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Features, Events and Processes and Performance Assessment Scenarios for Alternative Dual-Purpose Canister Disposal Concepts

Fuel Cycle Research & Development

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ACRONYMS

1-D	One-dimensional
2-D	Two-dimensional
BWR	Boiling Water Reactor
DOE	U.S. Department of Energy
DPC	Dual-Purpose Canister
DRZ	Disturbed Rock Zone
EBS	Engineered Barrier System
FEPs	Features, Events, and Processes
FY	Fiscal Year
MT	Metric Tonne
PA	Performance Assessment
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
R&D	Research and Development
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
UFD	Used Fuel Disposition

FEATURES, EVENTS AND PROCESSES AND PERFORMANCE ASSESSMENT SCENARIOS FOR ALTERNATIVE DUAL-PURPOSE CANISTER DISPOSAL CONCEPTS

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ABSTRACT

Options for disposal of commercial spent nuclear fuel could be expanded by demonstrating the safety and feasibility of directly disposing of fuel that has been stored in existing dual-purpose (storage and transportation) canisters. The safety aspects will be addressed using performance assessment, a probabilistic risk analysis methodology that has been applied to geologic disposal in the U.S. and other countries. The methodology relies on systematic identification of features, events and processes that could be significant to performance and should be included in the assessment. For the dual-purpose canister disposal application, this report identifies key features, events and processes that can distinguish direct disposal of fuel in existing dual-purpose canisters from disposal of the same fuel in smaller canisters designed specifically for disposal. It also identifies which scenarios should be considered, including nominal and human intrusion, and what numerical schemes are available and appropriate to conduct performance assessments with the expected level of detail.

Introduction

The purpose of performance assessment (PA) in evaluating the feasibility of direct disposal of spent nuclear fuel (SNF) in dual-purpose canisters (DPCs), such as those that currently exist, is to generate recommendations as to whether disposal can be accomplished safely as defined by regulatory performance objectives. The assessments will model the implementation of safety strategies developed by Pierce et al. (2013), for selected DPC disposal concepts proposed by Hardin and Voegele (2013). The PAs will evaluate significant differences, if any, in postclosure waste isolation performance for DPC direct disposal, compared with repackaging the same SNF in purpose-built containers and disposal in the same geologic setting. The hypothetical purpose-built containers could have any capacity, but would likely contain fewer SNF assemblies than DPCs.

The PAs will be generic, i.e., not site-specific, consistent with the current objectives of the Used Fuel Disposition (UFD) R&D program. This is reflected in the safety strategies, which identify and describe the functions for the engineered and natural barriers, for a total of six generic disposal concepts (Pierce et al. 2013). More concepts and variations are certainly possible, but these six (simplified to three below) are sufficient to support the safety aspects of feasibility evaluation.

This report recommends which FEPs from a comprehensive generic list (Freeze et al. 2011) should be included in a base case, and which might be included in more detailed assessments with greater detail ("simulation case" assessments). The base case is described here with a minimum number of included FEPs to facilitate model development. This report also includes a discussion of possible additional simulation cases that could be used to represent and evaluate certain FEPs with greater detail.

In general, PA models are developed for defined cases which are then grouped into scenarios or scenario classes. Scenario classes are based on separate and independent initiating conditions or events (e.g., separate nominal scenario, human intrusion scenario, etc.) so that the probability-weighted consequences for scenario each can be summed (or convolved using annual event probabilities) to assess system performance. This report recommends scenario classes for structuring assessments of DPC direct disposal safety. Finally, it briefly discusses software tools and numerical strategies that could be sufficient for implementing first a base case model, then more detailed simulation cases. Importantly, for any tool selected the PAs will be supported by side calculations, abstractions, uncertainty estimates, and other inputs.

