion. Very rough estimates of other costs are $10 billion for associated site characterization, performance assessment analysis, and license application, $20 billion for disposal operations, monitoring, and decommissioning, $12 billion for ancillary program activities, and $10 billion for transportation, resulting in a total life-cycle cost for a hypothetical deep borehole disposal program of $71 billion (in 2007 dollars). Although there are significant uncertainties in the cost estimates for deep borehole disposal presented here, the estimated total life-cycle cost may be significantly lower than the estimated total cost of Yucca Mountain. Note in particular the lower construction/operation and transportation outlays that borehole disposal would allow.

This document outlines a technical and performance assessment analysis of deep borehole disposal of US HLW and SNF. Section 2 examines how federal regulations might be applied to deep borehole disposal. Section 3 outlines the technical basis for deep borehole disposal and the engineering obstacles that must be overcome. Sections 4 and 5 consider potential release

scenarios and present a preliminary performance assessment of the deep borehole disposal safety case. Section 6 concludes with a summary and recommendations of future work.

2. ASSUMPTIONS ABOUT A REGULATORY FRAMEWORK

The current regulatory and legal framework for radioactive waste management is centered on mined geologic repositories, and was not intended to be applied to the long-term performance of deep borehole disposal systems. The Nuclear Waste Policy Act (NWPA) restricts consideration of geologic repositories in the United States to a single site, Yucca Mountain in Nevada, and EPA and NRC regulations (40 CFR part 197 and 10 CFR part 63, respectively) have been written specific for that site. Implementation of a deep borehole disposal system would, therefore, at a minimum, require amendment of the Nuclear Waste Policy Act. In principle, existing regulations from the 1980s that predate the selection of Yucca Mountain (i.e., 40 CFR part 191 and 10 CFR part 60) could be applied to borehole disposal systems without modification. However, these early regulations are inconsistent with recommendations provided to the EPA in 1995 by the National Research Council of the National Academies of Science and Engineering at the request of Congress, which called for system-level performance metrics based on annual risk, and may therefore be viewed as inadequate.

In order to evaluate the system performance of a deep borehole disposal concept, it it necessary to adopt or develop a regulatory standard by which the performance can be measured. For the purposes of this preliminary analysis, the NWPA is assumed to be amended to allow consideration of sites other than Yucca Mountain and alternative disposal concepts, and new regulations are assumed to be promulgated that are similar in key regards to the current Yucca Mountain regulations, consistent with the EPA's interpretation of the National Academies' recommendations as promulgated in 40 CFR part 197. Thus, the primary overall performance measure of interest is mean annual dose to a hypothetical individual, with limits set at 0.15 mSv/yr for 10,000 years following disposal and for 1 mSv/yr for the period between 10,000 years and 1 million years. Other details of the regulatory framework, including screening criteria for potentially relevant features, events, and processes, as described in Section 4, are also assumed to be unchanged from those stated in 40 CFR part 197 and 10 CFR part 63, with the exception of human intrusion scenarios, for which new regulatory requirements would need to be developed. Four assumptions warrant further explanation.

First, for simplicity in modeling, all characteristics of the hypothetically exposed individual are assumed to be identical to those of the "reasonably maximally exposed individual" defined in 40 CFR part 197: these characteristics are appropriate for humans living in arid regions similar to Yucca Mountain, but may need to be reconsidered for disposal sites in other regions. The assumption should in no way be interpreted as indicating a preference in this analysis for one geographic region over another: the assumption was made solely to allow the use of existing information regarding biosphere pathway analyses. As shown later in this report (see Section 5), this assumption has little or no impact on overall estimates of performance.

Second, the exposed individual is assumed for the purposes of this analysis to live directly above the waste, rather than 18 kilometers away from the repository, as specified in 40 CFR part 197. This assumption focuses the analysis on the isolation provided by the deep geologic setting, and avoids speculation about site-specific aspects of geology closer to the land surface.

Third, requirements in both the NWPA and the EPA and NRC regulations specific to the retrievability of waste are assumed to be modified to reflect the more permanent disposal nature of a deep borehole disposal system. Although retrievability would be maintained during emplacement operations, waste may not be fully recoverable once the borehole has been sealed, and deep borehole systems may not be the best choice if permanent and irreversible disposal is not intended. Consistent with this observation, it should be noted that although the analysis presented in this report treats the direct disposal of SNF as a bounding performance case, deep borehole disposal systems may be particularly appropriate for other waste forms, including reprocessing wastes.

Fourth, this analysis considers only a single disposal borehole. Actual disposal systems would likely contain an array of multiple boreholes, and it may be appropriate therefore to scale performance estimates upward for larger numbers of boreholes. Individual boreholes in a disposal array are assumed to be placed sufficiently far apart, however, that interactions among the holes will be insignificant and it would be conservative to assume that any single individual human could be exposed to the sum of the releases from all boreholes in a repository.

A feature of deep borehole disposal concepts is the potential for multiple implementations where several disposal fields (borehole arrays) could be developed, each serving a given region, and each expected to encounter similar conditions at depth. The hydrogeologic and hydrochemical conditions common to deep granitic basement rock are thought to be advantageous to borehole disposal system performance. As shown in Figure 2, many regions within the US have granitic rocks at an appropriate depth and therefore many viable sites for borehole disposal are conceivable. In this regard, future regulatory frameworks developed for deep borehole disposal may best be served by establishing generic criteria (analogous to 10 CFR 60) rather than attempt to create multiple site-specific standards.

Lastly, although the analysis presented here is for SNF as a bounding performance case, it should be recognized that borehole disposal systems may be particularly appropriate for other waste forms (e.g., spent sealed sources), and, thus, new regulations could reflect the generic factors which favor borehole disposal system performance, as well as acknowledge particular waste form characteristics (e.g., low heat production, low radionuclide concentration, etc).

3. TECHNICAL BASIS AND CHARACTERIZATION

Deep emplacement of HLW and SNF in crystalline basement rocks underlying sedimentary strata is expected to provide effective long-term (> 1 million years) isolation of radionuclides from the biosphere due to the following thermal, hydrologic, chemical, and mechanical characteristics of the borehole and the surrounding rock at depths of several kilometers:

- **Long transport pathways** - Potential transport pathways to the biosphere are long and would therefore involve extensive radioactive decay, dilution, formation of radionuclide-bearing phases, and retardation, given the impediments to vertical migration of radionuclides from several kilometers depth.
- **Slow fluid movement** - Fluid movement at > 4 km depth is inhibited by low porosities (< 1%), very low permeabilities (10^{-16} to 10^{-20} m^2), and the presence of convectively-stable, high ionic strength brines (≥ 150 g/L) (See Table 1) in the rock. The permeabilities of deep crystalline rock are roughly 10 orders of magnitude less than those of gravel aquifers. The porosities of deep crystalline rock are 10 to 40 times less. Deep crystalline rocks typically have low water content. Minimal hydrologic flow is thought to occur, primarily through discontinuous fractures. Fluid movement up boreholes will likewise be limited by low permeabilities in the filled borehole and/or disturbed rock annulus which are expected to range from 10^{-13} m^2 for fractured rock to 10^{-16} m^2 for packed sediments, to 10^{-18} m^2 for clay or bentonite (Freeze and Cherry, 1979; Table 2.2).
- **Insufficient upward ambient driving pressure** – Basement rocks do not typically contain pressurized aquifers or other flow features that would produce significant upward flow gradients under ambient conditions. Therefore, the most significant driving force for fluid flow and radionuclide migration away from a deep borehole is likely to be minor thermal pressurization from decay heat.
- **Chemical conditions limit radionuclide release and transport** – Reducing conditions are likely to prevail at depth which will maintain fuel and most radionuclides at very low solubilities. High ionic strength brines will limit the formation and movement of radionuclide-bearing colloids. Finally, sorption of many radionuclides onto the crystalline rock and/or borehole fill material will retard transport.
- **Mechanical stability** – Crystalline rocks such as granites are particularly attractive for borehole emplacement because of their large size, relatively homogeneous nature, low permeability and porosity, and high mechanical strength (to resist borehole deformation). In addition, high overburden pressures contribute to sealing of some of the fractures that provide transport pathways.

Table 1. Typical Deep Borehole Characteristics (Juhlin and Sandstedt 1989).

Borehole	Maximum depth of water circulation (m)	Minimum depth to high salinity water (m)	Permeability below 1000 m (m^2)
USA-10	900	1800	10^{-18}
FRG-2	500	3500	Not Reported
SWT-1	1050	1326	$10^{-16} – 10^{-20}$
URS-1	800	1200	10^{-19}
SWE-1	1200	>6000	10^{-16} -10^{-17}

To support the performance assessment analysis of Section 5, an underlying technical basis must be selected for, at a minimum, the physical design, the predicted thermal effects, and the near-field chemical characteristics. Section 3.1 lays out a deep borehole design. Section 3.2 describes the thermal effects from decay heat on the hydrologic behavior of the borehole. Section 3.3 outlines the chemical characteristics of the borehole and the surrounding rock.

3.1. Deep Borehole Design

As noted in Section 1, the projected US waste inventory of 109,300 MTHM would require several hundred deep boreholes for disposal, assuming no reprocessing or other mechnical consolidation of SNF. The analysis in this section focuses on the design, drilling, and performance of a single borehole.

3.1.1. Waste Canisters

Emplacing intact spent fuel assemblages, without pre-consolidation, is one of the simplest approaches to borehole disposal (Hoag 2006), and is the one considered here. CSNF assemblages come in two types: those used in pressurized water reactors (PWRs) and those used in boiling water reactors (BWRs). Nearly all (98%) of US BWR assemblies are 4476 mm long and 139 mm wide, or smaller. Most (80%) of PWR assemblies are 214 mm wide and 4059 mm long (See Table 2), or smaller (DIANE Publishing Company 1995).

Table 2. Reference PWR and BWR Fuel Assembly Dimensions and Masses.

	Height (mm)	Width (mm)	Mass (kg)
PWR	4059	214	666
BWR	4476	139	297
	(feet/inches)	**(inches)**	
PWR	13’ 3”	8.4	
BWR	14’ 7”	5.5	

Source: Dimensions are from Table 28 of (DIANE Publishing Company 1995). Masses are from Section 7.2.2 of (Juhlin and Sandstedt 1989).

The transverse (i.e., diagonal width) dimension of a PWR assembly is 11.9" (302 mm); that of a BWR assembly is 7.8" (198 mm). A canister made of standard oilfield casing 5 m tall and having an inner diameter of 12-1/2" (318 mm) and an outside diameter of 13-3/8" (340 mm) could therefore hold one PWR assembly (Hoag 2006) or, with considerable extra space, one BWR assembly. End-caps would be welded on after assemblies had been inserted into the canisters. The disposal canister must be strong enough to prevent releases and exposure through the waste emplacement phase, including recovery operations for canisters that are stuck or damaged during emplacement. To maintain early physical stability, the inner void spaces would be filled with powdered bentonite. The canister is expected to possess no other intrinsically waste-isolating characteristics.

3.1.2. Boreholes

It is anticipated that boreholes will be on the order of 5 km (~16,400 ft) deep. A 1-2 km long waste disposal zone (the lower portion of the borehole) might conceivably hold 200-400 canisters. The canisters could be emplaced one at a time or as part of a canister string – a grouping of 10 or 20 canisters.

The in situ stress of the basement rock at depth will be assessed to determine deep borehole compatibility with the stress condition. The large boreholes will need to remain stable during the construction phase until the casing is cemented in, the waste canisters are emplaced, and the boreholes are plugged/backfilled. Also, horizontal stresses in the borehole region will increase after waste emplacement due to thermal expansion of the rock caused by heat from radioactive decay of the emplaced waste. These anticipated stresses will be evaluated as part of the borehole design.

The design concept for deep borehole disposal is such that a borehole will accommodate a 13-3/8" (340 mm) OD canister. The depths for each borehole section are approximate and are presented as examples of the design which may vary depending on the specific site geology. However, the disposal concept is keyed to deep placement of waste at depths of 3-5 km (~10,000-16,400 ft).

From the surface down the design is as follows (Figure 3):

1. 48" (1219 mm) Conductor hole with 40" (1016 mm) conductor pipe to 50 ft (~15 m) depth
2. 36" (914 mm) Surface Hole with 30" (762 mm) 310 ppf X-56 Line Pipe to 500 ft (~150 m)
3. 26" (660 mm) Intermediate Hole with 20" (508 mm) 169 ppf N-80 BTC Seamless to 5,000 ft (~1,500 m)
4. 17 ½" (445 mm) Bottom Hole with 16" (406 mm) casing to 17,000 ft (~5,200 m) (cemented from 5000 ft to total depth, upper 5000 ft removed after canister placement and sealing).

The cement in the waste disposal zone will be engineered to accommodate thermally induced stresses during the emplacement time and chemical requirements for appropriately longer time periods.

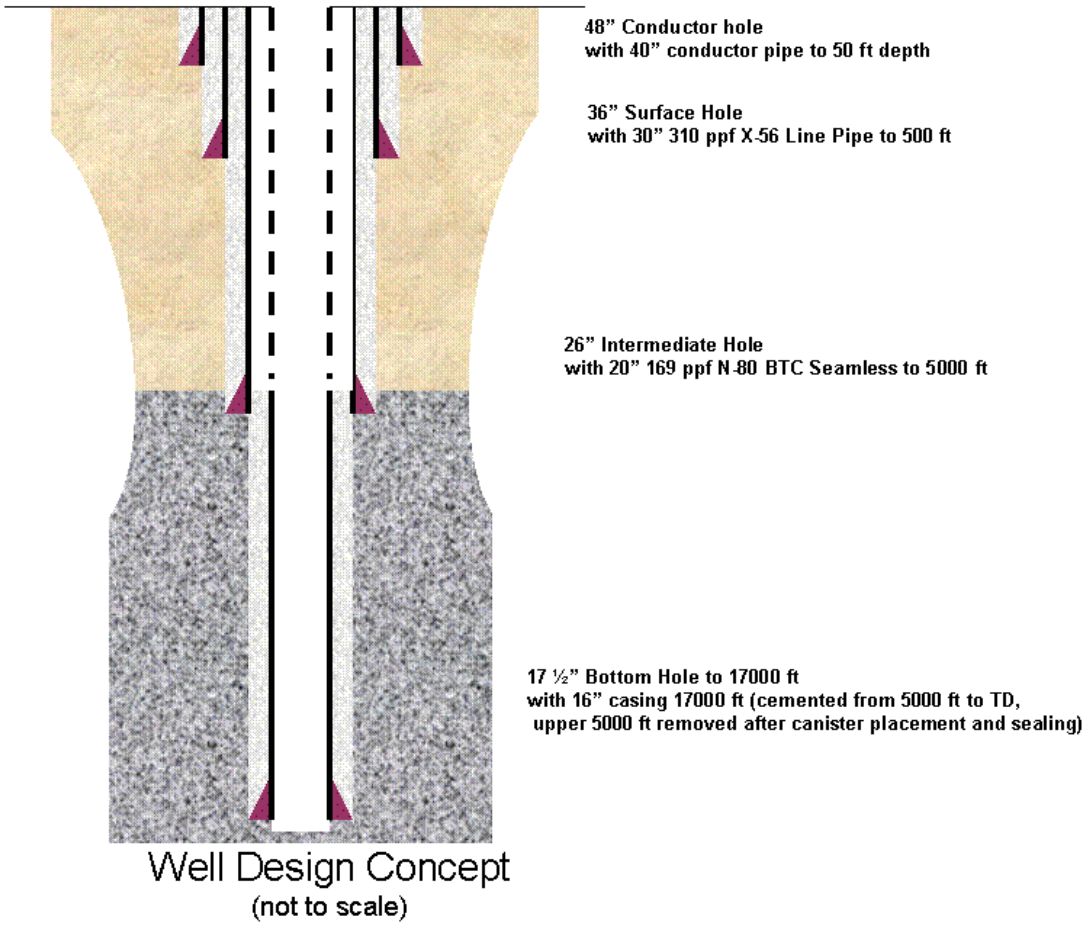


Figure 3. Deep Borehole Drilling Design Concept.

3.1.3. Seals

The borehole seal system is designed to limit entry of water and migration of contaminants through the borehole after it is decommissioned. The key features of the seal system design are that it exhibits excellent durability and performance and is constructible using existing technology. The design approach applies redundancy to functional elements and specifies multiple, common, low-permeability materials to reduce uncertainty in performance.

In the waste disposal zone itself, bentonite will be used as a buffer/seal material because of its low permeability, high sorption capacity, self-sealing characteristics, and durability. The canister strings will be surrounded by "deployment mud" comprised of bentonite-water slurry.

Canister strings will be separated by an approximately 1 m interval of compacted bentonite. Compacted bentonite will also be used at the top of the waste disposal zone, above the canister strings.

Mechanical barriers (bridge plug, packer, etc.) in the casing at the top of the waste disposal zone could be used to isolate the wellbore. However, the elastomeric materials typically used as part of their sealing element will degrade over time and there may be operational difficulties in running (or retrieving) the plugs. Therefore this option is not considered to be desirable or highly feasible.

The upper 1,500 m (5,000 ft) of the emplacement borehole casing will be removed after canister placement and sealing. A borehole seal system extending from the top of the waste disposal zone to the surface will be deployed to further isolate the emplaced wastes from the accessible environment. This borehole seal system will use a combination of bentonite, asphalt and concrete. The main seal will consist of compacted bentonite packs placed in a bentonite-water slurry (deployment mud). If the intermediate 20" casing is left in the borehole, this casing can be milled out at appropriate intervals to allow free movement of the sealing medium from the hole to the annulus and surrounding rock.

A top seal will consist of asphalt from 500 m to 250 m, with a concrete plug extending from 250 m to the surface. Seal materials are discussed below.

Compacted Clay

Compacted clays are commonly proposed as primary sealing materials for nuclear waste repositories and have been extensively investigated against rigorous performance requirements (e.g., Van Geet 2007). Advantages of clays for sealing purposes include: low permeability, demonstrated longevity in many types of natural environments, deformability, sorptive capacity, and demonstrated successful utilization in practice for a variety of sealing purposes. Compacted clay as a borehole sealing component functions as a barrier to water flow and radionuclide movement and possibly to gas flow.

The exact specification for compacted clays used in borehole sealing will depend upon site-specific details such as water chemistry, but an extensive experimental data base exists for the permeability of a variety of bentonite clays under a variety of conditions. Bentonite clay, a highly plastic swelling clay material (Mitchell 1993) is chosen here because of its positive sealing characteristics. Compacted bentonitic clay can generate swelling pressure and wetted swelling clay will seal fractures as it expands into available space and will ensure conformance between the clay seal component and the borehole walls.

Bentonitic clays have been widely used in field and laboratory experiments concerned with radioactive waste disposal. Verification of engineering properties such as density, moisture content, permeability, or strength of compacted clay seals can be determined by direct and indirect measurement during construction.

Asphalt

Asphalt is used to prevent water migration down the borehole. Asphalt is a strong cement, readily adhesive, highly waterproof, and durable. Furthermore, it is a plastic substance that is readily mixed with mineral aggregates. A range of viscosity is achievable for asphalt mixtures. It is highly resistant to most acids, salts, and alkalis. Asphalt has existed for tens of thousands of years as natural seeps. Longevity studies specific to DOE's Hanford site have utilized asphalt artifacts buried in ancient ceremonies to assess long-term stability (Wing and Gee 1994). Asphalt used as a seal component deep in the borehole will encounter a benign environment, devoid of ultraviolet light or an oxidizing atmosphere. For these reasons, it is believed that asphalt components will possess their design characteristics for an extended period of time. For example, studies conducted for WIPP indicate that the permeability of a massive asphalt column is expected to have an upper limit of 1×10^{-18} m^2 for an extensive period of time (DOE 1996).

Construction of the seal components containing asphalt can be accomplished using a slickline process where low-viscosity heated material is effectively pumped into the borehole. Sufficient construction practice and laboratory testing information is available to assure performance of the asphalt component. Laboratory validation tests to optimize viscosity may be desirable before final installation specifications are prepared.

Concrete

Concrete has low permeability and is widely used for hydraulic applications. The exact concrete composition will depend upon site-specific geology and water chemistry, but performance can be established through analogous industrial applications and in laboratory and field testing. For example, laboratory and field testing have shown that the Salado Mass Concrete used in the WIPP will remain structurally sound and possess very low permeability (between 2×10^{-21} and 1×10^{-17} m^2) for long periods (DOE 1996). Standard ASTM specifications exist for both green and hydrated concrete properties. Quality control and a history of successful use in both civil construction and mining applications will assure proper placement and performance.

3.1.4. Cost and Schedule

The deep disposal borehole design presented above is similar to the geothermal well design analyzed by Polsky et al. (2008) in well diameter, depth, and lithology. Therefore, the geothermal well construction cost and schedule analysis (combinations of labor, equipment, and materials) from Polsky et al. (2008) can be used to estimate costs and schedule for a deep disposal borehole. In 2008 dollars, a 5 km (~16,400 ft) deep well will cost about $20 million and take about 110 days to construct (Figure 4). Thus base costs for ~1000 boreholes (to accommodate the total projected US inventory) would be ~$20B, not including emplacement operations, licensing, etc. Assuming emplacement and sealing could be accomplished in ~100 additional days, and with 10 separate disposal fields of ~100 holes each (covering ~3 square kilometers or 1-2 square miles), then ~50 years would be needed to emplace the total projected US inventory.

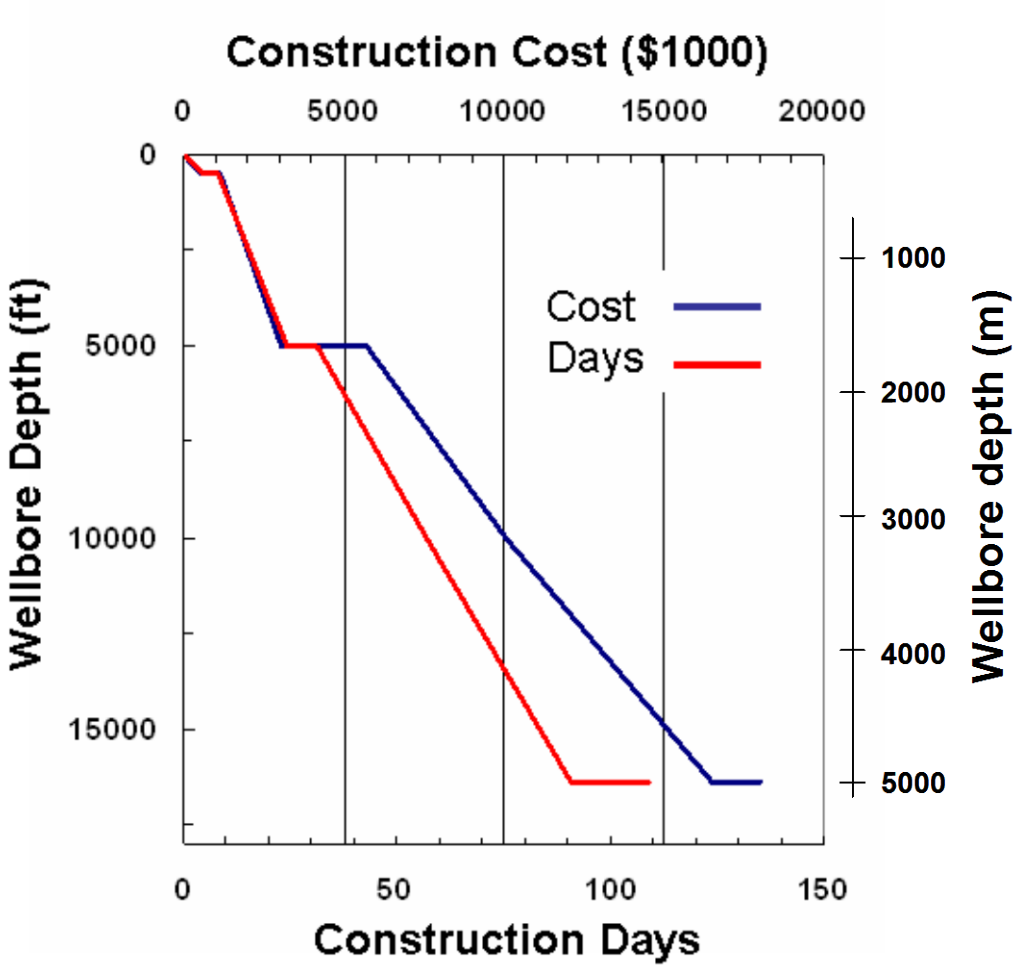


Figure 4. Deep Borehole Drilling Design Schedule and Cost.

3.2. Thermal Effects on Hydrologic Environment

Thermal conditions in deep boreholes have been considered in detail recent years by Gibb and co-workers (e.g., Gibb, McTaggart et al. 2008). The most significant driving force for fluid flow and radionuclide migration away from a deep borehole is likely to be due to thermal pressurization from decay heat. An analysis of these effects on the hydrologic behavior of the deep borehole is presented here.

3.2.1. Heat Conduction

Temperatures within the borehole and the host rock were simulated using a horizontal, two-dimensional model of thermal conduction implemented with the FEHM software code (Zyvoloski, Robinson et al. 1997). The model domain is 2,000 m square, centered on the

borehole, with an unstructured grid of progressively higher resolution near the waste canister. The thermal conduction model was constructed using the design basis concepts and dimensions from Hoag (2006), with a borehole diameter of about 50 cm and assuming a depth of 4 km.

Constant temperature boundary conditions of 110 ^{o}C are assigned at the lateral boundaries of the model, which are sufficiently distant from the borehole to minimize impacts on the temperature simulations near the borehole. The geothermal gradient is assumed to be 25 ^{o}C/km and the average near surface temperature is assumed to be 10 ^{o}C. The model uses the heat output curves for a single average pressurized water reactor (PWR) fuel assembly that has been aged for 25 years, as used for the Yucca Mountain performance assessment modeling (Sandia National Laboratories 2008). Representative values of thermal conductivity for granite (3.0 W/ m ^{o}K), thermal conductivity of bentonite grout (0.8 W/ m ^{o}K), bulk density of granite (2750 kg/m^{3}), specific heat of granite (790 J/kg ^{o}K), and porosity of granite (0.01) are used in the thermal conduction model.

Figure 5 shows the temperature histories for the waste package wall, borehole wall, and several distances from the centerline of the borehole simulated in the vicinity of a borehole containing stacked individual spent fuel assemblies. The model did not attempt to simulate the temperatures within the waste canister. Temperature increases in the vicinity of the borehole are not large, do not persist for long periods of time, and drop off rapidly with distance from the borehole. Temperatures at the borehole wall peak at about 30 ^{o}C higher than the ambient temperature of the host rock within ten years of waste emplacement. Temperature increases would be significantly higher for fuel assemblies that have not been aged as long or if the thermal conductivity of the granite were significantly lower than the assumed value (3.0 W/ m ^{o}K).

Simulated temperature increases near the waste emplacement borehole from the thermal conduction model are significantly lower than those calculated in a previous study by ONWI (Woodward-Clyde Consultants 1983), which showed simulated peak temperature increases at the borehole wall of 150 ^{o}C to 200 ^{o}C. However, the ONWI (Woodward-Clyde Consultants 1983) modeling considered reprocessed high-level waste (HLW) that had been aged only 10 years and which had a higher initial heat output of 2,600 W/canister compared to 580 W/canister of the older spent nuclear fuel considered here.

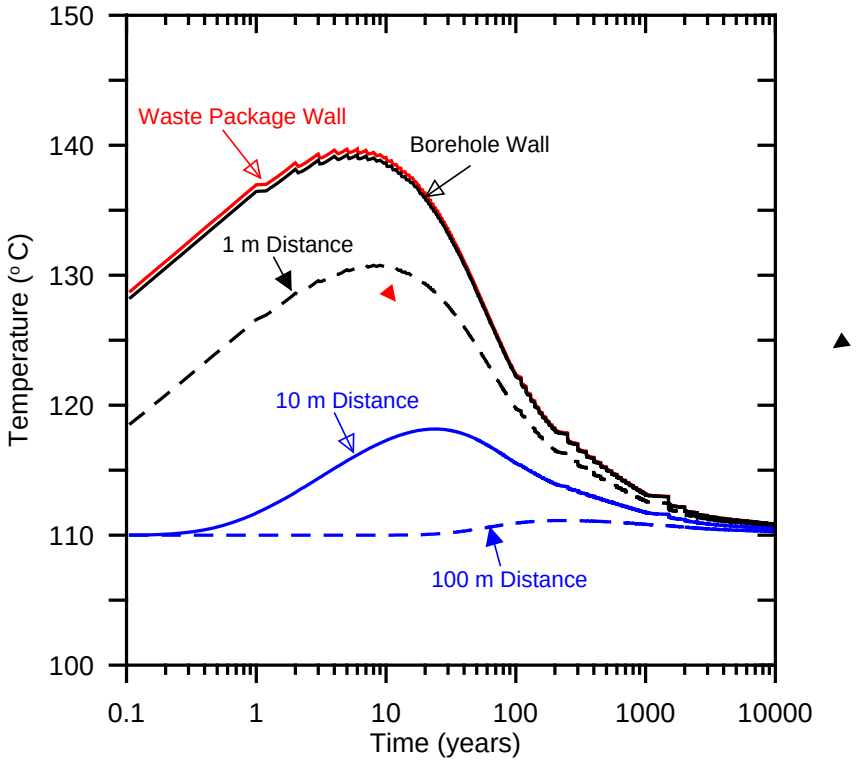


Figure 5. Temperature as a Function of Time and Distance from the Borehole for PWR Spent Fuel Assembly Disposal

A similar analysis of thermal conduction was performed for borehole disposal of vitrified HLW from the reprocessing of spent nuclear fuel. This model uses the same model domain and parameter values as those described above. The heat output curves are for the current vitrified waste produced by reprocessing of commercial spent nuclear fuel in France (Andra 2005). For this analysis it is assumed that the waste is aged for 10 years before disposal and that the vitrified waste fills the waste canister with an inside diameter of 318 mm.

The resulting temperature histories for varying distances from the centerline of the disposal borehole are shown in Figure 6. The simulated temperature increases are significantly higher for the disposal of HLW than those for disposal of spent fuel assemblies, with the temperature increasing by about 125 ^{o}C at the borehole wall at the time of peak temperature. Temperatures decline more rapidly for the disposal of HLW because the heat output from the reprocessing waste is dominated by the relatively short-lived fission products ^{90}Sr and ^{137}Cs. It should be noted that the thermal impacts of HLW disposal could easily be controlled by reducing the diameter of the waste canisters or by reducing the concentrations of fission products in the waste glass. Reducing the diameter of the waste canister by a factor of two would reduce the thermal output per meter of borehole and the peak increase in temperatures by about a factor of four.

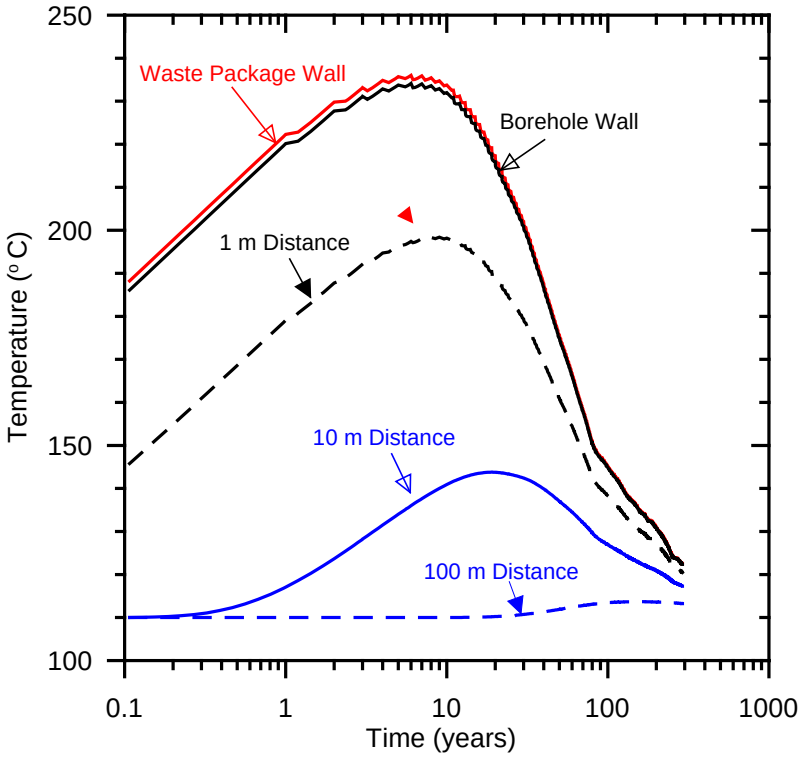


Figure 6. Temperature as a Function of Time and Distance from the Borehole for Disposal of Vitrified HLW from Reprocessing.

3.2.2. Thermally Driven Hydrologic Flow

The heat generated from the waste emplaced in the borehole will cause fluid temperatures and pressures to rise in the vicinity of the waste. The elevated pressure will drive fluid away from the heated zone. The path of least resistance will be up the sealed borehole and adjacent disturbed host rock, where permeabilities are likely to be higher than that of the undisturbed bedrock. To assess potential transport, vertical fluid flow rates were estimated using a vertical, radial, two-dimensional model of coupled heat and fluid flow implemented with the FEHM software code (Zyvoloski, Robinson et al. 1997).

The model domain is a cylinder with a radius of 100 m and height of 4,000 m (Figure 7). Constant temperature boundary conditions of 60 ^{o}C for the top (depth = 2 km) of the domain and 160 ^{o}C for the bottom (depth = 6 km). The sides were held at a constant temperature consistent with the assumed geothermal gradient.

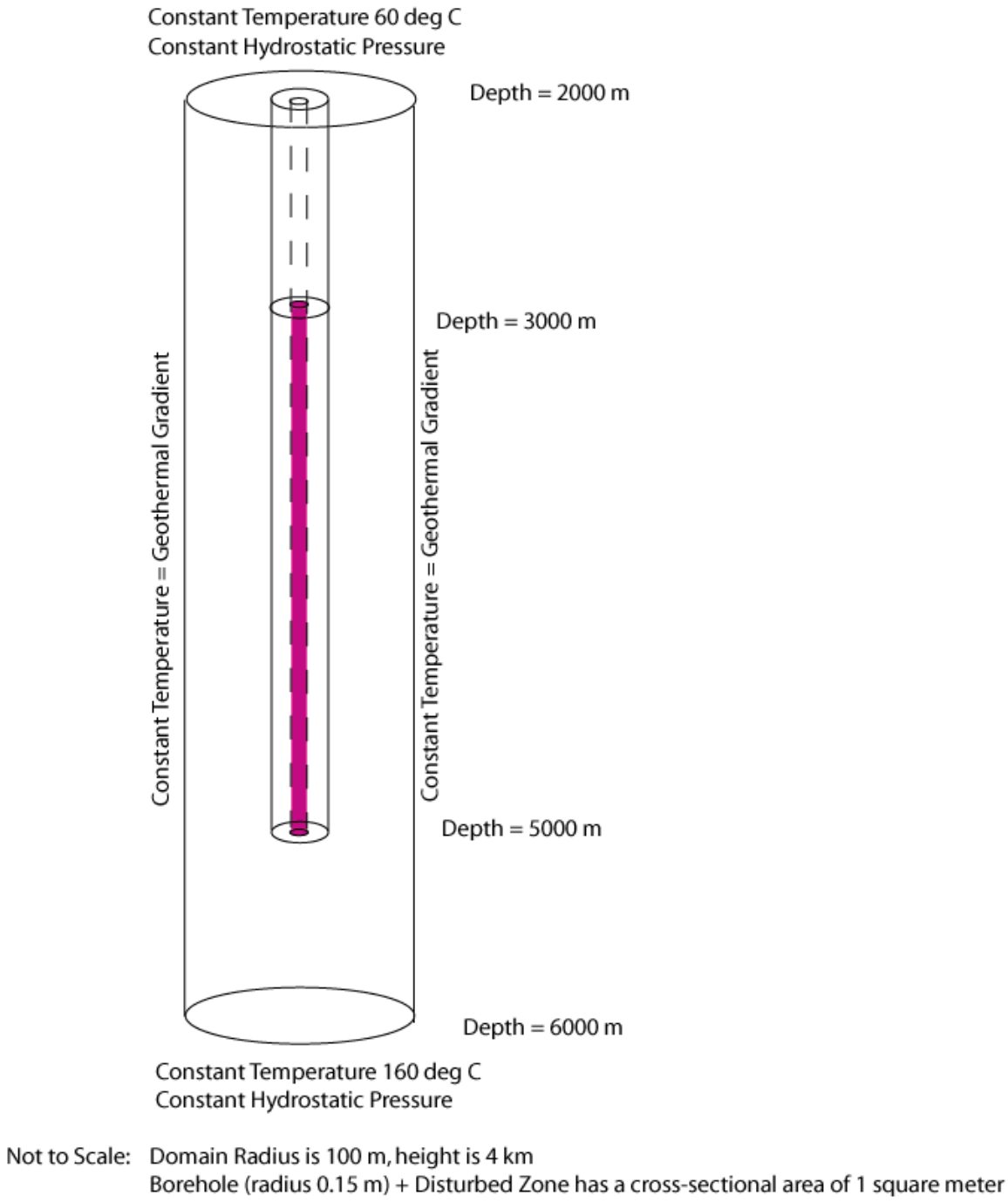


Figure 7. Model Domain for Coupled Heat and Fluid Flow Simulation to Estimate Vertical Fluid Velocities in the Heated Borehole. The waste disposal zone (the waste filled-borehole region that generates heat) is shown in pink.

The simulation was initiated with hydrostatic conditions in equilibrium with the geothermal gradient. Flow was allowed through the top and bottom boundaries by fixing the flowing pressure at the boundaries to the initial hydrostatic pressures. The domain is divided into four materials: undisturbed bedrock, disturbed bedrock, sealed borehole (above the waste disposal

zone) and waste-filled borehole (the 2,000-m waste disposal zone). The flow path for fluids to be transported toward the surface is conceptualized to be in the combined sealed borehole and disturbed zone surrounding the borehole. The cross sectional area of this combined zone is assumed to be 1 m^2. Properties assigned to these materials are listed in Table 3 and are consistent with the properties used in the thermal-conduction model described in the previous section. Properties assigned to bedrock are representative of typical granite. The sealed borehole (radius = 0.15 m in this calculation) is characterized as being sealed with bentonite. The waste filled borehole is assigned a high thermal conductivity, typical of steel, a low porosity, and a permeability equal to the disturbed bedrock. The waste filled borehole material (i.e., the waste disposal zone) is modeled as a time-dependent heat source, consistent with the source used in the thermal-conduction model for typical PWR fuel assemblies that have been aged 25 years and subsequently stacked one on top of another 2,000 m deep. Disposal of reprocessing HLW with a higher heat output could have a larger impact on thermally-driven flow than analyzed for PWR here.

Table 3. Material Properties for Borehole Flow Model.

Property	Bedrock	[a]Disturbed Bedrock	Sealed Borehole	Waste-Filled Borehole
Permeability [m^2]	10^{-19}	10^{-16}	10^{-16}	10^{-16}
Density [kg/m^3]	2,750	2,750	2,750	2,750
Specific heat [MJ/kg-^oK]	790	790	760	760
Thermal Conductivity [W/m-^oK]	3.0	3.0	0.8	46.0
Porosity	0.01	0.01	0.35	0.0001

[a]Assumes presence of grout/backfill.

The model was used to simulate flow conditions for 100,000 years, although no significant flow occurred after 10,000 years. Figure 8, shows the vertical fluid specific discharge as a function of time for two locations in the borehole: (1) a depth of 3,000 m corresponding to the top of the waste disposal zone, and (2) a depth of 2,000 m corresponding to the top of the model domain.

The results demonstrate that upward fluid velocities at the top of the waste disposal zone occur immediately upon the addition of heat to the system. Flow at the top of the model domain is delayed slightly and is of lower magnitude than at the top of the waste disposal zone. This result is expected since the vertical head gradient decreases with distance away from the heat source and, also, a fraction of the flow will be oriented horizontally into the bedrock, thus decreasing the vertical flow with distance up the borehole. Flow increases quickly and then gradually decreases as the radioactive heat source decays with time.

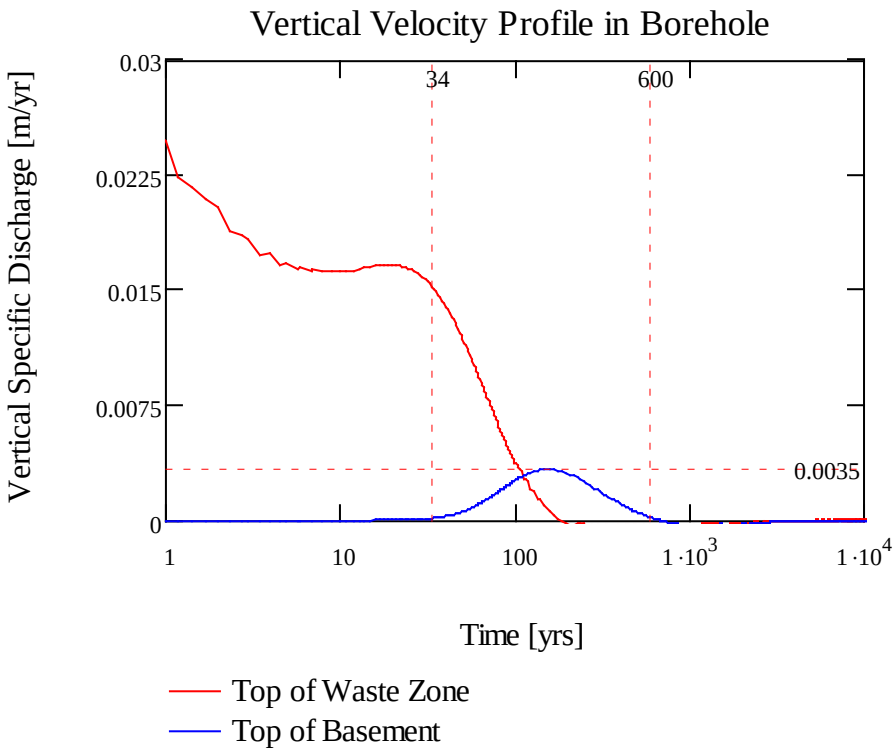


Figure 8. Vertical Specific Discharge at Two Locations as a Function of Time (Log Axis).

Hydrologic pore velocity is equal to specific discharge divided by porosity. Pore velocity is equivalent to the transport velocity for an unretarded radionuclide. Since the flow path above the waste zone is comprised of an inner sealed borehole of radius 0.15 m and a porosity of 0.35 and the outer ring-shaped disturbed zone of radius $1/\sqrt{\pi}$ = 0.564 m and a porosity of 0.01, the area weighted average porosity of the flow path is 0.034. Thus the maximum pore velocity at the top of the waste zone is 0.662 m/yr, but upward flow in this area only occurs for the first approximately 180 years. Maximum pore velocity at the top of the basement domain peaks at 0.103 m/yr at about 150 years. Upward flow will occur from approximately 34 to 600 years.