1. Disposal Concepts for Performance Assessment

A disposal concept is defined to consist of a waste stream, geologic setting, and engineering concept of operations. Alternative concepts for disposal of commercial SNF in various settings using appropriate concepts of operation, were proposed by Hardin and Voegele (2013) based on earlier work (Hardin et al. 2012). These were reviewed by Pierce et al. (2013) who selected six representative concepts for consideration of safety strategies and performance assessment:

- **Salt** – An enclosed emplacement mode in bedded or domal salt, whereby waste packages would be emplaced on the floor and immediately covered with crushed salt backfill. A variation would emplace packages into large-diameter, vertical or horizontal boreholes constructed from underground disposal rooms or drifts. Fuel canisters would be sealed into disposal overpacks made from low-alloy steel. The host salt formation would gradually collapse onto the emplacement drifts, and the applied stress would reconsolidate the crushed salt backfill, fully encapsulating each package in salt with low porosity and very low permeability.
- **Hard-Rock Unbackfilled Open** – A repository constructed in competent rock (e.g., igneous, metamorphic or well indurated carbonate or other sedimentary rock) using in-drift emplacement, and forced ventilation for 50 to 100 years after waste emplacement. Emplacement drifts would remain open after closure (until eventual collapse). Because this concept does not use backfill or otherwise seal the emplacement rooms or drifts, its application is limited to unsaturated hydrogeologic settings. Disposal overpacks would be made from corrosion resistant materials for containment longevity in oxidizing disposal environments. Other engineered barriers (e.g., barrier coatings, drip shields, etc.) would be added as necessary for multiple-barrier defense-in-depth. This concept would be similar to that previously developed in the United States for this type of geologic setting (DOE 2008).
- **Hard Rock Backfilled Open** – For application in saturated hydrogeologic settings the repository emplacement drifts, access drifts, and other openings would be ventilated for 50 to 100 years, then backfilled with low-permeability materials at closure to prevent preferential groundwater flow. Backfill would also control rock deformation (i.e., rockfall

and drift collapse) and limit the dynamic response to seismic ground motion. Swelling clay-based materials have been proposed to ensure low-permeability given practical limitations on the consistency of backfill emplacement (which are compensated by swelling behavior). However, clay-based materials may be sensitive to elevated temperature (e.g., above 100°C), limiting thermal loading at closure and thereby extending the required duration of surface decay storage and/or repository ventilation operations (Hardin and Voegele 2013).

- **Sedimentary Unbackfilled Open** – In-drift disposal concept, designed to remain open and ventilated until the SNF age is 150 years out-of-reactor. Ground support would be designed to maintain opening stability sufficient for ventilation, and to control desiccation. At repository closure plugs and seals (but not backfill) would be installed to isolate waste packages, preventing preferential groundwater flow. Sedimentary settings would be selected for thickness and extent, low permeability, chemically reducing conditions, and tectonic stability. Peak temperature of the host rock would be limited (e.g., 100°C) to control thermal degradation. Accordingly, for hotter conditions (e.g., higher fuel burnup, less heat dissipation) longer decay storage and/or repository ventilation could be required.
- **Sedimentary Backfilled Open** – Backfill could be added as an option any time during repository operations, right up to the time of closure. All waste emplacement and other openings would be backfilled. A structural backfill (e.g., sand or gravel) could be used in conjunction with the plugs and seals discussed above, to stabilize drift collapse behavior and limit dynamic response to seismic ground motion. Backfill with low permeability would also isolate packages and reduce the need for plugs and seals. Given the thermal limitations on the unbackfilled mode above, addition of backfill might impose only minor changes in the manner and timing of disposal.
- **Cavern-Retrievable** – Storage and disposal facility developed within a few hundred meters of the ground surface, in competent rock capable of supporting large excavations (e.g., 8-m spans). Shielded, dry-cask storage systems such as those currently used for surface storage would be moved underground in the cavern, accessed by a waste handling ramp. After sufficient ventilation duration, or when the SNF age is 150 years out-of-reactor, the repository would be closed by fully encapsulating each cask with low-permeability buffer/backfill material. Each cask would be self-shielding, facilitating access to the storage/disposal cavern for maintenance, moving or retrieval of casks, and closure operations.