The model results shown in Figure 8 indicate that upward fluid flow in the heated borehole only persists for a relatively short period of time (<1,000 yrs) after emplacement. Fluid movement is primarily caused by the local elevated pressures due to thermal expansion of the pore water. As the heat generation decreases, the temperature of the waste decreases and the fluid begins to contract, lowering pressure. Buoyancy forces are not significant in this system because heat flow is primarily conductive rather than advective. The permeability of the sealed borehole would have to be significantly higher and there would have to be a source of water connected to the borehole by a high-permeability conduit in order for buoyancy-driven flow (i.e., a chimney effect) to be an important factor. Because the actual pore water density will likely increase with depth due to salinity stratification, this simulation probably represents an upper bound on the fluid flow rates.

Figure 9 displays the temperature histories as a function of horizontal distance away from the borehole at the depth in the middle of the waste disposal zone (at ~4 km depth). Note that the modeled temperatures are very similar to those calculated with the thermal model (see Figure 5). The main difference is the assumption that the temperatures at 100 m remain constant in the flow model. This assumption is not expected to significantly affect the flow rates up the borehole.

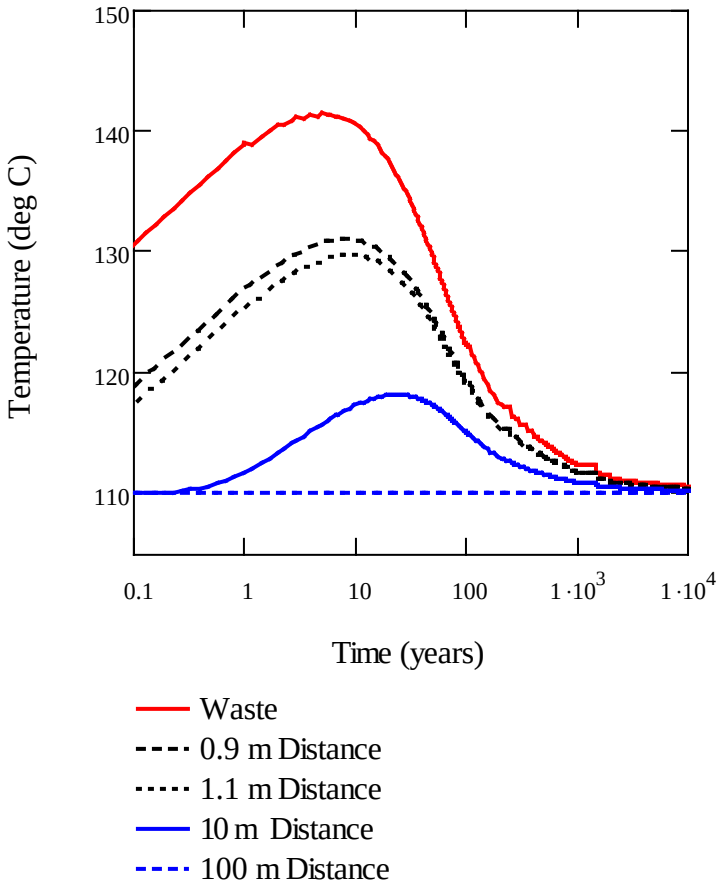
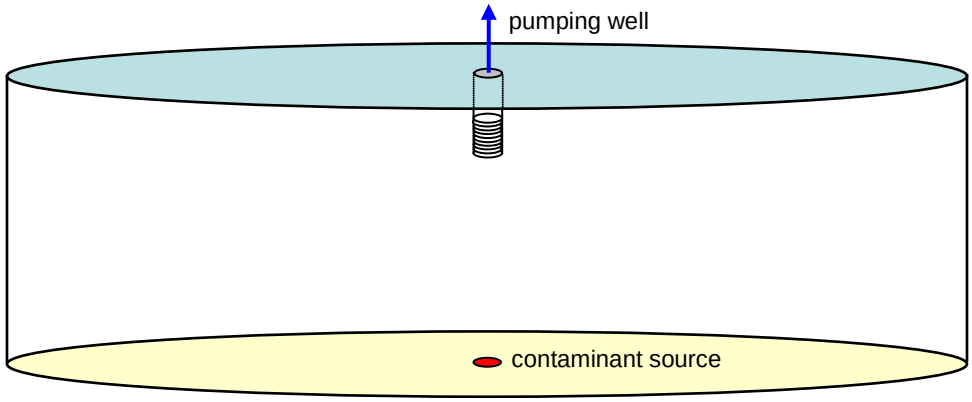


Figure 9. Temperature Histories for Locations at a Depth in the Middle of the Waste Zone at Several Horizontal Distances from the Center of the Waste–Filled Borehole.

3.2.3. Groundwater Pumping and Dilution Above the Borehole Disposal System

If there is significant migration of radionuclides from the deep borehole, the most likely and highest-impact mechanism by which radionuclides could be released to the biosphere from the disposal system is groundwater pumping. The analysis of thermally driven flow in Section 3.2.1 simulated the potential hydrologic movement to a location 1,000 m above the waste disposal zone. Release to the biosphere requires the transport of radionuclides an additional 2,000 m to the land surface in the borehole disposal system described in this study.

A simplified, but conservative, model of groundwater pumping and radionuclide transport is constructed to simulate the transport time between a release point 1,000 m above the waste and a hypothetical pumping well located near the disposal borehole. The model also simulates the amount of dilution associated with capturing radionuclide mass in the pumping well. The conceptual model is shown diagrammatically in Figure 10. The model domain is cylindrical with a radius of 10,000 m and a depth of 2,000 m. Specified-pressure boundary conditions corresponding to hydrostatic conditions are applied on the sides and bottom of the model domain, with a no-flow boundary condition at the upper surface. A continuous contaminant source with approximately 1 m^2 area is specified on the bottom boundary directly beneath the pumping well. A specified volumetric flow rate of 0.0035 m^3/year at the contaminant source corresponds to the maximum flow rate in the borehole simulated by the thermal-hydrologic model (Figure 8). The pumping well has a screened interval between 100 m and 200 m depth from which a specified volumetric flow rate is withdrawn.



Not to Scale: Model domain has a radius of 10 km and depth of 2 km.
Contaminant source has a cross-sectional area of approximately 1 m^2.

Figure 10. Model Domain for Groundwater Pumping and Radionuclide Transport.

The numerical model is implemented with the FEHM software code using a two-dimensional radial representation in which the grid resolution is finer near the axis of the well and the vertical grid spacing is 5 m. The horizontal permeability is 10^{-13} m^2 and the vertical permeability is 10^{-14} m^2 for a horizontal/vertical anisotropy ratio of 10. The permeability of the disposal borehole plus disturbed zone between the contaminant source and the pumping well is a factor of 10 higher than the surrounding rock. The porosity is assumed to be 0.01, which is appropriate for fractured bedrock, but is very low for most clastic sedimentary rocks. The aquifer compressibility is assigned a representative value of 10^{-4} MPa^{-1}. Two pumping cases are simulated for differing capacity wells, one as a water supply for 25 people and one supplying water to 1000 people. Pumping rates are calculated using the average domestic water consumption in the U.S. of 86.5 gal/day/person (Van der Leeden et al. 1990).

The groundwater pumping and radionuclide transport model is generic in nature and consequently is constructed with simplifying assumptions barring site-specific information. There are several aspects of this simplified groundwater pumping model that tend to underestimate the transport time between the contaminant source and the pumping well, and underestimate the amount of dilution of radionuclide concentrations:

- No recharge is applied to the upper boundary of the model. In areas where there is substantial precipitation much of the groundwater captured by the pumping well would come from local recharge.
- No ambient horizontal shallow groundwater flow is included in the model. The capture zone for a pumping well located in a regional horizontal groundwater flow field extends to a finite depth. The radionuclide source at 2,000 m depth would be below the capture zone of the pumping well for even moderate horizontal flow.
- The permeability of the system does not decrease with depth in the model. Average permeability typically decreases by orders of magnitude over the depth range of 2,000 m in fractured bedrock, significantly reducing the fraction of deep fluids that would be captured in the pumping well.
- The vertical anisotropy in permeability is a factor of 10 in the model. The vertical anisotropy in groundwater flow systems is often much greater than 10, particularly in sedimentary strata with shale aquitards. Higher values of vertical anisotropy significantly reduce the fraction of deep fluids that would be captured in the pumping well.
- The value of porosity used in the model is representative of fractured bedrock. The value of porosity would be much higher for most porous sedimentary rocks. The low value of porosity used in the model would tend to underestimate the transport time between the contaminant source and the pumping well.
- The volumetric inflow rate of contaminated fluid at the base of the model is held constant at the maximum rate simulated by the coupled heat and hydrologic flow model in Section 3.2.2. The contaminant inflow into the upper 2 km of the system would stop before 1,000 years based on the results shown in Figure 8.
- Simulations are conducted only for a non-sorbing, non-decaying species. The transport time between the contaminant source and the pumping well would be much greater for sorbing radionuclides.

Thus, the results noted here are considered conservative and perhaps bounding. The simulated radionuclide breakthrough curves at the pumping well for the two pumping cases are shown in Figure 11. The contamination arrives at the higher capacity pumping well for 1,000 people in significant quantities after several thousand years and at the pumping well for 25 people after more than 200,000 years of continuous pumping. The model results in Figure 11 show that although the contaminants arrive at the higher capacity well sooner, the maximum relative concentration is much lower than for the lower pumping rate because of the greater dilution in the larger volume of well water. The maximum relative concentrations in the pumping wells indicate dilution factors of 3.16×10^7 and 8.19×10^5 for the higher capacity pumping case and the lower capacity pumping case, respectively. Overall, the pumping well model indicates

significant delays in the transport of radionuclides to the pumping well and large dilution factors relative to the radionuclide concentrations in the disposal borehole driven upward by thermal expansion of fluids near the disposal zone. In addition, the pumping well model significantly underestimates radionuclide transport times and the amount of dilution in radionuclide concentrations, as described above.

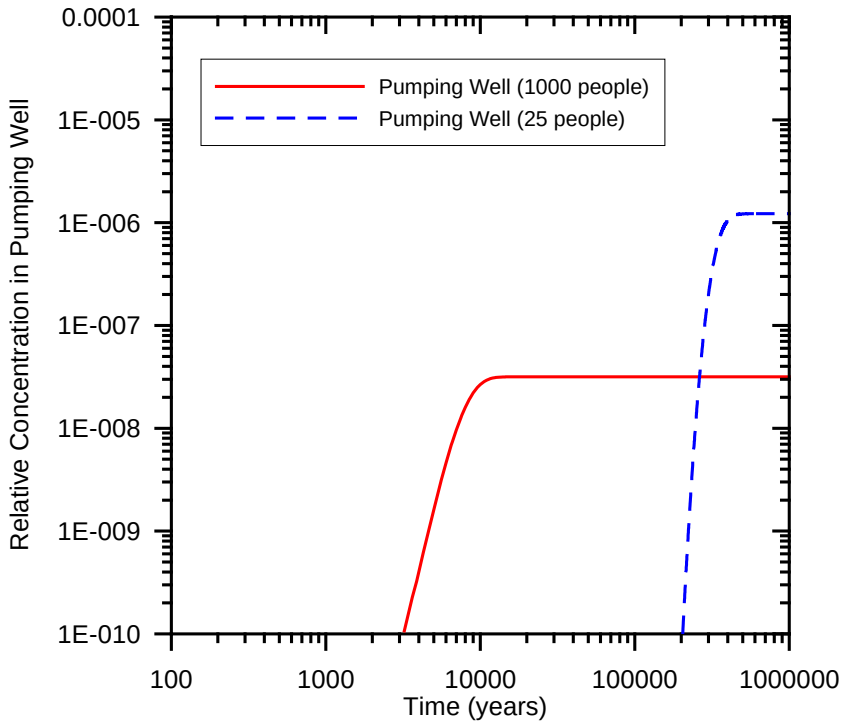


Figure 11. Simulated Breakthrough Curves for Two Groundwater Pumping Scenarios (Unit concentration at source).

In summary, even in the unlikely event of a water supply well located directly above the disposal borehole, significant delays in time and large amounts of dilution would occur during the capture of contaminants from the deep disposal system. Both of these factors would greatly reduce the potential radiological dose to hypothetical human receptors using that water supply.

3.3. Chemical Environment

The geochemical behavior (solubility, sorption, colloidal behavior, etc.) of the projected waste inventory in the deep borehole environment sets limits on the stability of the uranium spent fuel matrix and on radionuclide transport to the biosphere. Radionuclide solubilities and sorption coefficients are therefore important input parameters for performance assessment calculations (Section 5). The US inventory of high-level radioactive waste and spent nuclear fuel used for the purposes of this analysis is 109,300 metric tons (DOE Office of Public Affairs, August 5, 2008) which includes the 70,000 MTHM considered for disposal at Yucca Mountain in addition to

waste to be generated in the future. The inventory and the important isotopes are discussed in greater detail in Appendix A.

Fluids recovered from deep boreholes tend to be rich in sodium, calcium, and chloride. Lesser amounts of sulfate and carbonate are likely to be present. For the purposes of estimating radionuclide solubilities, a reasonable salinity is ~ 2-3 M/L, pHs are 8-9 and the system E_H is ~ -300 mV (Anderson 2004). As discussed in Section 3.2, geothermal gradients are such that the temperatures at the bottom of the deep boreholes are expected to be above 100 ^oC. Oxygen tends to be scavenged, and the low redox state anchored, by the presence of reduced Fe and Mn in the basement rocks.

Additional geochemically appealing features of deep boreholes are that the elevated temperatures of deep boreholes should stabilize the less soluble crystalline forms of radioelement oxide minerals, while high temperatures and high salinities will both favor the less soluble anhydrous forms of the oxide phases. Note though that the relatively high temperatures and salinities of deep fluids should accelerate the corrosion of steel pipes, fuel assemblies, and the waste itself. The scarcity of oxygen might slow the oxidation of spent fuel.

3.3.1. Radionuclide Solubilities

Given the conditions outlined above, bounding estimates can be made of the dissolved levels of radionuclides likely to be present once basement fluids come into contact with spent fuel assemblages. Table 4 identifies likely solubility-limiting phases and provides estimates of dissolved radioelement concentrations at depth. Because of the uncertainty associated with estimating thermodynamic constants and the activity coefficients of aqueous species in high temperature, high ionic strength brines, the numbers in Table 4 are probably only accurate to within an order of magnitude.

The relatively low solubility of UO_2 under deep borehole conditions will favor stabilization of spent fuel rods. When contacted by water, fuel rods will have diminished thermodynamic drive to dissolve, thus slowing the matrix release of actinides and fission products. Yet even if fuel rods were to instantly dissolve to the thermodynamically stable actinide oxides, the solubilities of isotopes of Am, Ac, Cm, Np, Pa, Pu, Tc, and Th are lower than that of uranium – sometimes several orders of magnitude lower – suggesting that aqueous releases of these radionuclides will be small. Some species (e.g., ^{99}Tc) have solubility limits that are below drinking water limits.

It is less clear whether iodine, radium, and strontium will form solubility-limiting solids. If deep fluids contain appreciable sulfate, $SrSO_4$ and $RaSO_4$ might form to limit dissolved Sr and Ra levels. Dissolved carbonate might also lead to the formation of $SrCO_3$. Radioiodine is a fission product that should become reduced to iodide given sufficient electron donors in the borehole domain. Unless iodide forms insoluble metal iodides, radioidide levels in solution adjacent to the fuel will probably be set by the available inventory. Pending closer examination of sulfate, carbonate, and heavy metal contents of borehole fluids, no limiting concentrations are set for I, Sr, and Ra.

Table 4. Radionuclide Solubilities in Deep Boreholes at T = 200°C, pH 8.5, E_H = -300 mV, 2M NaCl solution.

Radioelement	Solubility-limiting phase	[a]Dissolved concentration (moles/L)	Notes
Am	Am_2O_3	1×10^{-9}	$AmOH(CO_3)$ would control Am solubilities if carbonate present.
Ac	Ac_2O_3	1×10^{-9}	Am solubility is used as proxy for chemically similar Ac.
C	*	*	No solubility limiting phase
Cm	Cm_2O_3	1×10^{-9}	Am solubility is used as proxy for chemically similar Cm.
Cs	*	*	No solubility limiting phase
I	Metal iodides ?	*	See discussion
Np	NpO_2	1.1×10^{-18}	
Pa	PaO_2	1.1×10^{-18}	Np solubility is used as proxy for chemically similar Pa.
Pu	PuO_2	9.1×10^{-12}	
Ra	$RaSO_4$	*	See discussion
Sr	$SrCO_3$, $SrSO_4$?	*	See discussion
Tc	TcO_2	4.3×10^{-38}	
Th	ThO_2	6.0×10^{-15}	
U	UO_2	1.0×10^{-8}	

[a]Calculated using the PHREEQC code version 2.12.03 and the thermo.com.V8.R6.230 database from Lawrence Livermore National Laboratories, except for the 25°C TcO_2 solubility product and enthalpy, which came from the R5 version of the Yucca Mountain Project thermodynamic database.

3.3.2. Radionuclide Sorption

Radionuclide sorption has rarely been measured at temperatures much greater than 25 °C. Nevertheless, there is sufficient experimental data to suggest that most radionuclides released from the bottoms of deep boreholes will adsorb to basement rocks, to overlying sediments, and to the bentonite used to seal the borehole. Table 5 provides a compilation of representative distribution coefficients, k_ds. A radioelement k_d (mL/g) is the ratio of radioelement sorbed on a material (moles/g) to the amount of radioelement remaining in solution (moles/mL). Distribution coefficients tend to lump together multiple equilibrium and kinetic reactions, are specific to the conditions under which they were measured (e.g., pH, ionic strength, temperature, fluid-to-rock ratio, among others) and, therefore provide only a rough predictor of the potential for contaminant retardation (McKinley and Scholtis 1993; Bethke and Brady 2000). Nevertheless, k_ds are useful in examining boundary level controls over radioelement transport. Elements with k_ds of 0 (for example, iodine) won't sorb and will therefore move at the velocity of the fluids that carry them. Elements with k_d's of 10 or more will move at less than 1% of the velocity of deep

fluids. Table 5 emphasizes that sorption will sharply limit the transport of most radionuclides from deep boreholes. The two exceptions are isotopes of iodine and carbon – ^{129}I and ^{14}C.

Table 5. [a]Deep Borehole k_ds (ml/g).

Element	$k_{d\ basement}$	$k_{d\ sediment}$	$k_{d\ bentonite}$
Am, [b]Ac, [b]Cm	50-5000	100-100,000	300-29,400
C	0-6	0-2000	5
Cs	50-400	10-10,000	120-1000
Np, [b]Pa	10-5000	10-1000	30-1000
Pu	10-5000	300-100,000	150-16,800
[c]Ra	4-30	5-3000	50-3000
Sr	4-30	5-3000	50-3000
[d]Tc	0-250	0-1000	0-250
Th	30-5000	800-60,000	63-23,500
U	4-5000	20-1700	90-1000
I	0-1	0-100	0-13

[a]All values are from the review of McKinley and Scholtis (1993). Values less than one were rounded down to zero.

[b]k_ds for Ac and Cm are set equal to those of chemically similar Am. l_ds for Pa are set equal to those of chemically similar Np.

[c]k_ds for Ra were set equal to those of somewhat chemically similar Sr.

[d]Tc k_ds under reducing borehole conditions will likely be much greater than the zero values listed here which were measured under more oxidizing conditions.

4. SCENARIO ANALYSIS

The selection of scenarios for analysis in the deep borehole disposal performance assessment is based on the assumption that regulatory requirements for deep borehole disposal will be essentially the same as those currently extant in 10 CFR 63. Specifically, the performance measure of interest is assumed to be the mean annual dose to a hypothetical member of the public (the "reasonably maximally exposed individual" of 40 CFR 197.21) who lives in the accessible environment near the disposal site. Consistent with approach taken in 40 CFR 197, it is assumed that the mean annual dose shall include probability-weighted consequences of releases due to all significant features, events, and processes (FEPs), and shall account for uncertainty associated with those FEPs. As described in Section 4.1, a FEP screening approach similar to that taken for both Yucca Mountain and WIPP is adopted to identify the significant FEPs that should be included in the quantitative performance assessment. Section 4.2 describes how those FEPs that are identified as being significant to performance are combined into the scenarios analyzed in Section 5.

4.1. Identification of Relevant Features, Events, and Processes

Various programs in the US and other nations have compiled exhaustive lists of FEPs for mined geologic disposal that should be evaluated for potential relevance to deep borehole disposal of radioactive wastes. Depending on subjective decisions about how to partition the essentially infinite number of possible future occurrences, these lists can range from a relatively small number of broadly defined FEPs to a very large number of more narrowly defined FEPs. In practice, lists that aggregate phenomena at relatively coarse levels have proven to be suitable for evaluation in regulatory settings in the US (e.g., WIPP Compliance Certification Application [DOE 1996, DOE 2004], Yucca Mountain License Application [DOE 2008b, Sandia National Laboratories 2008b]).