With the exception of the salt concept, these selected disposal concepts are open emplacement modes whereby SNF waste packages would be emplaced in open drifts and ventilated for decades to remove heat. The enclosed modes described by Hardin et al. (2012) are based on disposal concepts being studied internationally, and they involve emplacing waste packages in direct contact with buffer, backfill, liner or host rock materials. For DPC direct disposal the enclosed modes would require decay storage (or repository ventilation) of many centuries, because of higher waste package heat output. The heat dissipation properties of salt, and its tolerance for temperatures of 200°C or higher, allow emplacement and immediate backfilling of large waste packages (e.g., 32-PWR or larger) after a few decades of decay storage (Hardin and Voegele 2013).

As a simplification, backfill can be represented by the base case, and the unbackfilled cases (hard rock and sedimentary, above) can be considered when additional FEPs (e.g., rockfall, drift collapse, mechanical damage, etc.) are included in "simulation case" assessments. As a further simplification, the cavern retrievable concept can be represented by the hard rock backfilled concept. The remaining three concepts are recommended for evaluation using a base case model:

- Salt Concept
- Hard Rock Backfilled Open Concept
- Sedimentary Backfilled Open Concept

The FEPs that would be included and excluded, and the PA scenarios that would be considered in the base case model are described in the following sections. For the other concepts discussed above in this section more process-level detail would be needed, for example to represent the effects from seismic ground motion for concepts that remain open after closure. The simulation cases described in Section 3.2 would include such additional detail.

2. Previous FEP Scoping Studies

A compact, generic set of FEPs was developed from international sources and prior experience in the U.S. (Freeze et al. 2011) and is currently being used by the UFD Campaign in the disposal R&D program. The FEP list was analyzed by Vaughn et al. (2011) who identified FEPs that were included in generic performance assessments for repositories in clay/shale media, crystalline rock, salt, and the deep crystalline basement (deep borehole disposal concept). The results for these three generic mined-disposal PA models are summarized in Table 1 of this report. The 2011 study included a generic PA model for clay/shale media that is considered below for use as the base case for DPC direct disposal PA.

Among the generic FEPs, some were identified in a planning exercise ("R&D Roadmap") as warranting more investigation because of the state of knowledge and the potential impact on waste isolation performance (Nutt 2011). Among these high priority FEPs the ones likely to distinguish DPC direct disposal from other disposal concepts are shown in Table 1.

A later analysis of FEPs considered which should be included in the engineered barrier system (EBS) components of a next-generation PA (Hardin 2012). The list identifies a simpler case that could be readily implemented, and a more advanced case that could be used to evaluate impacts from additional processes and repository design features. The FEP list for the simpler case is included in Table 1 and compared to that recommended here for DPC PA.

3. Features, Events and Processes

This section identifies a minimum set of FEPs that could be included in a base case for evaluating DPC disposal safety. FEPs recommended for inclusion in a base case and more detailed "simulation" cases are listed in Table 1. Given the extent of previous FEP studies, there is little need to reiterate except to point out which FEPs are needed to distinguish DPC direct disposal from repackaging and disposal of the same SNF in purpose-built disposal canisters.

The base case and simulation cases reference a disposal system architecture (Figure 1). This depiction is adapted to both advection and diffusion dominated transport environments, and includes advective conditions upstream as well as downstream.

Upstream (Flow)				Upstream (Flow)			Downstream (F&T)																	
Natural System				Engineered Barrier system (EBS)															Natural System				Receptor
Recharge	Aquifer	Host Rock	EDZ	Far-Field EBS	Near-Field EBS	WP (diversion features)	Waste Form	Insert	Filler	WP (structural features)	WP (containment features)	WP Support	Clay Buffer	Envelope	Near-Field EBS (drip shield, etc.)	Backfill (access drifts, in-drift emplacement)	Liner, Ground Support, Invert	Far-Field EBS (other WPs, seals, plugs, etc.)	EDZ	Host Rock	Aquifer	Surface/UZ & Atmospheric	Biosphere

Notes:

1. Clay Buffer = Includes reservoir used to manage heat and/or multiphase flow around waste packages
2. Envelope = container for pre-fab. EBS

Figure 1. Disposal System Architecture (from Hardin 2012)

Potential differences between direct disposal of DPCs and disposal of the same SNF in packages (including canisters) designed for disposal, may include:

- **Emplacement Mode and EBS Design** – With the exception of the salt disposal concept, DPC disposal concepts are open emplacement modes that use ventilation to remove heat. Whereas the enclosed modes in crystalline and sedimentary rock types (Hardin et al. 2012) have low-permeability, clay-based swelling buffer materials directly contacting the waste package; the open modes differ with respect to materials present in the near field. For the open modes waste packages may be surrounded by void space, or by backfill installed at closure. After closure, void spaces will gradually fill with debris from rockfall and collapse. Backfill emplaced remotely in emplacement drifts will have less density and uniformity than manually emplaced buffer/backfill materials. Hence, comparisons of DPC direct disposal with other concepts involving repackaging, are likely to include effects associated with greater permeability and potential for radionuclide transport in the near field.
- **Thermal Effects (comparing DPC direct disposal to other open modes)** – The most common DPC sizes currently in use have the capacity for 24- or 32-PWR assemblies (or BWR equivalent). Future DPCs may contain more SNF, such as the Magnastor 37-PWR canister recently developed by NAC International. DPCs are not necessarily much larger than purpose-built disposal canisters, depending on the disposal concept under consideration. For example, previously in the United States the transport/aging/disposal (TAD) canister was designed to contain 21 pressurized water reactor (PWR) assemblies. A 21-PWR reference package size was recommended for open emplacement modes (Hardin et al. 2012). In both applications the 21-PWR size reduces the number of packages required to dispose of the U.S. SNF inventory, compared to smaller packages used with enclosed modes, while taking advantage of thermal management by the extended ventilation that is possible with open modes.

  Peak temperatures for larger-capacity packages can be controlled by decay storage and repository ventilation, but post-peak temperature will remain higher for hundreds to thousands of years. (Aging can attenuate short-lived fission products, but larger packages contain more heat-generating actinides with intermediate half-lives, such as ^{241}Am.)

Thus, although the peak drift wall temperature can be managed and may be equivalent for 21 and 32 PWR sizes, for larger packages containing more SNF the peak temperature further into the host rock may be greater, and elevated temperature is likely to persist longer. In the backfill, the extent and duration of elevated temperatures (e.g., in the axial direction between packages) will also be greater. These differences can eventually impact radionuclide transport if the controlling rock and backfill characteristics are thermally sensitive. The direction of affected radionuclide transport could be radial or axial.

- **Thermal Effects (comparing DPC direct disposal to enclosed modes)** – Enclosed emplacement modes in crystalline and sedimentary rock types were shown to require 4-PWR size waste packages (or smaller) to limit peak temperature at the waste package surface to less than 100°C (Hardin et al. 2012). The additional time required for 50-year old SNF to cool by 8-fold (the difference between 32 and four assemblies per package) is on the order of 400 to 1,000 years depending on burnup. It is impractical to cool DPCs that long before disposal (see assumptions from Miller et al. 2012) and even after disposal they would have greater heat output than smaller canisters as discussed above. Thus, both the peak temperature throughout the near field, and the duration of elevated temperature, will generally be greater for in-drift disposal of DPC-based packages (with decades of repository ventilation) than for smaller packages using enclosed emplacement modes (without extended ventilation). Thermal effects from DPC direct disposal could be radial or axial as discussed above, while performance of enclosed modes would more closely resemble that analyzed for the Swedish (SKB 2011) and French (Andra 2005) SNF disposal concepts. In accordance with this discussion, assessment of DPC direct disposal should include thermal effects on the near-field environment, especially when compared with alternative enclosed modes of SNF disposal in much smaller packages.

  A notable exception to the need for small packages with enclosed emplacement modes is the salt repository concept, which can accommodate SNF waste packages up to 32-PWR size or larger (or BWR equivalent). Peak salt temperature is directly related to package thermal power at emplacement, and the power limit can be met by 32-PWR size packages with high-burnup SNF, after decay storage of approximately 70 years (Hardin and Voegele 2013). A reference 12-PWR package size was selected previously based on shaft hoist considerations (Hardin et al. 2012).