Once potentially relevant FEPs for deep borehole disposal have been identified, they must be evaluated against screening criteria provided in US regulations. Specifically, EPA regulations for Yucca Mountain state that FEPs that have an annual probability of occurrence less than one chance in 100,000,000 in the first 10,000 years after closure may be excluded from the analysis. Features, events, and processes that have higher probabilities, but do not significantly change the results of long-term performance assessments, may also be omitted from the analysis (40 CFR 197.36(a)(1)). In addition, some potentially relevant FEPs are screened from further consideration because they are inconsistent with specific aspects of the regulatory requirements. For example, existing regulations for WIPP and Yucca Mountain indicate that performance assessments should not include consequences of deliberate human acts of sabotage or disruption in the far future. For this analysis it is assumed that all regulatory requirements relevant to FEP analyses for Yucca Mountain apply equally to deep borehole disposal.

The FEP list from the Yucca Mountain license application (see Appendix B, Table B-1) was adopted as a reasonable starting point for evaluation. Each of the 374 FEPs on this list has been considered (screened) for potential relevance to deep borehole disposal; FEPs that may be unique to deep borehole disposal have been considered and compared to the list to identify existing

FEPs that capture the processes of interest and concern for boreholes. No new FEPs were identified in this process, confirming that, although the Yucca Mountain list was specifically tailored for a mined repository, it remains a useful starting point for this preliminary analysis.

In evaluating Yucca Mountain FEPs for the deep borehole disposal performance assessment, the following assumptions are made that go beyond the basic assumption that regulatory criteria are the same as those stated in 40 CFR part 197.

- Biosphere exposure is assumed to occur via a contaminated groundwater well immediately adjacent to the borehole. There is therefore no release pathway of interest in the unsaturated zone (UZ). All relevant biosphere pathways associated with contaminated well water (e.g., irrigation, crops, livestock, drinking, etc.) are included.
- No credit is taken for the waste package or waste form as flow barriers. Therefore, all FEPs related to the performance of waste package and waste form as flow and transport barriers are excluded from the analysis.
- Chemical effects of the waste package and waste form are of interest and must be evaluated further.
- The "Drift" is the portion of the borehole that contains waste (i.e., the waste disposal zone).
- The engineered barrier system (EBS) includes seals and drifts, but the effective contribution comes from the borehole seals.
- Backfill, to the extent that it is used, is the material that is emplaced in the waste disposal zone of the borehole surrounding waste canisters.
- There are two release pathways of primary interest: transport through the EBS (seals), and transport through the saturated zone (SZ) in the surrounding rock
- Naval and DOE spent fuels (called out specifically in the YM analysis) are omitted from this analysis.
- Retrievability of waste, which is required to be feasible under current regulations, is assumed to be excluded as a position of policy.

Tables B-1 and B-2 in Appendix B summarize the screening decisions for each FEP (whether a FEP is likely to need to be included in or excluded from a full performance assessment for deep borehole disposal) and also includes a qualitative estimate of the level of effort likely to be required to provide a robust basis for the screening of the FEP. For excluded FEPs, 1 means the technical or regulatory basis is readily available and all that is needed is documentation; 2 means new technical work likely is needed, and 3 indicates a potentially significant amount of work is needed. For included FEPs, 1 indicates that this is a normal part of modeling, 2 indicates that this is a significant aspect of the modeling, and 3 indicates possible modeling challenges. Notes entered in this column provide clarification about how the FEP may need to be considered for deep borehole disposal.

Section 4.3 provides additional support for the decision to exclude criticality, molecular diffusion, and thermal hydrofracturing from the performance assessment.

4.2. Scenario Selection

Consideration of the FEPs that have a preliminary screening of "included" in Table 9 shows that radionuclides emplaced in deep boreholes might reach the biosphere along one, or a combination, of three principal paths: 1) up the borehole (includes accidental release during emplacement); 2) along the annulus of disturbed rock; and/or 3) radially out through groundwater. These pathways are described below as three scenarios chosen for analysis in a preliminary performance assessment. A more complete screening of the FEPs may identify additional scenarios of interest, and may also show that some aspects of the chosen scenarios do not need further analysis.

Scenario 1: Transport in the borehole. *Hydrologic flow up the borehole transports radionuclides to a shallow aquifer from which they are pumped to the biosphere* – This scenario requires sufficiently high permeability within the borehole and a sustained upward gradient in hydrologic potential for it to occur. Vertical permeability within the borehole in the waste disposal zone may be relatively high, given the presumably rapid degradation of the disposal canisters stacked within the borehole. Vertical permeability within the borehole above the level of waste emplacement will be engineered to be very low and would require failure of the borehole grout and seals (or bypassing of such seals) to permit significant fluid flow up the borehole. An upward gradient in hydrologic potential within the borehole could result from: a) ambient hydrologic conditions, b) thermal pressurization of fluid within the waste disposal zone from waste heat, c) buoyancy of heated fluid within the waste disposal zone, or d) thermo-chemical reactions that release water and/or gases within the waste disposal zone.

Scenario 2: Transport in disturbed rock around the borehole. *Hydrologic flow up the annulus of disturbed rock surrounding the borehole transports radionuclides to a shallow aquifer from which they are pumped to the biosphere* – This scenario requires sufficiently high permeability in the rock surrounding the borehole and a sustained upward gradient in hydrologic potential for it to occur. Vertical permeability within disturbed rock in the waste disposal zone and in the overlying rock may be relatively high if the annular space is not effectively grouted during borehole construction and/or abandonment. Vertical permeability in the crystalline rock immediately outside the heated volume near the waste disposal zone could be increased because thermo-mechanical effects would reduce the vertical mechanical stress. An upward gradient in hydrologic potential within the annulus of the borehole could result from: a) ambient hydrologic conditions, b) thermal pressurization of fluids within the waste disposal zone from waste heat, c) buoyancy of heated fluids within the waste disposal zone, or d) thermo-chemical reactions that release water and/or gases within the waste disposal zone.

Scenario 3: Transport in surrounding rock away from the borehole. *Hydrologic flow up through the crystalline basement and sedimentary cover transports radionuclides to a shallow aquifer from which they are pumped to the biosphere* – This scenario requires sufficiently high permeability within fracture zones and/or faults in the crystalline basement and sedimentary cover and a sustained upward gradient in hydrologic potential for it to occur. Given the low

vertical permeability of the crystalline basement rocks and the stratified sedimentary cover, a through-going feature such as an interconnected group of fracture zones or faults would be required to conduct significant quantities of fluid to a shallow aquifer.

4.3. Justification for Exclusion of Selected Features, Events, and Processes

4.3.1. Exclusion of Criticality from Deep Borehole Disposal

The possibility of a self-sustained nuclear chain reaction event (critical event or "criticality") has always been a consideration of geologic disposal, similar to any facility that handles fissile material. As early as 1974, the criticality scenario class was identified as a potential event in the Waste Isolation Pilot Plant (WIPP) in southern New Mexico, a repository for transuranic (TRU) waste which opened in 1999 (Rechard, Sanchez et al. 2001). Because of the potential interest, a preliminary discussion is provided concerning the credibility of a down-hole criticality with respect to inclusion or exclusion from a formal, site-specific performance assessment for SNF. HLW and other radioactive waste such as small spent sealed sources would present a much lower potential for criticality.

During transportation to the site and during repository operations when humans are present, stringent administrative and physical measures would be in place to prevent criticality. These standard operational aspects are not discussed here. Rather, this discussion focuses on the low probability of criticality after deep borehole disposal in two general locations: in the waste canister (Section 4.3.1.1); and outside the waste canister in the near or far field (Section 4.3.1.1). The focus here is on direct disposal of spent fuel assemblies rather than HLW which has most of the fissile mass removed.

4.3.1.1. Low Probability of Criticality in a Single Waste Canister

As noted in Section 4.1, a FEP can be excluded if (a) the annual probability of occurrence is less than one chance in 10^{-8} (i.e., low probability), or (b) its omission does not significantly change the results of long-term performance assessments (i.e., low consequence). New regulations applicable to deep borehole disposal (see Section 2) would likely retain this concept.

Fissile material cannot become critical after disposal unless several conditions are met. Specifically, several features must be present, and events and especially geologic processes must act to alter the waste canister and its contents for a critical event to occur inside the canister. However, physical constraints limit the possibility of criticality inside the waste canister.

To elaborate, because of the small diameter of a deep borehole, the number of CSNF assemblies that can be placed in a canister is limited. This criticality analysis assumes one PWR assembly is placed in a canister. One PWR assembly cannot become critical even when fully flooded. For low enriched uranium, the heterogeneous lumping of the uranium in an assembly is the most reactive configuration. Hence, any re-arrangement to a more homogeneous configuration lowers the reactivity. Based on 383 kg of uranium in a reference PWR (derived from Table 7), the amount of fissile ^{235}U would vary between 3% (11.5 kg) for older fuel, 5% (19 kg) for fuel

currently in use, and perhaps a maximum of 10% (38 kg) for fuel sometime in the future. Yet, homogeneous mixtures of rock with high silica content (~75%wt silica), typically require >350 kg, >65 kg, or >30 kg of fissile ^{235}U, respectively, ignoring the presence of any neutron absorbing elements such fission products, actinides, or purposely placed boron or gadolinium (Figure 9 from Rechard, Sanchez et al. 2003). Hence, only a homogeneous mixture of future fresh fuel at 10% enrichment could be critical in a single canister. In reality fission products and actinides would also be present in spent fuel, which would lower reactivity, hence, even future CSNF at an initial 10% enrichment would not be critical. More importantly, the diameter of the canister or borehole is not sufficient to prevent excess loss of neutrons within the fissile material as discussed in Section 4.3.1.2 for criticality outside the waste canister.

For DOE SNF, the packaging scheme could limit the fissile ^{235}U roughly to those amounts listed above (i.e., <350 kg for DOE SNF with <3% enrichment, <65 kg for DOE SNF with <5% enrichment, and <30 kg for DOE SNF with any other enrichment.

4.3.1.2. Low Probability of Criticality Outside the Waste Canisters

Because of the physical constraint on the amount of fissile mass in a canister, criticality is not credible inside the canister. Criticality directly outside the canister also has physical constraints. Specifically, the minimum diameter of a homogeneous critical sphere is greater than the 0.445 m (17.5 in.) diameter borehole at depth (Figure 3). For example, the minimum diameter for a critical sphere at 10% enrichment and a 20 kg/m^3 concentration at the minimum mass of 30 kg is 0.71 m; More realistic depositional concentrations of 5 kg/m^3 (concentrations found in high grade ores ~2300 ppm) result in a minimum diameter of 1.1 m. Ideal planar configurations must also be at least 0.5 m thick, as corroborated by the natural reactors at Oklo that were about 1 m thick (Rechard et al. 2001; Section 3.5). Hence, criticality is not credible in the confines of the borehole at depths where disposal occurs.

If a critical event is to occur outside the package, geologic processes must transport fissile material from several packages into the host rock or to depositional zones away from the disposal area and then assemble the fissile material into a critical configuration. These geologic processes are the same as must be invoked to remove fission products and actinides from the waste and transport them to the biosphere.

As discussed in Section 3.3, the chemical environment in a deep borehole greatly limits the mobility of radionuclides, in general, and fissile material, in particular. There is no likely mechanism to oxidize the uranium to the more mobile species (i.e., U^{+6}); hence, the solubility of uranium (U^{+4}) in the anoxic environment of the borehole is 10^{-8} mole/L (2.38×10^{-6} kg/m^3) (Table 4). As noted above, the concentration, either as a liquid or solid, must reach ~5 kg/m^3 (~2300 ppm) to go critical (6 orders of magnitude higher concentration). More importantly, enough mass must be released from the borehole waste disposal zone. As noted below in Section 5, uranium is not transported out of the waste disposal zone. At the upward velocities from thermal effects that might occur in the initial 200 years after disposal, it would take 9 billion years to deplete the uranium in a single waste canister (383 kg). In one million years, about 0.04 kg would be depleted using the thermal upward velocity in the initial 200 years. If a disposal borehole had 450 canisters, the maximum release from the disposal zone would only be

about 19 kg, of which at most 10% would be fissile. A release of 1.9 kg of fissile ^{235}U is much less than the 30 kg necessary to become critical. Hence, criticality in the far field is not credible.

4.3.2. Exclusion of Molecular Diffusion from Deep Borehole Disposal

Chemical diffusion of radionuclides through the host rock matrix and borehole seals will result in the migration of contaminant mass, even in the absence of fluid flow. The potential impact of diffusion on radionuclide containment is evaluated here using an analytical solution for one-dimensional diffusive transport through a porous medium, assuming a constant radionuclide concentration in the waste disposal zone. The solution is for a non-sorbing species without radioactive decay, according to the following equation (Crank 1956):

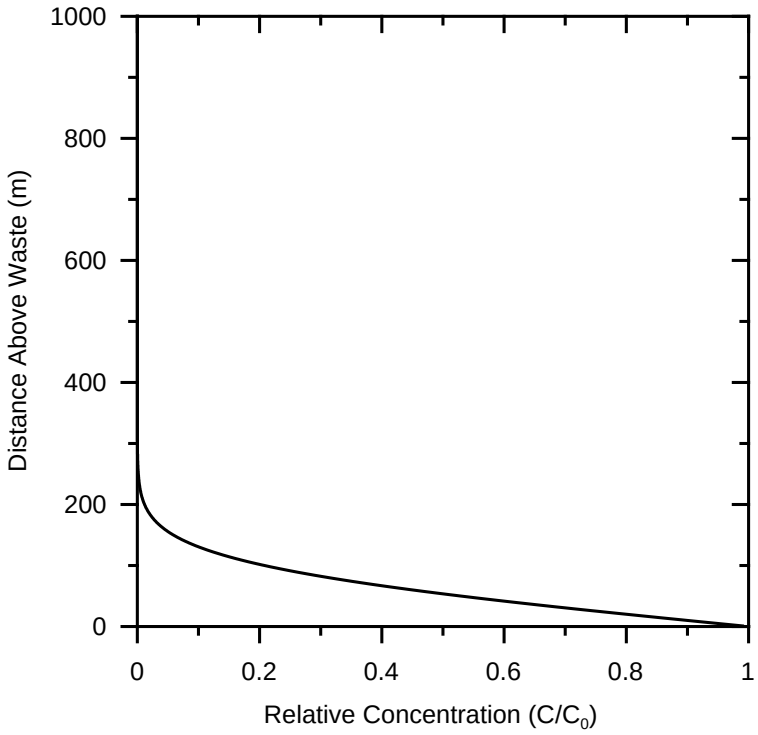
$$\frac{C}{C_0} = erfc\left[\frac{z}{2\sqrt{D_{eff}\,t}}\right] \qquad \text{(Eq. 4-1)}$$

where C is the radionuclide concentration, C_0 is the radionuclide concentration in the waste zone, *erfc* is the complementary error function, z is the distance above the waste, D_{eff} is the effective diffusion coefficient, and t is time.

The vertical concentration profile above the waste from this solution is plotted in Figure 12 at 1,000,000 years after waste emplacement, assuming an effective diffusion coefficient of 1×10^{-10} m^2/s. Migration of radionuclide mass via diffusion has occurred to a vertical distance of about 200 m above the waste in this time.

The concentrations shown in Figure 12 are overestimated with regard to the geometry of the system. Diffusion from the top of the waste disposal zone would have a radial component as well as a vertical component, reducing the migration rate in the vertical direction. Radionuclides that sorb on the rock matrix and borehole sealing material would be significantly retarded during diffusive migration. In addition, radioactive decay for radionuclides with half lives less than the time frame of the calculation would decrease concentrations. The value of the effective diffusion coefficient (1×10^{-10} m^2/s) used in the analysis is relatively high for granite, but is approximately representative of the elevated temperature conditions in the deep borehole disposal system.

Overall, diffusion in crystalline host rock and borehole seals is a slow process for the migration of radionuclide contamination, even on geologic time scales. Given the depth of deep borehole disposal system, diffusion can be excluded as a significant process from further consideration in performance assessment analyses.



Note: Assuming constant concentration of C_0 at the waste and effective diffusion coefficient of 1×10^{-10} m^2/s.

Figure 12. Concentration Profile for a Non-sorbing Species from Diffusion at 1,000,000 Years After Waste Emplacement.

4.3.3. Exclusion of Thermal Hydrofracturing from Deep Borehole Disposal

Permeability of the host rock near the borehole potentially could be enhanced by hydrofracturing resulting from the thermal expansion of fluid. This might increase the permeability in the host rock around the sealed borehole and provide a pathway for upward vertical hydrologic flow and radionuclide migration toward the surface.

This potential process was evaluated using a modified version of the two-dimensional heat conduction model in which heat and fluid flow were coupled. The model was run assuming a permeability of 1.0×10^{-20} m^2 for the granite, which is a very low permeability, near the lower end of the range for unfractured crystalline rocks and shales. Low permeability tends to maximize the fluid pressures in the system during heating.

The simulated fluid pressures as a function of time for varying distances from the waste container are shown in Figure 13. The peak pressures occur near the borehole in the time frame of a few days after emplacement and borehole sealing. Note that the ambient (hydrostatic) fluid pressure in the model is 39.2 MPa. For hydrofracturing to occur, the fluid pressure would have to exceed the ambient stress in the host rock. Horizontal stress is generally lower than vertical stress, so the induced fractures would be vertical and preferentially oriented in the direction of

the maximum horizontal stress. Based on a compilation of data on horizontal stress in the crust, the average horizontal stress increases with depth by a factor of about 24 MPa/km (Japan Nuclear Cycle Development Institute 2000) – the lithostatic gradient. Using this estimate, the average horizontal stress at 4 km depth would be about 96 MPa. The hydrothermal modeling results suggest that comparable fluid pressures would not be achieved and that no hydrofracturing would occur by this process.

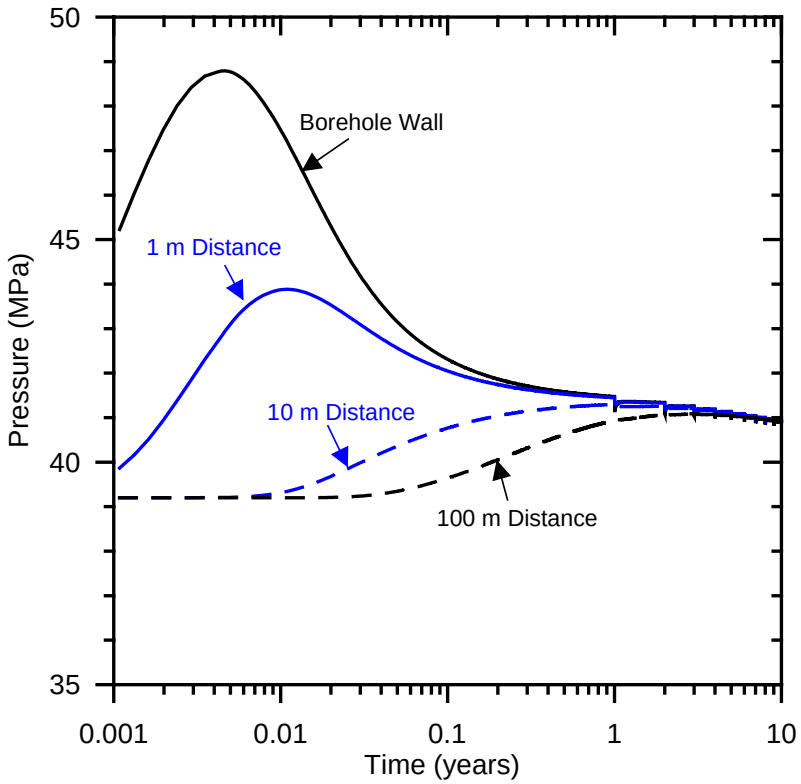


Figure 13. Fluid Pressure Histories for Locations at a Depth in the Middle of the Waste Zone at Several Horizontal Distances from the Center of the Waste–Filled Borehole.

5. PERFORMANCE ASSESSMENT

Based on the scenario analysis described in Section 4, a preliminary deep borehole performance assessment (DB-PA) was performed for a simplified and conservative representation of combined radionuclide releases from Scenarios 1 and 2 from Section 4.2. The conceptual model is as follows:

- 400 PWR assemblies (~150 MTHM) vertically stacked down the length of the waste disposal zone (~ 2 km).
- Initial radionuclide inventory consistent with Appendix A (CSNF/PWR aged to year 2117). Effects of ingrowth accounted for in a bounding fashion.
- Dissolved concentrations in the waste disposal zone limited by thermal-chemical conditions (see Table 4).
- Thermally driven hydrologic flow from the top of the waste disposal zone upward through 1000 m of a bentonite sealed borehole with a specific discharge of 0.017 m/yr for 200 years (see Figure 8).
- Radionuclide transport up the borehole calculated using a 1-dimensional analytical solution to the advection-dispersion equation (see Equation 5-1 below).
- Pumping of borehole water (from the location 1000 m above the top of the waste disposal zone) to the surface (biosphere) via a withdrawal well. No credit is taken for sorption or decay along the saturated zone transport pathway from the borehole to the withdrawal well.
- A dilution factor of 3.16×10^7 (see Section 3.2.3) is applied to account for the fact that the borehole water would mix with water in an existing aquifer before it would be captured by the withdrawal well (assumed to supply 1,000 people).
- A transport time of 8,000 years (see Figure 11) is applied to account for the time taken for the bulk of the dissolved radionuclide mass to be captured by the withdrawal well (at a constant pumping rate necessary to supply 1,000 people).
- Doses to a hypothetical person living near the withdrawal well are based on biosphere dose conversion factors (BDCFs) consistent with the lifestyle of the Yucca Mountain reasonably maximally exposed individual (RMEI), as specified by the EPA in 40 CFR 197.

The conceptual model was implemented numerically in a Microsoft Excel spreadsheet. Equation 5-1 gives the analytical solution for dissolved radionuclide concentration in the sealed borehole, C (in mg/L), as a function of time, *t*, and distance, *x*, from the source that is used in the numerical model. It is based on the Ogata-Banks solution for 1-dimensional advection-dispersion from a continuous source with retardation (sorption as described by kds in Table 5) and radioactive decay (Domenico and Schwartz 1990, Equation 17.10).

$$C(x,t) = (C_o/2) * \exp\{[x/2\alpha_x][1-(1+4\lambda\alpha_x/v_c)^{1/2}]\} * \operatorname{erfc}\{[x - v_c t(1+4\lambda\alpha_x/v_c)^{1/2}]/[2(\alpha_x v_c t)^{1/2}]\} \quad \text{(Eq. 5-1)}$$

where:

$$v_c = v / R_f \quad \text{(Eq. 5-2)}$$

$$R_f = 1 + (\rho_b k_d)/n \quad \text{(Eq. 5-3)}$$

and:

C_o	=	initial source concentration (mg/L)
v_c	=	dissolved radionuclide velocity (m/yr)
v	=	hydrologic pore velocity (m/yr)
R_f	=	retardation factor
k_d	=	distribution coefficient (L/g)
n	=	porosity of sealed borehole
ρ_b	=	bulk density of sealed borehole (kg/m^3)
α_x	=	longitudinal dispersivity (m)
λ	=	decay constant (yr^{-1})

In addition to the continuous source solution described by Equation 5-1, the DB-PA model also contains an instantaneous source solution. However, for the base-case DB-PA conditions the instantaneous source solution was not required.

Radionuclide transport up the borehole from the source (waste disposal) zone occurs for 200 years, corresponding to the duration of the thermally driven flow in Figure 8. Subsequent to the the thermal period, ambient conditions are not expected to provide any upward gradient, and upward radionuclide transport was assumed to cease.

The source concentration at the top of the waste disposal zone was determined by (a) calculating a maximum potential concentration based on dissolving the entire initial mass inventory in a PWR into the void volume (i.e., the potential volume of water) of a waste canister, and (b) selecting the lower of the maximum potential concentration and the solubility limits (see Table 4) as the source concentration.

Sealed borehole properties representative of bentonite (permeability of 1×10^{-16} m^2, porosity of 0.034, and bulk density of 1200 kg/ m^3) in conjunction with the thermally driven driving pressure produced a hydrologic pore velocity of 0.502 m/yr and a corresponding 1000 m borehole travel time (for an unretarded radionuclide) of 1991.3 years. Because the period of thermally driven flow (200 years) is short relative to the hydrologic travel time up the sealed borehole (1991.3 yrs), the only radionuclide with a non-zero concentration 1000 m above the waste disposal zone in the sealed borehole is ^{129}I, which is the only radionuclide that has no retardation. The non-zero ^{129}I concentration (which is only 5.3×10^{-8} mg/L) represents the leading edge of the dispersive transport front. However, the center of mass never reaches the top

of the 1000 m sealed section of the borehole because there is no further movement after 200 years.

Accounting for the 8,000-year travel time for the radionuclides to reach the withdrawal well, results in a peak dose to the RMEI at 8,200 years. The DB-PA calculated results (dose to the RMEI) for all radionuclides at 8,200 years are shown in Table 6. The total dose to the RMEI at 8,200 years is 1.4×10^{-10} mrem/yr. The only contributor to the dose is ^{129}I.

These DB-PA results are based on several bounding and conservative assumptions, such as: all waste is assumed to instantly degrade and dissolve inside the waste canisters; all waste is assumed to be PWR assemblies; no credit is taken for sorption or decay along the saturated zone transport pathway from the sealed borehole to the withdrawal well. Thus, as a first approximation, more refined performance assessments may indicate lower doses, or later peak doses, or both, than established here.

Other scenarios, with larger or longer flows, higher permeabilities, and different source configurations, would require refinements to the conceptual model.

Table 6. Total Peak Dose (mrem/yr) to RMEI and Travel Distance Resulting From 200 Years of Thermally Driven Transport

Radionuclide	Center of Mass Travel Distance From Source at 200 yrs (m)	Concentration in Borehole 1000 m above Source at 200 yrs (mg/L)	Dose to RMEI at 8,200 yrs (mrem/yr)
Actinium Series			
^{243}Am	0.00	0.00	0.00
^{239}Pu	0.00	0.00	0.00
^{235}U	0.01	0.00	0.00
^{231}Pa	0.03	0.00	0.00
^{227}Ac	0.00	0.00	0.00
Uranium Series			
^{242}Pu	0.00	0.00	0.00
^{238}U	0.01	0.00	0.00
^{238}Pu	0.00	0.00	0.00
^{234}U	0.01	0.00	0.00
^{230}Th	0.00	0.00	0.00
^{226}Ra	0.01	0.00	0.00
Neptunium Series			
^{245}Cm	0.00	0.00	0.00
^{241}Pu	0.00	0.00	0.00
^{241}Am	0.00	0.00	0.00
^{237}Np	0.03	0.00	0.00
^{233}U	0.01	0.00	0.00
^{229}Th	0.00	0.00	0.00
Thorium Series			
^{240}Pu	0.00	0.00	0.00
^{236}U	0.01	0.00	0.00
^{232}Th	0.00	0.00	0.00
^{228}Ra	0.01	0.00	0.00
^{232}U	0.01	0.00	0.00
Fission Products			
^{14}C	0.57	0.00	0.00
^{90}Sr	0.01	0.00	0.00
^{99}Tc	0.14	0.00	0.00
^{129}I	100.44	5.32×10^{-8}	1.42×10^{-10}
^{135}Cs	0.01	0.00	0.00
^{137}Cs	0.01	0.00	0.00
Ingrowth (from all RNs)		0.00	0.00
TOTAL DOSE			**1.42×10^{-10}**

6. SUMMARY AND CONCLUSIONS

6.1. Preliminary Results

Thermal, hydrologic, and geochemical calculations suggest that radionuclides in spent fuel emplaced in deep boreholes will experience little physical reason to leave the borehole/near borehole domain. The vast majority of radionuclides, and the fuel itself, will be thermodynamically stable and will therefore resist dissolution into borehole fluids, or movement into and through the adjacent rocks. Thermal-hydrologic calculations indicate that, except for an early window extending from the time of emplacement to ~ 150 years post-emplacement (in the borehole), and ~ 600 years (to the top of the basement), there will be no vertical fluid flow to transport radionuclides towards the surface. Vertical transport velocities in the early flow window will be between 0.1 (basement) and 0.7 (borehole) m/yr. This means that total vertical fluid movement in, and adjacent to, deep borehole disposal zones should not exceed roughly 100 meters. In the absence of advection, chemical diffusion cannot move radionuclides from boreholes through discontinuous, stagnant, and density-stratified waters over distances much greater than about 200 meters in the 1,000,000 years needed for the vast bulk of the radioactivity to decay away. Simplified and conservative performance assessment calculations indicate that radiological dose to a human receptor via the groundwater pathway would be limited to a single radionuclide (^{129}I) and would be negligibly small, ~10 order of magnitude below current criteria.

6.2. Recommendations for Additional Work

A more complete technical analysis of the deep borehole option requires a comprehensive evaluation of potentially relevant features, events, and processes, beginning with the preliminary list identified in Appendix B and expanding that list as appropriate. More detailed analyses should be performed to confirm that FEPs that have been excluded from this preliminary analysis do not significantly impact long-term performance. Future performance assessment modeling should consider all relevant release scenarios and pathways based on FEP analyses, rather than focusing on the single pathway considered in this report. FEP analyses and future iterations of performance assessment modeling will provide guidance regarding where resources should be focused to build confidence in the understanding of borehole disposal systems.

Three specific areas for future research are noted here, based on preliminary analyses:

1. The coupled thermal-hydrologic-chemical-mechanical behavior of the borehole and disturbed region during the thermal pulse, and in the presence of density-stratified waters, should be modeled more accurately.

2. Additional consideration should be focused on the design and long-term performance of deep seals. Calculated releases might be lowered even further from the already low values predicted above by development and deployment of sorbents that sorb/sequester ^{129}I in the borehole, or in the seals. Layered bismuth hydroxide compounds have shown great promise for limiting ^{129}I transport to the biosphere (Krumhansl et al., 2006). The performance of bismuth compounds must be verified

(and possibly optimized) under the temperature-salinity conditions that will prevail in deep boreholes.

3. Modeling of both the detailed thermal-hydrologic-chemical-mechanical behavior and the full-system performance of multi-borehole arrays should be undertaken, consistent with an assumption that a regional borehole disposal facility could entail an array of 10-100 individual boreholes. Such investigations could elaborate on the potential for cross-hole effects, help determine minimum inter-holes distances, etc. In order to establish a better sense of the potential performance variability that might be expected in multiple implementations of borehole disposal fields, individual preliminary performance assessments should be performed for several specific regions. Specific regions could be identified based on the availability of pre-existing geohydrologic data for depths of ~ 3 - 5 kilometers.

In addition to the technical issues related to the post-closure performance of the deep borehole disposal system described above, several other topics that are beyond the scope of this report should be examined in further detail:

1. A more comprehensive and detailed cost analysis would provide a firmer basis for quantitative comparisons with other disposal system options;

2. A detailed description of the changes to legal and regulatory requirements for implementation of deep borehole disposal would provide policymakers with a roadmap for necessary actions (specifically, consideration might be given to developing a risk-based standard); and

3. Detailed analyses of engineering systems and operational practices for waste emplacement are needed to demonstrate the viability of the deep borehole disposal concept. Also, the advantages of applying deep borehole disposal in countries possessing smaller and/or non-fuel waste inventories should be explored further.

It is recommended that ultimately a full-scale pilot project be undertaken, perhaps with surrogate waste, in order to fully explore the viability of a borehole disposal concept. The scientific and engineering advances gained from a single pilot project, and the applicability to subsequent borehole disposal implementations, are in contrast to site-specific mined repositories and their unique site characterization demands with relatively little transferable knowledge to subsequent repositories. Given the potential for standardizing the borehole design, and thus the ready extension to multiple borehole facilities, a single pilot project could provide significant gains on the scientific and engineering issues needing to be resolved, enable the development of international standards, and accelerate the evaluation of the viability of deep borehole disposal of spent nuclear fuel and high-level radioactive waste.

7. REFERENCES

ANDRA (Agence nationale pour la gestion des déchets radioactifs) (2005), *Dossier 2005: Argile. Tome: Safety Evaluation of a Geological Repository*

Anderson, V. K. (2004). An evaluation of the feasibility of disposal of nuclear waste in very deep boreholes. Dept. of Nuclear Engineering. Cambridge, MA, MIT.

Bethke, C. M. and P. V. Brady (2000). "How the Kd approach undermines ground water cleanup." Ground Water **321**: 435-442.

Crank, J. (1956). *The Mathematics of Diffusion*. Oxford University Press, New York.

DIANE Publishing Company (1995). Spent Nuclear Fuel Discharges from U.S. Reactors (1993), DIANE Publishing Company.

DOE (1996). Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant DOE/CAO-1996-2184, U.S. Department of Energy, Waste Isolation Pilot Plant, Carlsbad Area Office, Carlsbad, NM.

DOE (2004). Title 40 CFR Part 191 Compliance Recertification Application for the Waste Isolation Pilot Plant DOE/WIPP 2004-3231, U.S. Department of Energy Waste Isolation Pilot Plant, Carlsbad Field Office, Carlsbad, NM.

DOE (2008a). Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007, DOE/RW-0591.

DOE (2008b). Yucca Mountain License Application. DOE/RW-0753 Rev. 0.

Gibb, F. G. F., N. A. McTaggart, et al. (2008). "High-density suport matrices: Key to the deep borehole disposal of spent nuclear fuel." J. of Nuclear Materials **374**: 370-377.

Heiken, G., G. Woldegabriel, R. Morley, H. Plannerer, and J. Rowley (1996). Disposition of excess weapon plutonium in deep boreholes – site selection handbook. Los Alamos, NM, Los Alamos National Laboratory.

Hoag, C. I. (2006). Canister design for deep borehole disposal of nuclear waste. Dept of Nuclear Engineering. Cambridge, MA, MIT.

Japan Nuclear Cycle Development Institute (2000). The geological environment of Japan. In Geological Isolation Research Project, Overview Report H12, English version.

Juhlin, C. and H. Sandstedt (1989). Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economic potential. Part I: Geological considerations. Part II: Overall facility plan and cost analysis., Svensk Karnbranslehantering AB.

Krumhansl, J. L., J. D. Pless, et al. (2006). Yucca Mountain Project Getter Program Results (Year 1): I-129 and Other Anions of Concern: SAND2006-3869.

Langmuir, D. L. (1996). Aqueous environmental geochemistry. Upper Saddle River, NJ, Prentice-Hall.

McKinley, I. G. and A. Scholtis (1993). "A comparison of radionuclide sorption databases used in recent performance assessments." Journal of Contaminant Hydrology **13**: 347-363.

MIT (2006). The Future of Geothermal Energy. Cambridge, MA, MIT.

Mitchell, J. K. (1993). Fundamentals of Soil Behavior. 2nd Ed. . New York, NY, John Wiley & Sons, Inc.

National Academy of Sciences (1957). The Disposal of Radioactive Waste on Land.

O'Brien, M.T, L.H. Cohen, T.N. Narasimhan, T.L. Simkin, H.A. Wollenberg, W.F. Brace, S. Green, H.P. Platt, (1979), The very deep hole concept: evaluation of an alternative for nuclear waste disposal, Berkeley, CA, Lawrence Berkeley Laboratory, LBL- 7089.

Polsky, Y., L. Capuano, et al. (2008). Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report, Sandia Report SAND2008-7866.

Rechard, R. P., L. E. Sanchez, et al. (2001). "Unfavorable Conditions for Nuclear Criticality Following Disposal of Transuranic Waste at the Waste Isolation Pilot Plant." Nuclear Technology **136**: 99-129.

Rechard, R. P., L. C. Sanchez, et al. (2003). "Consideration of Nuclear Criticality when Disposing Highly Enriched Spent Nuclear Fuel in Unsaturated Tuff—I: Nuclear Criticality Constraints." Nuclear Technology **144**: 201-221.

Sandia National Laboratories (2008a). "Total System Performance Assessment Model/Analysis for the License Application." MDL-WIS-PA-000005 REV 00 AD 01.

Sandia National Laboratories (2008b), "Features, Events, and Processes for the Total System Performance Assessment: Analyses"ANL-WIS-MD-0000027 REV 00,

Van der Leeden, F., F. L. Troise, and D. K. Todd, (1990). The Water Encyclopedia –Second Edition, Geraghty and Miller Groundwater Series.

Van Geet, M. e. a. (2007). "Efficiency of a Borehole Seal by Means of Pre-Compacted Bentonite Blocks." Physics and Chemistry of the Earth, Parts A/B/C **32**(1-7): 123-134.

Wing, N. R. and G. E. Gee (1994). "Quest for the Perfect Cap." Civil Engineering **64**(10): 38041.

Woodward-Clyde Consultants (1983). Very deep hole systems engineering studies. Columbus, OH, ONWI.

Zyvoloski, G. A., B. A. Robinson, et al. (1997). Summary of models and methods for FEHM application – A finite element heat and mass transfer code. Los Alamos National Laboratory Report LA-13307-MS.

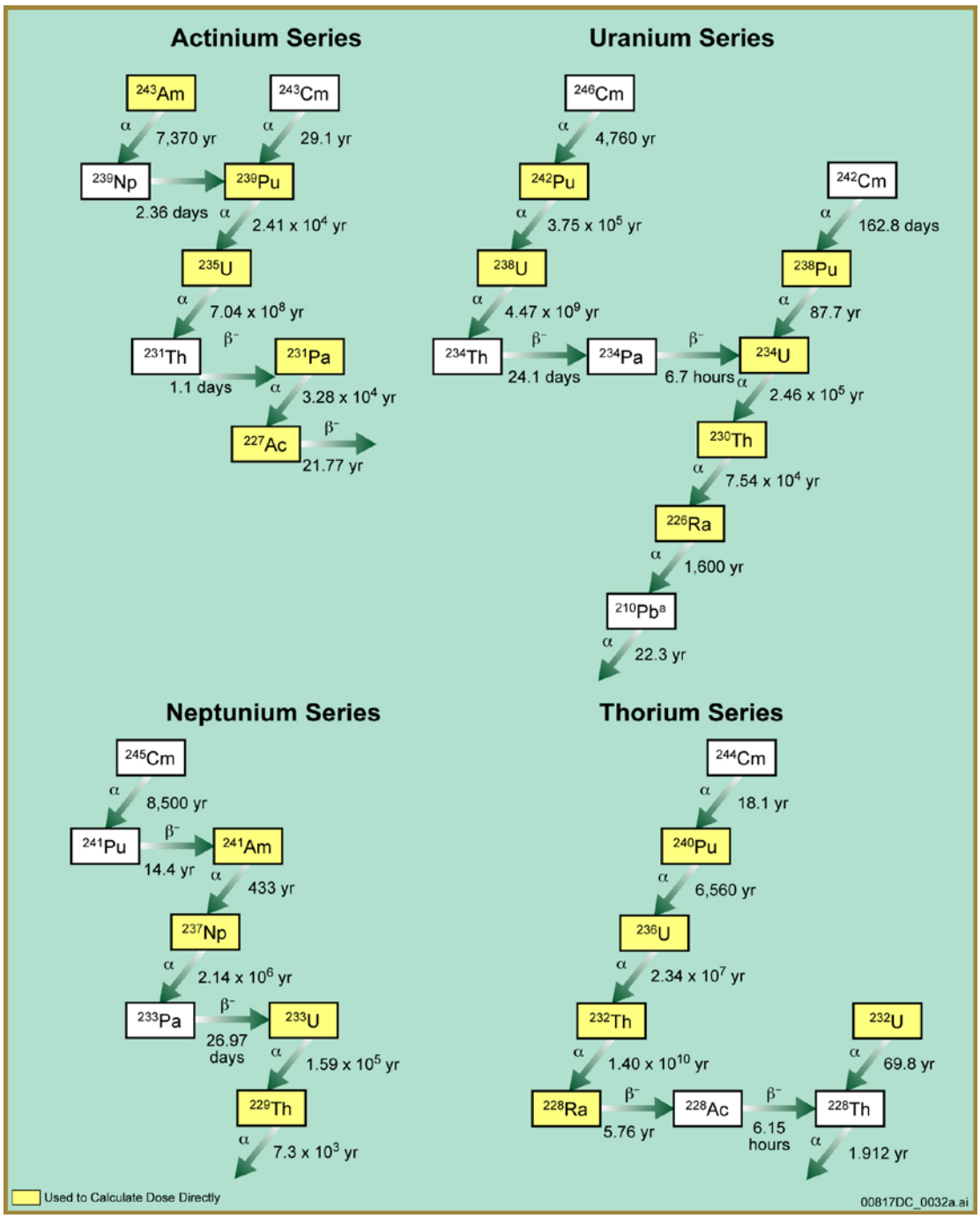
APPENDIX A: U.S. HLW AND SNF INVENTORY

Evaluation of the deep borehole disposal concept in this report is based on estimates of current and projected future quantities of high-level radioactive waste and spent nuclear fuel in the U.S. In 2007, DOE estimated that 109,300 metric tons heavy metal (MTHM) of high-level waste and spent nuclear fuel in the U.S. will ultimately need to be stored (DOE Office of Public Affairs, August 5, 2008). This inventory consists of 70,000 MTHM that is included in the Yucca Mountain license application, with the remainder that will need to be disposed of from future production. The inventory includes commercial spent nuclear fuel (CSNF), DOE spent nuclear fuel (DSNF), and high-level waste glass (HLWG). The inventory consists of actinide elements in several radionuclide decay chains (Figure 14) along with a number of fission products.

The 70,000 MTHM Yucca Mountain inventory is predominantly (about 70%) CSNF, which in turn consists of spent fuel assemblies from pressurized water reactors (PWRs) and boiling water reactors (BWRs). A representative inventory, showing the important actinide elements from Figure 14 and the important fission products, for a single Yucca Mountain waste package is provided in Table 7. The 31-radionuclide inventory is shown for an initial time (either 2030 or 2067 depending on waste type) and aged to a common year, 2117, about 100 years from the present. Note that this table actually represents two different types of waste packages: a CSNF waste package that contains the CSNF inventory (a single CSNF waste package would contain either 21 PWR assemblies or 44 BWR assemblies); and a codisposal waste package that combines the DSNF and HLWG inventory. Also, note that the inventories in Table 7 do not include any Mixed Oxide (MOX) fuel or Lanthanide Borosilicate (LaBS) waste.

For the purposes of discussing and characterizing the waste for deep borehole disposal, the relative radionuclide inventories for CSNF shown in Table 7 are considered representative of the entire US HLW and SNF inventory. The other waste streams (DSNF and HLWG) contains similar relative radionuclide inventories (Table 7) as the CSNF waste stream.

By weight, CSNF is about 97% ^{238}U, with contributions of 0.3-0.8% from ^{235}U, ^{236}U, ^{239}Pu, and ^{240}Pu. All other radionuclides contribute less than 0.1%. Figure 15 shows the relative contributions of the 31 radionuclides by activity (in curies), which is a more direct indicator of their potential effect on dose. Note that Figure 15 includes all waste (not just CSNF), but the relative contributions are likely to be the same. The change in importance of the various radionuclides over time is indicative of the effects decay and ingrowth. The same information is tabulated in Table 8, which also shows the decline in total activity over time.



Source: Figure 6.3.7-4 of (Sandia National Laboratories 2008).

[a] A series of short-lived daughters between ^{226}Ra and ^{210}Pb are not shown. Also, ^{210}Pb is not used to calculate dose directly, but its biosphere dose conversion factor is included with that of ^{226}Ra.

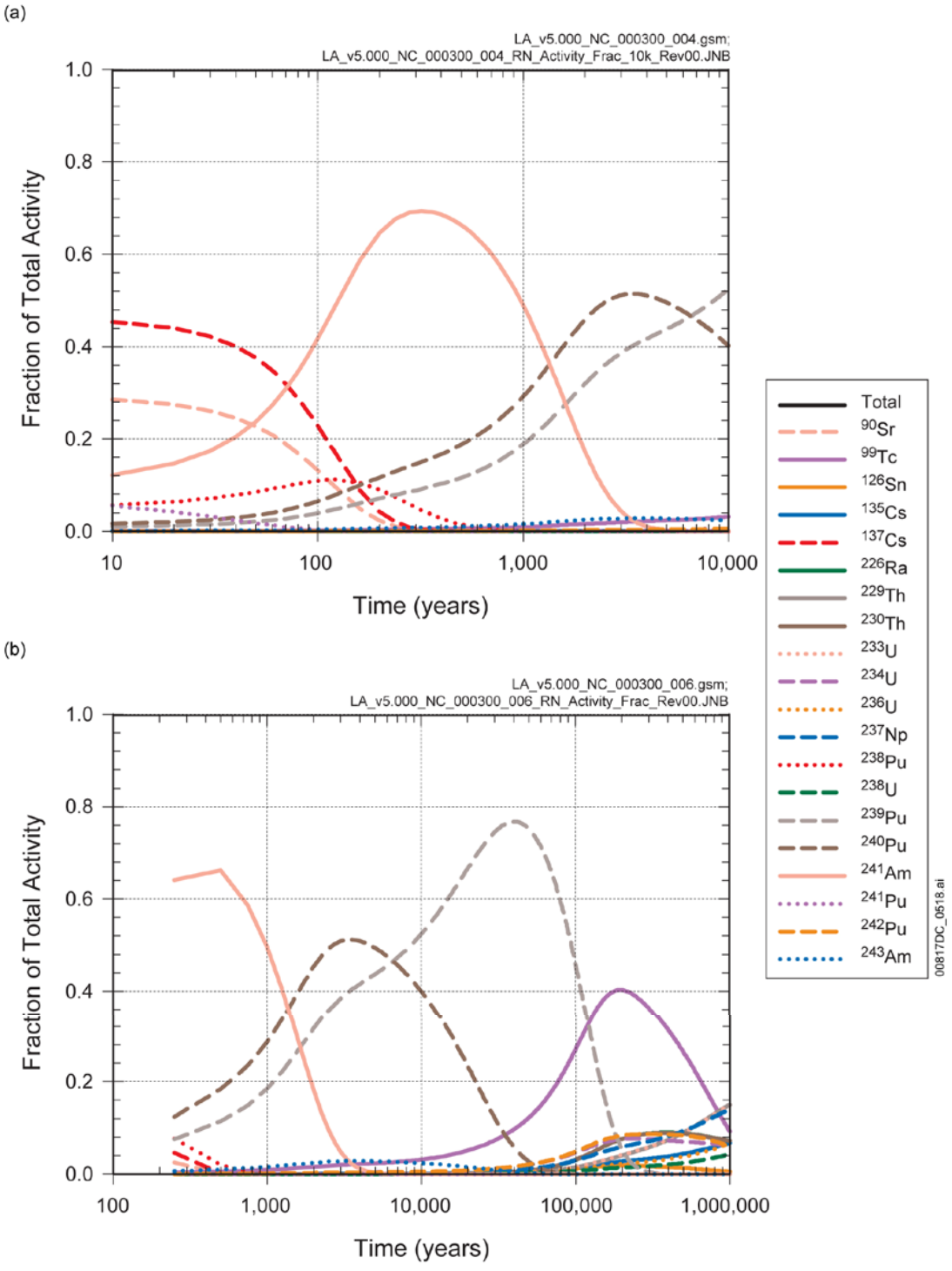
[b] Value listed under each radionuclide is the approximate decay half-life for the radionuclide.

Figure 14. Decay Chains of the Actinide Elements.

Table 7. Yucca Mountain Nuclear Waste Inventory per Waste Package by Radionuclide.

Waste Package Inventory (g/pkg)						
Radionuclide	CSNF at 2067	CSNF after 50 Years	DSNF at 2030	DSNF after 87 Years	HLWG at 2030	HLWG after 87 Years
^{227}Ac	2.47E-06	6.27E-06	1.22E-03	1.39E-03	1.91E-04	9.47E-04
^{241}Am	8.18E+03	9.84E+03	2.18E+02	2.15E+02	3.75E+01	3.37E+01
^{243}Am	1.24E+03	1.23E+03	6.73E+00	6.68E+00	5.75E-01	5.70E-01
^{14}C	1.35E+00	1.34E+00	1.81E+00	1.79E+00	0.00E+00	0.00E+00
^{36}Cl	3.23E+00	3.23E+00	4.23E+00	4.23E+00	0.00E+00	0.00E+00
^{245}Cm	1.75E+01	1.74E+01	9.25E-02	9.18E-02	5.43E-02	5.39E-02
^{135}Cs	4.36E+03	4.36E+03	9.74E+01	9.74E+01	1.27E+02	1.27E+02
^{137}Cs	5.90E+03	1.86E+03	9.72E+01	1.31E+01	3.02E+02	4.07E+01
^{129}I	1.73E+03	1.73E+03	3.56E+01	3.56E+01	7.27E+01	7.27E+01
^{237}Np	4.57E+03	5.32E+03	8.14E+01	1.12E+02	9.95E+01	1.04E+02
^{231}Pa	9.17E-03	1.22E-02	2.14E+00	2.14E+00	1.53E+00	1.53E+00
^{238}Pu	1.52E+03	1.02E+03	1.25E+01	6.28E+00	3.91E+01	1.96E+01
^{239}Pu	4.32E+04	4.31E+04	2.21E+03	2.20E+03	5.58E+02	5.57E+02
^{240}Pu	2.05E+04	2.04E+04	4.35E+02	4.31E+02	4.61E+01	4.57E+01
^{241}Pu	2.66E+03	2.40E+02	2.92E+01	4.49E-01	1.22E+00	1.89E-02
^{242}Pu	5.28E+03	5.28E+03	3.02E+01	3.02E+01	3.89E+00	3.89E+00
^{226}Ra	0.00E+00	1.29E-04	4.57E-05	1.80E-04	2.42E-05	2.68E-05
^{228}Ra	0.00E+00	1.90E-11	1.51E-05	8.77E-06	6.00E-06	1.20E-05
^{79}Se	4.19E+01	4.19E+01	6.82E+00	6.82E+00	7.01E+00	7.01E+00
^{126}Sn	4.63E+02	4.63E+02	9.40E+00	9.40E+00	1.70E+01	1.70E+01
^{90}Sr	2.49E+03	7.46E+02	5.22E+01	6.43E+00	1.74E+02	2.14E+01
^{99}Tc	7.55E+03	7.55E+03	1.58E+02	1.58E+02	1.01E+03	1.01E+03
^{229}Th	0.00E+00	2.07E-05	3.24E-01	5.22E-01	3.30E-03	1.05E-02
^{230}Th	1.52E-01	4.32E-01	1.18E-01	2.33E-01	8.12E-04	9.02E-03
^{232}Th	0.00E+00	5.63E-02	2.17E+04	2.17E+04	2.98E+04	2.98E+04
^{232}U	1.02E-02	6.20E-03	1.28E+00	5.39E-01	4.08E-04	1.72E-04
^{233}U	5.76E-02	1.37E-01	5.38E+02	5.38E+02	1.94E+01	1.94E+01
^{234}U	1.75E+03	2.24E+03	4.73E+02	4.79E+02	2.33E+01	4.24E+01
^{235}U	6.26E+04	6.27E+04	2.51E+04	2.51E+04	1.41E+03	1.41E+03
^{236}U	3.84E+04	3.85E+04	1.25E+03	1.25E+03	5.99E+01	6.03E+01
^{238}U	7.82E+06	7.82E+06	6.84E+05	6.84E+05	2.37E+05	2.37E+05

Source: Sandia National Laboratories 2008a; Table 6.3.7-4a



Source:Sandia National Laboratories 2008a, Figure 8.3-2.

Figure 15. Mean Radionuclide Contributions to the Total Yucca Mountain Nuclear Waste Inventory as a Function of Time for (a) 10,000 Years and (b) 1,000,000 Years After 2117.

Table 8. Decay of Total Yucca Mountain Nuclear Waste Inventory as a Function of Time and Dominant Contributors to Total Curie Inventory.

Time After Closure, 2117 (yrs)	Percent of Total Initial Curie Inventory	Major Contributors to Total Inventory at Time after Closure
0	100.00	^{137}Cs (46%), ^{90}Sr (29%), ^{241}Am (10%)
10	81.2	^{137}Cs (45%), ^{90}Sr (28%), ^{241}Am (12%)
100	20.75	^{241}Am (41%), ^{137}Cs (22 %), ^{90}Sr (13%), ^{238}Pu (11%))
1,000	4.20	^{241}Am (48%), ^{240}Pu (29%), ^{239}Pu (19%)
10,000	1.18	^{239}Pu-239 (52%), ^{240}Pu (40%)
100,000	0.10	^{239}Pu-239 (46%), ^{99}Tc-99 (27%)
500,000	0.03	^{99}Tc-99 (26%), ^{229}Th-229 (9%), ^{230}Th (9%), ^{226}Ra-226 (9%), ^{233}U (9%), ^{237}Np-237 (9%), ^{242}Pu (8%), ^{234}U-234 (7%)
1,000,000	0.02	^{233}U-233 (15%), ^{229}Th (15%), ^{237}Np-237 (14%), ^{99}Tc-99 (9%), ^{230}Th (7%), ^{226}Ra-226 (7%), ^{135}Cs (7%), ^{236}U-236 (6%), ^{242}Pu (6%)

Source: Table 8.3-1 of (Sandia National Laboratories 2008)

At early time (the first few hundred years after emplacement) the radionuclides with the highest activity are all short-lived (half-lives less than 500 years): ^{137}Cs, ^{90}Sr, ^{241}Am, and ^{238}Pu. From about 100 years to 1,500 years after emplacement, ^{241}Am is the largest contributor to the total activity. Subsequent to that, moderate half-life radionuclides become more important. ^{240}Pu (half-life of 6,560 years) is the largest contributor to total activity from about 1,500 years to 7,000 years after emplacement, then ^{239}Pu (half-life of 24,100 years) becomes the largest contributor until about 100,000 years after emplacement. At very long times (greater than 100,000 years after emplacement), the following long-lived radionuclides become most important to total activity: ^{99}Tc, ^{242}Pu, ^{237}Np, ^{234}U, ^{230}Th, ^{226}Ra, ^{233}U, ^{229}Th, ^{135}Cs, and ^{236}U.

Table 8 shows that the total activity (in curies) of the inventory decays to about 20% of the initial activity after 100 years, to about 4% after 1,000 years, and to about 1% of the initial activity after 10,000 years. Roughly 1000 years is required before the total radioactivity in CSNF would decay to the background level of a 0.2% U ore body. The radiation in un-processed spent fuel requires roughly 10,000 years to decay to the background levels of an ore body (Langmuir 1996).

APPENDIX B: COMPARISON OF DEEP BOREHOLE DISPOSAL AND YMP FEPS

Table B-1. Yucca Mountain Project Features, Events, and Processes List and Screening Decisions Listed by FEP Number. (based on: Sandia National Laboratories 2008b, Table 7.1). A "?" denotes a lower level of confidence in the preliminary analysis.

FEP Number	*FEP Name*	*YMP Screening Decision*	*Likely DBD Decision*	*Estimated DBD Level of Effort*
0.1.02.00.0A	*Timescales of Concern*	*Included*	*Include*	*1*
0.1.03.00.0A	*Spatial Domain of Concern*	*Included*	*Include*	*1*
0.1.09.00.0A	*Regulatory Requirements and Exclusions*	*Included*	*Include*	*3 Regulations and laws will need to be revised*
0.1.10.00.0A	*Model and Data Issues*	*Included*	*Include*	*1*
1.1.01.01.0A	*Open Site Investigation Boreholes*	*Excluded*	*Exclude*	*1*
1.1.01.01.0B	*Influx Through Holes Drilled in Drift Wall or Crown*	*Excluded*	*Exclude (NA)*	*1*
1.1.02.00.0A	*Chemical Effects of Excavation and Construction in EBS*	*Excluded*	*Exclude*	*2*
1.1.02.00.0B	*Mechanical Effects of Excavation and Construction in EBS*	*Excluded*	*Include*	*2*
1.1.02.01.0A	*Site Flooding (During Construction and Operation)*	*Excluded*	*Exclude*	*1*
1.1.02.02.0A	*Preclosure Ventilation*	*Included*	*Exclude (NA)*	*1*
1.1.02.03.0A	*Undesirable Materials Left*	*Excluded*	*Exclude (NA)*	*2*
1.1.03.01.0A	*Error in Waste Emplacement*	*Excluded*	*Exclude*	*3 Need to consider the emplacement that may get stuck halfway down. Also need to consider canisters that are crushed by overlying canisters*
1.1.03.01.0B	*Error in Backfill Emplacement*	*Excluded*	*Include?*	*Maybe be difficult to ensure that backfill is emplaced uniformly, may be simplest to include FEP and take no credit for backfill1*
1.1.04.01.0A	*Incomplete Closure*	*Excluded*	*Exclude*	*2*
1.1.05.00.0A	*Records and Markers for the Repository*	*Excluded*	*Exclude (regulatory)*	*1*
1.1.07.00.0A	*Repository Design*	*Included*	*Include*	*1*
1.1.08.00.0A	*Inadequate Quality Control and Deviations from Design*	*Excluded*	*Exclude (regulatory or low consequence)*	*1*

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
1.1.09.00.0A	Schedule and Planning	Excluded	Exclude	1
1.1.10.00.0A	Administrative Control of the Repository Site	Excluded	Exclude	1
1.1.11.00.0A	Monitoring of the Repository	Excluded	Exclude	1
1.1.12.01.0A	Accidents and Unplanned Events During Construction and Operation	Excluded	Exclude	1
1.1.13.00.0A	Retrievability	Included	Exclude (policy)	2
1.2.01.01.0A	Tectonic Activity - Large Scale	Excluded	Exclude	1
1.2.02.01.0A	Fractures	Included	Include	2
1.2.02.02.0A	Faults	Included	Include	2
1.2.02.03.0A	Fault Displacement Damages EBS Components	Included	Include?	2 Note—if no credit is taken for WP and WF components, all EBS FEPs are simplified to the consideration of the borehole seals
1.2.03.02.0A	Seismic Ground Motion Damages EBS Components	Included	Exclude	2
1.2.03.02.0B	Seismic-Induced Rockfall Damages EBS Components	Excluded	Exclude (NA)	1
1.2.03.02.0C	Seismic-Induced Drift Collapse Damages EBS Components	Included	Exclude (NA)	1
1.2.03.02.0D	Seismic-Induced Drift Collapse Alters In-Drift Thermohydrology	Included	Exclude (NA)	1
1.2.03.02.0E	Seismic-Induced Drift Collapse Alters In-Drift Chemistry	Excluded	Exclude (NA)	1
1.2.03.03.0A	Seismicity Associated With Igneous Activity	Included	Exclude	1
1.2.04.02.0A	Igneous Activity Changes Rock Properties	Excluded	Exclude	2 Need to evaluate potential for igneous activity at each site (should generically be low), also need to determine if repository heat can contribute to rock melting
1.2.04.03.0A	Igneous Intrusion Into Repository	Included	Exclude	2
1.2.04.04.0A	Igneous Intrusion Interacts With EBS Components	Included	Exclude	2
1.2.04.04.0B	Chemical Effects of Magma and Magmatic Volatiles	Included	Exclude	2 Volatiles may impact transport
1.2.04.05.0A	Magma Or Pyroclastic Base Surge Transports Waste	Excluded	Exclude (NA)	1
1.2.04.06.0A	Eruptive Conduit to Surface Intersects Repository	Included	Exclude	2
1.2.04.07.0A	Ashfall	Included	Exclude	1
1.2.04.07.0B	Ash Redistribution in Groundwater	Excluded	Exclude	1

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
1.2.04.07.0C	Ash Redistribution Via Soil and Sediment Transport	Included	Exclude	1
1.2.05.00.0A	Metamorphism	Excluded	Exclude	2 Repository heat may create metamorphic conditions
1.2.06.00.0A	Hydrothermal Activity	Excluded	Exclude	3 Repository heat may create local hydrothermal activity
1.2.07.01.0A	Erosion/Denudation	Excluded	Exclude	1
1.2.07.02.0A	Deposition	Excluded	Exclude	1
1.2.08.00.0A	Diagenesis	Excluded	Exclude	2
1.2.09.00.0A	Salt Diapirism and Dissolution	Excluded	Exclude	1
1.2.09.01.0A	Diapirism	Excluded	Exclude	2 Need to demonstrate that repository heat will not generate local diapirism
1.2.09.02.0A	Large-Scale Dissolution	Excluded	Exclude	1
1.2.10.01.0A	Hydrologic Response to Seismic Activity	Excluded	Exclude	1
1.2.10.02.0A	Hydrologic Response to Igneous Activity	Excluded	Exclude	2
1.3.01.00.0A	Climate Change	Included	Exclude	1
1.3.04.00.0A	Periglacial Effects	Excluded	Include	1
1.3.05.00.0A	Glacial and Ice Sheet Effect	Excluded	Include	2 Need to consider fluid pressure effects of future ice sheet loading
1.3.07.01.0A	Water Table Decline	Excluded	Exclude	1
1.3.07.02.0A	Water Table Rise Affects SZ	Included	Exclude	1
1.3.07.02.0B	Water Table Rise Affects UZ	Included	Exclude	1 All UZ FEPs are simplified
1.4.01.00.0A	Human Influences on Climate	Excluded	Exclude	1
1.4.01.01.0A	Climate Modification Increases Recharge	Included	Exclude	1
1.4.01.02.0A	Greenhouse Gas Effects	Excluded	Exclude	1
1.4.01.03.0A	Acid Rain	Excluded	Exclude	1
1.4.01.04.0A	Ozone Layer Failure	Excluded	Exclude	1
1.4.02.01.0A	Deliberate Human Intrusion	Excluded	Exclude	1
1.4.02.02.0A	Inadvertent Human Intrusion	Included	Exclude	1 (requires regulatory change)
1.4.02.03.0A	Igneous Event Precedes Human Intrusion	Excluded	Exclude	1
1.4.02.04.0A	Seismic Event Precedes Human Intrusion	Excluded	Exclude	1
1.4.03.00.0A	Unintrusive Site Investigation	Excluded	Exclude	1
1.4.04.00.0A	Drilling Activities (Human Intrusion)	Included	Exclude	1
1.4.04.01.0A	Effects of Drilling Intrusion	Included	Exclude	1
1.4.05.00.0A	Mining and Other Underground Activities	Excluded	Exclude	1

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	(Human Intrusion)			Includes natural resource issues
1.4.06.01.0A	Altered Soil Or Surface Water Chemistry	Excluded	Exclude	1
1.4.07.01.0A	Water Management Activities	Included	Exclude	1
1.4.07.02.0A	Wells	Included	Exclude	1
1.4.07.03.0A	Recycling of Accumulated Radionuclides from Soils to Groundwater	Excluded	Exclude	1
1.4.08.00.0A	Social and Institutional Developments	Excluded	Exclude	1
1.4.09.00.0A	Technological Developments	Excluded	Exclude	1
1.4.11.00.0A	Explosions and Crashes (Human Activities)	Excluded	Exclude	1
1.5.01.01.0A	Meteorite Impact	Excluded	Exclude	1
1.5.01.02.0A	Extraterrestrial Events	Excluded	Exclude	1
1.5.02.00.0A	Species Evolution	Excluded	Exclude	1
1.5.03.01.0A	Changes in the Earth's Magnetic Field	Excluded	Exclude	1
1.5.03.02.0A	Earth Tides	Excluded	Exclude	1
2.1.01.01.0A	Waste Inventory	Included	Include	1
2.1.01.02.0A	Interactions Between Co-Located Waste	Excluded	Exclude	1
2.1.01.02.0B	Interactions Between Co-Disposed Waste	Included	Exclude	1
2.1.01.03.0A	Heterogeneity of Waste Inventory	Included	Include	1
2.1.01.04.0A	Repository-Scale Spatial Heterogeneity of Emplaced Waste	Included	Include	1
2.1.02.01.0A	DSNF Degradation (Alteration, Dissolution, and Radionuclide Release)	Included	Exclude	1
2.1.02.02.0A	CSNF Degradation (Alteration, Dissolution, and Radionuclide Release)	Included	Exclude	1 Assume no credit for CSNF waste form
2.1.02.03.0A	HLW Glass Degradation (Alteration, Dissolution, and Radionuclide Release)	Included	Exclude	1 Assume no credit for HLW waste form?
2.1.02.04.0A	Alpha Recoil Enhances Dissolution	Excluded	Exclude	1
2.1.02.05.0A	HLW Glass Cracking	Included	Exclude	1
2.1.02.06.0A	HLW Glass Recrystallization	Excluded	Exclude	1
2.1.02.07.0A	Radionuclide Release from Gap and Grain Boundaries	Included	Exclude	1
2.1.02.08.0A	Pyrophoricity from DSNF	Excluded	Exclude	1
2.1.02.09.0A	Chemical Effects of Void Space in Waste Package	Included	Exclude	1
2.1.02.10.0A	Organic/Cellulosic Materials in Waste	Excluded	Exclude	1
2.1.02.11.0A	Degradation of Cladding from Waterlogged Rods	Excluded	Exclude	1
2.1.02.12.0A	Degradation of Cladding Prior to Disposal	Included	Exclude	1
2.1.02.13.0A	General Corrosion of Cladding	Excluded	Exclude	1
2.1.02.14.0A	Microbially Influenced Corrosion (MIC) of Cladding	Excluded	Include	1
2.1.02.15.0A	Localized (Radiolysis Enhanced) Corrosion of Cladding	Excluded	Exclude	1
2.1.02.16.0A	Localized (Pitting) Corrosion of Cladding	Excluded	Exclude	1
2.1.02.17.0A	Localized (Crevice) Corrosion of Cladding	Excluded	Exclude	1
2.1.02.18.0A	Enhanced Corrosion of Cladding from	Excluded	Exclude	1

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	Dissolved Silica			
2.1.02.19.0A	*Creep Rupture of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.20.0A	*Internal Pressurization of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.21.0A	*Stress Corrosion Cracking (SCC) of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.22.0A	*Hydride Cracking of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.23.0A	*Cladding Unzipping*	*Included*	*Exclude*	*1*
2.1.02.24.0A	*Mechanical Impact on Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.25.0A	*DSNF Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.25.0B	*Naval SNf Cladding*	*Included*	*Exclude*	*1 Exclude Naval SNF from analysis completely*
2.1.02.26.0A	*Diffusion-Controlled Cavity Growth in Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.27.0A	*Localized (Fluoride Enhanced) Corrosion of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.28.0A	*Grouping of DSNF Waste Types Into Categories*	*Included*	*Exclude*	*1*
2.1.02.29.0A	*Flammable Gas Generation from DSNF*	*Excluded*	*Exclude*	*1*
2.1.03.01.0A	*General Corrosion of Waste Packages*	*Included*	*Exclude*	*1 Assume no flow barrier credit for WP*
2.1.03.01.0B	*General Corrosion of Drip Shields*	*Included*	*Exclude (NA)*	*1*
2.1.03.02.0A	*Stress Corrosion Cracking (SCC) of Waste Packages*	*Included*	*Exclude*	*1*
2.1.03.02.0B	*Stress Corrosion Cracking (SCC) of Drip Shields*	*Excluded*	*Exclude (NA)*	*1*
2.1.03.03.0A	*Localized Corrosion of Waste Packages*	*Included*	*Exclude*	*1*
2.1.03.03.0B	*Localized Corrosion of Drip Shields*	*Excluded*	*Exclude*	*1*
2.1.03.04.0A	*Hydride Cracking of Waste Packages*	*Excluded*	*Exclude*	*1*
2.1.03.04.0B	*Hydride Cracking of Drip Shields*	*Excluded*	*Exclude (NA)*	*1*
2.1.03.05.0A	*Microbially Influenced Corrosion (MIC) of Waste Packages*	*Included*	*Exclude*	*1*
2.1.03.05.0B	*Microbially Influenced Corrosion (MIC) of Drip Shields*	*Excluded*	*Exclude*	*1*
2.1.03.06.0A	*Internal Corrosion of Waste Packages Prior to Breach*	*Excluded*	*Exclude*	*1*
2.1.03.07.0A	*Mechanical Impact on Waste Package*	*Excluded*	*Exclude*	*1 This FEP includes all damage to WPs after emplacement*
2.1.03.07.0B	*Mechanical Impact on Drip Shield*	*Excluded*	*Exclude (NA)*	*1*
2.1.03.08.0A	*Early Failure of Waste Packages*	*Included*	*Exclude*	*1*
2.1.03.08.0B	*Early Failure of Drip Shields*	*Included*	*Exclude (NA)*	*1*
2.1.03.09.0A	*Copper Corrosion in EBS*	*Excluded*	*Exclude*	*1*
2.1.03.10.0A	*Advection of Liquids and Solids Through Cracks in the Waste Package*	*Excluded*	*Exclude*	*1*
2.1.03.10.0B	*Advection of Liquids and Solids Through Cracks in the Drip Shield*	*Excluded*	*Exclude (NA)*	*1*
2.1.03.11.0A	*Physical Form of Waste Package and Drip*	*Included*	*Include*	*1*

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	Shield			
2.1.04.01.0A	*Flow in the Backfill*	*Excluded*	*Include*	*1* *Include FEPs that degrade backfill by assuming no credit due to difficulty in ensuring full emplacement*
2.1.04.02.0A	*Chemical Properties and Evolution of Backfill*	*Excluded*	*Include*	*1*
2.1.04.03.0A	*Erosion or Dissolution of Backfill*	*Excluded*	*Include*	*1*
2.1.04.04.0A	*Thermal-Mechanical Effects of Backfill*	*Excluded*	*Include*	*1*
2.1.04.05.0A	*Thermal-Mechanical Properties and Evolution of Backfill*	*Excluded*	*Include*	*1*
2.1.04.09.0A	*Radionuclide Transport in Backfill*	*Excluded*	*Exclude*	*1* *Exclude beneficial transport effects of backfill because of difficulty in ensuring full emplacement*
2.1.05.01.0A	*Flow Through Seals (Access Ramps and Ventilation Shafts)*	*Excluded*	*Include*	*3*
2.1.05.02.0A	*Radionuclide Transport Through Seals*	*Excluded*	*Include*	*3*
2.1.05.03.0A	*Degradation of Seals*	*Excluded*	*Include*	*3*
2.1.06.01.0A	*Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS*	*Excluded*	*Include (Seals are EBS, so one entire release pathway to RMEI is in EBS)*	*3*
2.1.06.02.0A	*Mechanical Effects of Rock Reinforcement Materials in EBS*	*Excluded*	*Include*	*3* *What happens to borehole seal as casing degrades?*
2.1.06.04.0A	*Flow Through Rock Reinforcement Materials in EBS*	*Excluded*	*Exclude*	*1*
2.1.06.05.0A	*Mechanical Degradation of Emplacement Pallet*	*Excluded*	*Exclude (NA)*	*1*
2.1.06.05.0B	*Mechanical Degradation of Invert*	*Excluded*	*Exclude (NA)*	*1*
2.1.06.05.0C	*Chemical Degradation of Emplacement Pallet*	*Included*	*Exclude (NA)*	*1*
2.1.06.05.0D	*Chemical Degradation of Invert*	*Excluded*	*Exclude (NA)*	*1*
2.1.06.06.0A	*Effects of Drip Shield on Flow*	*Included*	*Exclude (NA)*	*1*
2.1.06.06.0B	*Oxygen Embrittlement of Drip Shields*	*Excluded*	*Exclude (NA)*	*1*
2.1.06.07.0A	*Chemical Effects at EBS Component Interfaces*	*Excluded*	*Include?*	*2*
2.1.06.07.0B	*Mechanical Effects at EBS Component Interfaces*	*Excluded*	*Include*	*3*
2.1.07.01.0A	*Rockfall*	*Excluded*	*Exclude*	*1*
2.1.07.02.0A	*Drift Collapse*	*Excluded*	*Exclude*	*1* *If drift = borehole,*

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
				then this is a potentially significant operational FEP
2.1.07.04.0A	Hydrostatic Pressure on Waste Package	Excluded	Include	2
2.1.07.04.0B	Hydrostatic Pressure on Drip Shield	Excluded	Exclude (NA)	1
2.1.07.05.0A	Creep of Metallic Materials in the Waste Package	Excluded	Exclude	1
2.1.07.05.0B	Creep of Metallic Materials in the Drip Shield	Excluded	Exclude (NA)	1
2.1.07.06.0A	Floor Buckling	Excluded	Exclude	1
2.1.08.01.0A	Water Influx at the Repository	Included	Include	1
2.1.08.01.0B	Effects of Rapid Influx into the Repository	Excluded	Exclude	1
2.1.08.02.0A	Enhanced Influx at the Repository	Included	Exclude	1
2.1.08.03.0A	Repository Dry-Out Due to Waste Heat	Included	Include	1
2.1.08.04.0A	Condensation Forms on Roofs of Drifts (Drift-Scale Cold Traps)	Included	Exclude	1
2.1.08.04.0B	Condensation Forms at Repository Edges (Repository-Scale Cold Traps)	Included	Exclude	1
2.1.08.05.0A	Flow Through Invert	Included	Exclude (NA)	1
2.1.08.06.0A	Capillary Effects (Wicking) in EBS	Included	Exclude	1
2.1.08.07.0A	Unsaturated Flow in the EBS	Included	Exclude	1
2.1.08.09.0A	Saturated Flow in the EBS	Excluded	Include	3
2.1.08.11.0A	Repository Resaturation Due to Waste Cooling	Included	Include	1
2.1.08.12.0A	Induced Hydrologic Changes in Invert	Excluded	Exclude (NA)	1
2.1.08.14.0A	Condensation on Underside of Drip Shield	Excluded	Exclude (NA)	1
2.1.08.15.0A	Consolidation of EBS Components	Excluded	Include	3
2.1.09.01.0A	Chemical Characteristics of Water in Drifts	Included	Include	3
2.1.09.01.0B	Chemical Characteristics of Water in Waste Package	Included	Include	3
2.1.09.02.0A	Chemical Interaction With Corrosion Products	Included	Include	3
2.1.09.03.0A	Volume Increase of Corrosion Products Impacts Cladding	Excluded	Exclude	1
2.1.09.03.0B	Volume Increase of Corrosion Products Impacts Waste Package	Excluded	Exclude	1
2.1.09.03.0C	Volume Increase of Corrosion Products Impacts Other EBS Components	Excluded	Exclude	1
2.1.09.04.0A	Radionuclide Solubility, Solubility Limits, and Speciation in the Waste Form and EBS	Included	Include	3
2.1.09.05.0A	Sorption of Dissolved Radionuclides in EBS	Included	Include	3
2.1.09.06.0A	Reduction-Oxidation Potential in Waste Package	Included	Include	1
2.1.09.06.0B	Reduction-Oxidation Potential in Drifts	Included	Include	1
2.1.09.07.0A	Reaction Kinetics in Waste Package	Included	Exclude	2
2.1.09.07.0B	Reaction Kinetics in Drifts	Included	Exclude	2
2.1.09.08.0A	Diffusion of Dissolved Radionuclides in EBS	Included	Include	3
2.1.09.08.0B	Advection of Dissolved Radionuclides in EBS	Included	Include	3
2.1.09.09.0A	Electrochemical Effects in EBS	Excluded	Exclude	1
2.1.09.10.0A	Secondary Phase Effects on Dissolved	Excluded	Include	2

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	Radionuclide Concentrations			
2.1.09.11.0A	*Chemical Effects of Waste-Rock Contact*	*Excluded*	*Include*	*2*
2.1.09.12.0A	*Rind (Chemically Altered Zone) Forms in the Near-Field*	*Excluded*	*Exclude*	*2*
2.1.09.13.0A	*Complexation in EBS*	*Excluded*	*Exclude*	*2*
2.1.09.15.0A	*Formation of True (Intrinsic) Colloids in EBS*	*Excluded*	*Exclude*	*1*
2.1.09.16.0A	*Formation of Pseudo-Colloids (Natural) in EBS*	*Included*	*Exclude*	*1*
2.1.09.17.0A	*Formation of Pseudo-Colloids (Corrosion Product) in EBS*	*Included*	*Exclude*	*1*
2.1.09.18.0A	*Formation of Microbial Colloids in EBS*	*Excluded*	*Exclude*	*1*
2.1.09.19.0A	*Sorption of Colloids in EBS*	*Excluded*	*Exclude*	*1*
2.1.09.19.0B	*Advection of Colloids in EBS*	*Included*	*Exclude*	*1*
2.1.09.20.0A	*Filtration of Colloids in EBS*	*Excluded*	*Exclude*	*1*
2.1.09.21.0A	*Transport of Particles Larger Than Colloids in EBS*	*Excluded*	*Exclude*	*1*
2.1.09.21.0B	*Transport of Particles Larger Than Colloids in the SZ*	*Excluded*	*Exclude*	*1*
2.1.09.21.0C	*Transport of Particles Larger Than Colloids in the UZ*	*Excluded*	*Exclude*	*1*
2.1.09.22.0A	*Sorption of Colloids at Air-Water Interface*	*Excluded*	*Exclude*	*1*
2.1.09.23.0A	*Stability of Colloids in EBS*	*Included*	*Include*	*3*
2.1.09.24.0A	*Diffusion of Colloids in EBS*	*Included*	*Include*	*3*
2.1.09.25.0A	*Formation of Colloids (Waste-Form) By Co-Precipitation in EBS*	*Included*	*Include*	*?*
2.1.09.26.0A	*Gravitational Settling of Colloids in EBS*	*Excluded*	*Exclude*	*1*
2.1.09.27.0A	*Coupled Effects on Radionuclide Transport in EBS*	*Excluded*	*Include*	*2*
2.1.09.28.0A	*Localized Corrosion on Waste Package Outer Surface Due to Deliquescence*	*Excluded*	*Exclude*	*1*
2.1.09.28.0B	*Localized Corrosion on Drip Shield Surfaces Due to Deliquescence*	*Excluded*	*Exclude (NA)*	*1*
2.1.10.01.0A	*Microbial Activity in EBS*	*Excluded*	*Include*	*2*
2.1.11.01.0A	*Heat Generation in EBS*	*Included*	*Include*	*3*
2.1.11.02.0A	*Non-Uniform Heat Distribution in EBS*	*Included*	*Include*	*3*
2.1.11.03.0A	*Exothermic Reactions in the EBS*	*Excluded*	*Exclude*	*1*
2.1.11.05.0A	*Thermal Expansion/Stress of in-Package EBS Components*	*Excluded*	*Exclude*	*1*
2.1.11.06.0A	*Thermal Sensitization of Waste Packages*	*Excluded*	*Exclude*	*1*
2.1.11.06.0B	*Thermal Sensitization of Drip Shields*	*Excluded*	*Exclude*	*1*
2.1.11.07.0A	*Thermal Expansion/Stress of in-Drift EBS Components*	*Excluded*	*Include*	*3 This may be where thermal-mechanical effects on the seals is captured*
2.1.11.08.0A	*Thermal Effects on Chemistry and Microbial Activity in the EBS*	*Included*	*Include*	*3*
2.1.11.09.0A	*Thermal Effects on Flow in the EBS*	*Included*	*Include*	*3*
2.1.11.09.0B	*Thermally-Driven Flow (Convection) in Waste Packages*	*Excluded*	*Exclude*	*1*
2.1.11.09.0C	*Thermally Driven Flow (Convection) in Drifts*	*Included*	*Include*	*3*

FEP Number	*FEP Name*	*YMP Screening Decision*	*Likely DBD Decision*	*Estimated DBD Level of Effort*
				Drifts = boreholes with waste
2.1.11.10.0A	*Thermal Effects on Transport in EBS*	*Excluded*	*Include*	*3*
2.1.12.01.0A	*Gas Generation (Repository Pressurization)*	*Excluded*	*Exclude*	*3 Need to consider gas pressure effects on seals*
2.1.12.02.0A	*Gas Generation (He) from Waste Form Decay*	*Excluded*	*Exclude*	*3*
2.1.12.03.0A	*Gas Generation (H_2) from Waste Package Corrosion*	*Excluded*	*Exclude*	*3*
2.1.12.04.0A	*Gas Generation (CO_2, CH_4, H_2S) from Microbial Degradation*	*Excluded*	*Include*	*2*
2.1.12.06.0A	*Gas Transport in EBS*	*Excluded*	*Exclude*	*2*
2.1.12.07.0A	*Effects of Radioactive Gases in EBS*	*Excluded*	*Exclude*	*1*
2.1.12.08.0A	*Gas Explosions in EBS*	*Excluded*	*Exclude*	*1*
2.1.13.01.0A	*Radiolysis*	*Excluded*	*Exclude*	*3*
2.1.13.02.0A	*Radiation Damage in EBS*	*Excluded*	*Exclude*	*1*
2.1.13.03.0A	*Radiological Mutation of Microbes*	*Excluded*	*Include*	*1*
2.1.14.15.0A	*In-Package Criticality (Intact Configuration)*	*Excluded*	*Exclude*	*3*
2.1.14.16.0A	*In-Package Criticality (Degraded Configurations)*	*Excluded*	*Exclude*	*3 Criticality exclusion on Prob. of geometry? Consequence is low, but hard to quantify because of thermal effects*
2.1.14.17.0A	*Near-Field Criticality*	*Excluded*	*Exclude*	*2*
2.1.14.18.0A	*In-Package Criticality Resulting from a Seismic Event (Intact Configuration)*	*Excluded*	*Exclude*	*1*
2.1.14.19.0A	*In-Package Criticality Resulting from a Seismic Event (Degraded Configurations)*	*Excluded*	*Exclude*	*1*
2.1.14.20.0A	*Near-Field Criticality Resulting from a Seismic Event*	*Excluded*	*Exclude*	*1*
2.1.14.21.0A	*In-Package Criticality Resulting from Rockfall (Intact Configuration)*	*Excluded*	*Exclude*	*1*
2.1.14.22.0A	*In-Package Criticality Resulting from Rockfall (Degraded Configurations)*	*Excluded*	*Exclude*	*1*
2.1.14.23.0A	*Near-Field Criticality Resulting from Rockfall*	*Excluded*	*Exclude*	*1*
2.1.14.24.0A	*In-Package Criticality Resulting from an Igneous Event (Intact Configuration)*	*Excluded*	*Exclude*	*2*
2.1.14.25.0A	*In-Package Criticality Resulting from an Igneous Event (Degraded Configurations)*	*Excluded*	*Exclude*	*2*
2.1.14.26.0A	*Near-Field Criticality Resulting from an Igneous Event*	*Excluded*	*Exclude*	*1*
2.2.01.01.0A	*Mechanical Effects of Excavation and Construction in the Near-Field*	*Included*	*Include*	*3 High K pathways around borehole*
2.2.01.01.0B	*Chemical Effects of Excavation and Construction in the Near-Field*	*Excluded*	*Include*	*2 Altered rock properties near*

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
				borehole
2.2.01.02.0A	Thermally-Induced Stress Changes in the Near-Field	Excluded	Include	3
2.2.01.02.0B	Chemical Changes in the Near-Field from Backfill	Excluded	Exclude	1
2.2.01.03.0A	Changes In Fluid Saturations in the Excavation Disturbed Zone	Excluded	Exclude	1
2.2.01.04.0A	Radionuclide Solubility in the Excavation Disturbed Zone	Excluded	Include	2
2.2.01.05.0A	Radionuclide Transport in the Excavation Disturbed Zone	Excluded	Include	3
2.2.03.01.0A	Stratigraphy	Included	Include	1
2.2.03.02.0A	Rock Properties of Host Rock and Other Units	Included	Include	1
2.2.06.01.0A	Seismic Activity Changes Porosity and Permeability of Rock	Excluded	Exclude	1
2.2.06.02.0A	Seismic Activity Changes Porosity and Permeability of Faults	Excluded	Exclude	1
2.2.06.02.0B	Seismic Activity Changes Porosity and Permeability of Fractures	Excluded	Exclude	1
2.2.06.03.0A	Seismic Activity Alters Perched Water Zones	Excluded	Exclude	1
2.2.06.04.0A	Effects of Subsidence	Excluded	Exclude	1
2.2.06.05.0A	Salt Creep	Excluded	Exclude	1
2.2.07.01.0A	Locally Saturated Flow at Bedrock/Alluvium Contact	Excluded	Exclude	1
2.2.07.02.0A	Unsaturated Groundwater Flow in the Geosphere	Included	Exclude	1
2.2.07.03.0A	Capillary Rise in the UZ	Included	Exclude	1
2.2.07.04.0A	Focusing of Unsaturated Flow (Fingers, Weeps)	Included	Exclude	1
2.2.07.05.0A	Flow in the UZ from Episodic Infiltration	Excluded	Exclude	1
2.2.07.06.0A	Episodic Or Pulse Release from Repository	Excluded	Exclude	1
2.2.07.06.0B	Long-Term Release of Radionuclides from The Repository	Included	Include	2
2.2.07.07.0A	Perched Water Develops	Included	Exclude	1
2.2.07.08.0A	Fracture Flow in the UZ	Included	Exclude	1
2.2.07.09.0A	Matrix Imbibition in the UZ	Included	Exclude	1
2.2.07.10.0A	Condensation Zone Forms Around Drifts	Included	Exclude	1
2.2.07.11.0A	Resaturation of Geosphere Dry-Out Zone	Included	Include	1
2.2.07.12.0A	Saturated Groundwater Flow in the Geosphere	Included	Include	3 This is one of two release pathways (EBS transport through seals is the other)
2.2.07.13.0A	Water-Conducting Features in the SZ	Included	Included	3
2.2.07.14.0A	Chemically-Induced Density Effects on Groundwater Flow	Excluded	Exclude	1
2.2.07.15.0A	Advection and Dispersion in the SZ	Included	Include	3
2.2.07.15.0B	Advection and Dispersion in the UZ	Included	Exclude	1
2.2.07.16.0A	Dilution of Radionuclides in Groundwater	Included	Include	1

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
2.2.07.17.0A	Diffusion in the SZ	Included	Include	3
2.2.07.18.0A	Film Flow into the Repository	Included	Exclude	1
2.2.07.19.0A	Lateral Flow from Solitario Canyon Fault Enters Drifts	Included	Exclude (NA)	1
2.2.07.20.0A	Flow Diversion Around Repository Drifts	Included	Exclude	1
2.2.07.21.0A	Drift Shadow Forms Below Repository	Excluded	Exclude	1
2.2.08.01.0A	Chemical Characteristics of Groundwater in the SZ	Included	Include	1
2.2.08.01.0B	Chemical Characteristics of Groundwater in the UZ	Included	Exclude	1
2.2.08.03.0A	Geochemical Interactions and Evolution in the SZ	Excluded	Include	2
2.2.08.03.0B	Geochemical Interactions and Evolution in the UZ	Excluded	Exclude	1
2.2.08.04.0A	Re-Dissolution of Precipitates Directs More Corrosive Fluids to Waste Packages	Excluded	Exclude	1
2.2.08.05.0A	Diffusion in the UZ	Excluded	Exclude	1
2.2.08.06.0A	Complexation in the SZ	Included	Include?	?
2.2.08.06.0B	Complexation in the UZ	Included	Exclude	1
2.2.08.07.0A	Radionuclide Solubility Limits in the SZ	Excluded	Include	2
2.2.08.07.0B	Radionuclide Solubility Limits in the UZ	Excluded	Exclude	1
2.2.08.07.0C	Radionuclide Solubility Limits in the Biosphere	Excluded	Exclude	1
2.2.08.08.0A	Matrix Diffusion in the SZ	Included	Include	3
2.2.08.08.0B	Matrix Diffusion in the UZ	Included	Exclude	1
2.2.08.09.0A	Sorption in the SZ	Included	Include	3
2.2.08.09.0B	Sorption in the UZ	Included	Exclude	1
2.2.08.10.0A	Colloidal Transport in the SZ	Included	Include	3
2.2.08.10.0B	Colloidal Transport in the UZ	Included	Exclude	1
2.2.08.11.0A	Groundwater Discharge to Surface Within The Reference Biosphere	Excluded	Exclude	1
2.2.08.12.0A	Chemistry of Water Flowing into the Drift	Included	Include	2
2.2.08.12.0B	Chemistry of Water Flowing into the Waste Package	Included	Include	2
2.2.09.01.0A	Microbial Activity in the SZ	Excluded	Include	2
2.2.09.01.0B	Microbial Activity in the UZ	Excluded	Include	1
2.2.10.01.0A	Repository-Induced Thermal Effects on Flow in the UZ	Excluded	Exclude	1
2.2.10.02.0A	Thermal Convection Cell Develops in SZ	Excluded	Exclude ??	3
2.2.10.03.0A	Natural Geothermal Effects on Flow in the SZ	Included	Include	2
2.2.10.03.0B	Natural Geothermal Effects on Flow in the UZ	Included	Exclude	1
2.2.10.04.0A	Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository	Excluded	Exclude ??	3
2.2.10.04.0B	Thermo-Mechanical Stresses Alter Characteristics of Faults Near Repository	Excluded	Exclude ??	3
2.2.10.05.0A	Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below The Repository	Excluded	Exclude ??	3
2.2.10.06.0A	Thermo-Chemical Alteration in the UZ (Solubility, Speciation, Phase Changes,	Excluded	Exclude	1

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	Precipitation/Dissolution)			
2.2.10.07.0A	Thermo-Chemical Alteration of the Calico Hills Unit	Excluded	Exclude (NA)	1
2.2.10.08.0A	Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)	Excluded	Exclude ??	3
2.2.10.09.0A	Thermo-Chemical Alteration of the Topopah Spring Basal Vitrophyre	Excluded	Exclude (NA)	1
2.2.10.10.0A	Two-Phase Buoyant Flow/Heat Pipes	Included	Exclude	1
2.2.10.11.0A	Natural Air Flow in the UZ	Excluded	Exclude	1
2.2.10.12.0A	Geosphere Dry-Out Due to Waste Heat	Included	Include	1
2.2.10.13.0A	Repository-Induced Thermal Effects on Flow in the SZ	Excluded	Include ??	3
2.2.10.14.0A	Mineralogic Dehydration Reactions	Excluded	Exclude ??	3
2.2.11.01.0A	Gas Effects in the SZ	Excluded	Exclude	2
2.2.11.02.0A	Gas Effects in the UZ	Excluded	Exclude	1
2.2.11.03.0A	Gas Transport in Geosphere	Excluded	Exclude	1
2.2.12.00.0A	Undetected Features in the UZ	Excluded	Exclude	1
2.2.12.00.0B	Undetected Features in the SZ	Included	Include	1
2.2.14.09.0A	Far-Field Criticality	Excluded	Exclude	1
2.2.14.10.0A	Far-Field Criticality Resulting from a Seismic Event	Excluded	Exclude	1
2.2.14.11.0A	Far-Field Criticality Resulting from Rockfall	Excluded	Exclude	1
2.2.14.12.0A	Far-Field Criticality Resulting from an Igneous Event	Excluded	Exclude	1
2.3.01.00.0A	Topography and Morphology	Included	Exclude	1
2.3.02.01.0A	Soil Type	Included	Include	1 (Biosphere model inputs are all "included" assuming well water and farming)
2.3.02.02.0A	Radionuclide Accumulation in Soils	Included	Include	1
2.3.02.03.0A	Soil and Sediment Transport in the Biosphere	Included	Exclude	1
2.3.04.01.0A	Surface Water Transport and Mixing	Included	Exclude	1
2.3.06.00.0A	Marine Features	Excluded	Exclude	1
2.3.09.01.0A	Animal Burrowing/Intrusion	Excluded	Exclude	1
2.3.11.01.0A	Precipitation	Included	Exclude	1
2.3.11.02.0A	Surface Runoff and Evapotranspiration	Included	Exclude	1
2.3.11.03.0A	Infiltration and Recharge	Included	Exclude	1
2.3.11.04.0A	Groundwater Discharge to Surface Outside The Reference Biosphere	Excluded	Exclude	1
2.3.13.01.0A	Biosphere Characteristics	Included	Include	1 Assume well pumps from SZ at location of borehole
2.3.13.02.0A	Radionuclide Alteration During Biosphere Transport	Included	Include	1
2.3.13.03.0A	Effects of Repository Heat on The Biosphere	Excluded	Exclude	1
2.3.13.04.0A	Radionuclide Release Outside The Reference Biosphere	Excluded	Exclude	1
2.4.01.00.0A	Human Characteristics (Physiology,	Included	Include	1

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	Metabolism)			
2.4.04.01.0A	*Human Lifestyle*	*Included*	*Include*	*1*
2.4.07.00.0A	*Dwellings*	*Included*	*Include*	*1*
2.4.08.00.0A	*Wild and Natural Land and Water Use*	*Included*	*Include*	*1*
2.4.09.01.0A	*Implementation of New Agricultural Practices Or Land Use*	*Excluded*	*Exclude*	*1*
2.4.09.01.0B	*Agricultural Land Use and Irrigation*	*Included*	*Include*	*1*
2.4.09.02.0A	*Animal Farms and Fisheries*	*Included*	*Include*	*1*
2.4.10.00.0A	*Urban and Industrial Land and Water Use*	*Included*	*Include*	*1*
3.1.01.01.0A	*Radioactive Decay and Ingrowth*	*Included*	*Include*	*1*
3.2.07.01.0A	*Isotopic Dilution*	*Excluded*	*Exclude*	*1*
3.2.10.00.0A	*Atmospheric Transport of Contaminants*	*Included*	*Exclude*	*1*
3.3.01.00.0A	*Contaminated Drinking Water, Foodstuffs and Drugs*	*Included*	*Include*	*1*
3.3.02.01.0A	*Plant Uptake*	*Included*	*Include*	*1*
3.3.02.02.0A	*Animal Uptake*	*Included*	*Include*	*1*
3.3.02.03.0A	*Fish Uptake*	*Included*	*Include*	*1*
3.3.03.01.0A	*Contaminated Non-Food Products and Exposure*	*Included*	*Include*	*1*
3.3.04.01.0A	*Ingestion*	*Included*	*Include*	*1*
3.3.04.02.0A	*Inhalation*	*Included*	*Include*	*1*
3.3.04.03.0A	*External Exposure*	*Included*	*Include*	*1*
3.3.05.01.0A	*Radiation Doses*	*Included*	*Include*	*1*
3.3.06.00.0A	*Radiological Toxicity and Effects*	*Excluded*	*Exclude*	*1*
3.3.06.01.0A	*Repository Excavation*	*Excluded*	*Exclude*	*1*
3.3.06.02.0A	*Sensitization to Radiation*	*Excluded*	*Exclude*	*1*
3.3.07.00.0A	*Non-Radiological Toxicity and Effects*	*Excluded*	*Exclude*	*1*
3.3.08.00.0A	*Radon and Radon Decay Product Exposure*	*Included*	*Include*	*1*

CSNF = commercial SNF, DSNF = DOE-owned SNF, EBS = Engineered Barrier System, HLW = high-level waste, MIC = microbially influenced corrosion, SNF = spent nuclear fuel, SSC = stress corrosion cracking, SZ = saturated zone, UZ = unsaturated zone.

Table B-2. High Priority Borehole FEPs – Excluded FEPs That Need New Technical Work and Included FEPs That Require Significant Modeling or Possible Model Changes.

FEP Number	*FEP Name*	*Likely DBD Decision*	*Estimated DB Level of Effort*
0.1.09.00.0A	*Regulatory Requirements and Exclusions*	*Include*	*3 Regulations and laws will need to be revised*
1.1.02.00.0A	*Chemical Effects of Excavation and Construction in EBS*	*Exclude*	*2*
1.1.02.00.0B	*Mechanical Effects of Excavation and Construction in EBS*	*Include*	*2*
1.1.02.03.0A	*Undesirable Materials Left*	*Exclude (NA)*	*2*
1.1.03.01.0A	*Error in Waste Emplacement*	*Exclude*	*3 Need to consider the emplacement that gets stuck halfway down. Also need to consider canisters that are crushed by overlying canisters*
1.1.04.01.0A	*Incomplete Closure*	*Exclude*	*2*
1.1.13.00.0A	*Retrievability*	*Exclude (policy)*	*2*
1.2.02.01.0A	*Fractures*	*Include*	*2*
1.2.02.02.0A	*Faults*	*Include*	*2*
1.2.02.03.0A	*Fault Displacement Damages EBS Components*	*Include?*	*2 Note—if no credit is taken for WP and WF components, all EBS FEPs are simplified to the consideration of the borehole seals*
1.2.03.02.0A	*Seismic Ground Motion Damages EBS Components*	*Exclude*	*2*
1.2.04.02.0A	*Igneous Activity Changes Rock Properties*	*Exclude*	*2 Need to evaluate potential for igneous activity at each site (should generically be low), also need to determine if repository heat can contribute to rock melting*
1.2.04.03.0A	*Igneous Intrusion Into Repository*	*Exclude*	*2*
1.2.04.04.0A	*Igneous Intrusion Interacts With EBS Components*	*Exclude*	*2*
1.2.04.04.0B	*Chemical Effects of Magma and Magmatic Volatiles*	*Exclude*	*2 Volatiles may impact transport*

FEP Number	*FEP Name*	*Likely DBD Decision*	*Estimated DB Level of Effort*
1.2.04.06.0A	*Eruptive Conduit to Surface Intersects Repository*	*Exclude*	*2*
1.2.05.00.0A	*Metamorphism*	*Exclude*	*2 Repository heat may create metamorphic conditions*
1.2.06.00.0A	*Hydrothermal Activity*	*Exclude*	*3 Repository heat may creat local hydrothermal activity*
1.2.08.00.0A	*Diagenesis*	*Exclude*	*2*
1.2.09.01.0A	*Diapirism*	*Exclude*	*2 Need to demonstrate that repository heat will not generate local diapirism*
1.2.10.02.0A	*Hydrologic Response to Igneous Activity*	*Exclude*	*2*
1.3.07.02.0B	*Water Table Rise Affects UZ*	*Exclude*	*1 All UZ FEPs are simplified*
1.4.02.02.0A	*Inadvertent Human Intrusion*	*Exclude*	*1 (requires regulatory change)*
2.1.02.02.0A	*CSNF Degradation (Alteration, Dissolution, and Radionuclide Release)*	*Exclude*	*1 Assume no credit for CSNF waste form*
2.1.02.03.0A	*HLW Glass Degradation (Alteration, Dissolution, and Radionuclide Release)*	*Exclude*	*1 Assume no credit for HLW waste form*
2.1.05.01.0A	*Flow Through Seals (Access Ramps and Ventilation Shafts)*	*Include*	*3*
2.1.05.02.0A	*Radionuclide Transport Through Seals*	*Include*	*3*
2.1.05.03.0A	*Degradation of Seals*	*Include*	*3*
2.1.06.01.0A	*Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS*	*Include (Seals are EBS, so one entire release pathway to RMEI is in EBS)*	*3*
2.1.06.02.0A	*Mechanical Effects of Rock Reinforcement Materials in EBS*	*Include*	*3 What happens to borehole seal as casing degrades?*
2.1.06.07.0A	*Chemical Effects at EBS Component Interfaces*	*Include?*	*2*
2.1.06.07.0B	*Mechanical Effects at EBS Component Interfaces*	*Exclude?*	*3*
2.1.07.02.0A	*Drift Collapse*	*Exclude*	*1*

FEP Number	FEP Name	Likely DBD Decision	Estimated DB Level of Effort
			If drift = borehole, then this is a major operational FEP
2.1.07.04.0A	*Hydrostatic Pressure on Waste Package*	*Include*	*2*
2.1.08.09.0A	*Saturated Flow in the EBS*	*Include*	*3*
2.1.08.15.0A	*Consolidation of EBS Components*	*Include*	*3*
2.1.09.01.0A	*Chemical Characteristics of Water in Drifts*	*Include*	*3*
2.1.09.01.0B	*Chemical Characteristics of Water in Waste Package*	*Include*	*3*
2.1.09.02.0A	*Chemical Interaction With Corrosion Products*	*Include*	*3*
2.1.09.04.0A	*Radionuclide Solubility, Solubility Limits, and Speciation in the Waste Form and EBS*	*Include*	*3*
2.1.09.05.0A	*Sorption of Dissolved Radionuclides in EBS*	*Include*	*3*
2.1.09.07.0A	*Reaction Kinetics in Waste Package*	*Exclude*	*2*
2.1.09.07.0B	*Reaction Kinetics in Drifts*	*Exclude*	*2*
2.1.09.08.0A	*Diffusion of Dissolved Radionuclides in EBS*	*Include*	*3*
2.1.09.08.0B	*Advection of Dissolved Radionuclides in EBS*	*Include*	*3*
2.1.09.10.0A	*Secondary Phase Effects on Dissolved Radionuclide Concentrations*	*Include*	*2*
2.1.09.11.0A	*Chemical Effects of Waste-Rock Contact*	*Include*	*2*
2.1.09.12.0A	*Rind (Chemically Altered Zone) Forms in the Near-Field*	*Exclude*	*2*
2.1.09.13.0A	*Complexation in EBS*	*Exclude*	*2*
2.1.09.15.0A	*Formation of True (Intrinsic) Colloids in EBS*	*?*	*?*
2.1.09.16.0A	*Formation of Pseudo-Colloids (Natural) in EBS*	*?*	*?*
2.1.09.17.0A	*Formation of Pseudo-Colloids (Corrosion Product) in EBS*	*?*	*?*
2.1.09.18.0A	*Formation of Microbial Colloids in EBS*	*?*	*?*
2.1.09.19.0A	*Sorption of Colloids in EBS*	*Include?*	*2*
2.1.09.19.0B	*Advection of Colloids in EBS*	*Include?*	*2*
2.1.09.20.0A	*Filtration of Colloids in EBS*	*Include?*	*2*
2.1.09.23.0A	*Stability of Colloids in EBS*	*Include*	*3*
2.1.09.24.0A	*Diffusion of Colloids in EBS*	*Include*	*3*
2.1.09.25.0A	*Formation of Colloids (Waste-Form) By Co-Precipitation in EBS*	*Include*	*?*
2.1.09.26.0A	*Gravitational Settling of Colloids in EBS*	*?*	*?*
2.1.09.27.0A	*Coupled Effects on Radionuclide Transport in EBS*	*?*	*?*
2.1.10.01.0A	*Microbial Activity in EBS*	*Include*	*2*
2.1.11.01.0A	*Heat Generation in EBS*	*Include*	*3*
2.1.11.02.0A	*Non-Uniform Heat Distribution in EBS*	*Include*	*3*
2.1.11.07.0A	*Thermal Expansion/Stress of in-Drift EBS Components*	*Include*	*3 This may be where thermal-mechanical effects on the seals is captured*
2.1.11.08.0A	*Thermal Effects on Chemistry and Microbial Activity in the EBS*	*Include*	*3*
2.1.11.09.0A	*Thermal Effects on Flow in the EBS*	*Include*	*3*
2.1.11.09.0C	*Thermally Driven Flow (Convection) in Drifts*	*Include*	*3*

FEP Number	*FEP Name*	*Likely DBD Decision*	*Estimated DB Level of Effort*
			Drifts = boreholes with waste
2.1.11.10.0A	*Thermal Effects on Transport in EBS*	*Include*	*3*
2.1.12.01.0A	*Gas Generation (Repository Pressurization)*	*Exclude*	*3 Need to consider gas pressure effects on seals*
2.1.12.02.0A	*Gas Generation (He) from Waste Form Decay*	*Exclude*	*3*
2.1.12.03.0A	*Gas Generation (H_2) from Waste Package Corrosion*	*Exclude*	*3*
2.1.12.04.0A	*Gas Generation (CO_2, CH_4, H_2S) from Microbial Degradation*	*Include*	*2*
2.1.12.06.0A	*Gas Transport in EBS*	*Exclude*	*2*
2.1.13.01.0A	*Radiolysis*	*Exclude*	*3*
2.1.14.15.0A	*In-Package Criticality (Intact Configuration)*	*Exclude*	*3*
2.1.14.16.0A	*In-Package Criticality (Degraded Configurations)*	*Exclude*	*3 Criticality exclusion on Prob. of geometry? Consequence is low, but hard to quantify because of thermal effects.*
2.1.14.17.0A	*Near-Field Criticality*	*Exclude*	*2*
2.1.14.24.0A	*In-Package Criticality Resulting from an Igneous Event (Intact Configuration)*	*Exclude*	*2*
2.1.14.25.0A	*In-Package Criticality Resulting from an Igneous Event (Degraded Configurations)*	*Exclude*	*2*
2.2.01.01.0A	*Mechanical Effects of Excavation and Construction in the Near-Field*	*Include*	*3 High K pathways around borehole*
2.2.01.01.0B	*Chemical Effects of Excavation and Construction in the Near-Field*	*Include*	*2 Altered rock properties near borehole*
2.2.01.02.0A	*Thermally-Induced Stress Changes in the Near-Field*	*Include*	*3*
2.2.01.04.0A	*Radionuclide Solubility in the Excavation Disturbed Zone*	*Include*	*2*
2.2.01.05.0A	*Radionuclide Transport in the Excavation Disturbed Zone*	*Include*	*3*
2.2.07.06.0B	*Long-Term Release of Radionuclides from The Repository*	*Include*	*2*
2.2.07.12.0A	*Saturated Groundwater Flow in the Geosphere*	*Include*	*3 This is one of two release pathways (EBS transport through seals is the other)*
2.2.07.13.0A	*Water-Conducting Features in the SZ*	*Included*	*3*
2.2.07.15.0A	*Advection and Dispersion in the SZ*	*Include*	*3*
2.2.07.17.0A	*Diffusion in the SZ*	*Include*	*3*

FEP Number	*FEP Name*	*Likely DBD Decision*	*Estimated DB Level of Effort*
2.2.08.03.0A	*Geochemical Interactions and Evolution in the SZ*	*Include*	*2*
2.2.08.06.0A	*Complexation in the SZ*	*Include?*	*?*
2.2.08.07.0A	*Radionuclide Solubility Limits in the SZ*	*Include*	*2*
2.2.08.08.0A	*Matrix Diffusion in the SZ*	*Include*	*3*
2.2.08.09.0A	*Sorption in the SZ*	*Include*	*3*
2.2.08.10.0A	*Colloidal Transport in the SZ*	*Include*	*3*
2.2.08.12.0A	*Chemistry of Water Flowing into the Drift*	*Include*	*2*
2.2.08.12.0B	*Chemistry of Water Flowing into the Waste Package*	*Include*	*2*
2.2.09.01.0A	*Microbial Activity in the SZ*	*Include*	*2*
2.2.10.02.0A	*Thermal Convection Cell Develops in SZ*	*Exclude ??*	*3*
2.2.10.03.0A	*Natural Geothermal Effects on Flow in the SZ*	*Include*	*2*
2.2.10.04.0A	*Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository*	*Exclude ??*	*3*
2.2.10.04.0B	*Thermo-Mechanical Stresses Alter Characteristics of Faults Near Repository*	*Exclude ??*	*3*
2.2.10.05.0A	*Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below The Repository*	*Exclude ??*	*3*
2.2.10.08.0A	*Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)*	*Exclude ??*	*3*
2.2.10.13.0A	*Repository-Induced Thermal Effects on Flow in the SZ*	*Include ??*	*3*
2.2.10.14.0A	*Mineralogic Dehydration Reactions*	*Exclude ??*	*3*
2.2.11.01.0A	*Gas Effects in the SZ*	*Exclude*	*2*
2.3.02.01.0A	*Soil Type*	*Include*	*1 (Biosphere model inputs are all "included" assuming well water and farming)*
2.3.13.01.0A	*Biosphere Characteristics*	*Include*	*1 Assume well pumps from SZ at location of borehole*

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