- **Quantity of SNF –** Once a waste package breach occurs more SNF will be exposed to the disposal environment with DPCs, than with smaller containers. The difference would be greatest in comparing DPCs with smaller canisters (4-PWR size) used for enclosed emplacement modes. The greatest potential for differences in radionuclide mobility would result from advection dominated transport, which is not expected for disposal concepts in low-permeability host media (except possibly for human intrusion scenarios) but might occur. Even the most massive, homogeneous sedimentary host units can be traversed by through-going discontinuities with greater permeability, such as faults or fracture zones which could act as advective pathways in and out of the emplacement drifts. The possibility for advection dominated transport is a factor of interest in the safety of DPC direct disposal, related to quantity of SNF per package.

- **Inner Canister Design** – Canisters purpose-built for disposal may have different features not found in existing DPCs, such as: inserts (in lieu of baskets); thicker shells, plates and/or spacers to extend structural lifetime in corrosion environments; thicker neutron absorbing elements that can function after 10^4 years of degradation; and fillers that can exclude moderating groundwater after package breach. Existing DPCs cannot include any of these features (assuming they cannot be reopened) which is the major reason that the potential for postclosure criticality may be greater for some disposal concepts.

For comparison of DPC direct disposal with disposal of the same waste repackaged in purpose-designed containers using the same *open* emplacement mode, performance of the SNF waste form, waste package, other engineered barriers, and the far field will be simliar (i.e., same concept and safety strategy). Relating to package size, thermal effects and inner canister design are potentially important. Impacts from inner canister design differences may be limited to the technical analysis that is relied upon to disposition postclosure criticality (FEP 2.1.14.01, see Table 1). Quantity of SNF is likely not significant for comparing packages differing only slightly in size (e.g., 21- vs. 32-PWR) but will be more important for comparing to alternative concepts involving much smaller packages (discussed below). In accordance with this discussion, the FEPs needed for comparing DPC direct disposal with similar *open* modes of emplacement are limited to an appropriate base case that includes thermal effects and advective transport of radionuclides (as well as other transport processes).

For comparing DPC disposal to disposal of the same SNF in the same host medium but smaller canisters using an *enclosed* emplacement mode, more FEPs need to be included. For example, reference enclosed crystalline or clay/shale concepts for spent fuel use 4-PWR packages encapsulated in clay-based swelling buffer/backfill, which would involve buffer degradation (FEP 2.1.04.01). The additional FEPs needed to compare *open* emplacement of DPC-based packages (with backfilling at closure) vs. *enclosed* emplacement of smaller waste packages, are included among those recommended for the base case (Table 1).

All canisters, whether existing DPCs or purpose-built for disposal, will have disposal overpacks (Hardin et al. 2012; Hardin and Voegele 2013). These will provide additional benefits to the safety of handling, transport and emplacement in the repository, and provide containment integrity for some period of time after emplacement. Disposal overpacks for existing DPCs might differ with respect to dimensions, shape and lifting features. However, for this study they can be assumed to have the same characteristics as disposal overpacks for purpose-built disposal canisters, such as material type, thickness, fabrication method, surface treatment, etc., that could affect waste isolation performance.

The value of generic assessments is increased when the assessments include comparisons to cases in which DPCs are repackaged, and the same SNF is emplaced in purpose-built waste packages in the same geologic setting.

3.1 Base Case

The base case is designed to be implemented using off-the-shelf system modeling software. As discussed in Section 5, a standardized model framework can be used, and the connectivity of model components and the uncertainty distributions describing key parameters can be modified to represent different disposal concepts. A base case model implemented this way will have limited dimensionality (e.g., 1-D or 2-D) and will rely on simplifications or abstractions, especially to represent processes in the near-field and EBS (Vaughn et al. 2011).

FEPs applicable to the base case model for DPC disposal (and for alternative concepts with smaller, purpose-built canisters) are listed in Table 1. Formulation of the base case is predicated on the following model limitations and FEP exclusion rationale:

- Preclosure events and processes do not affect postclosure performance and/or do not discriminate direct disposal of DPCs (Table 1, Section 1.1.00.00).
- Seismic and faulting events do not significantly impact the natural system and biosphere, which have been exposed to these events for geologic time (FEPs 1.2.03.02, 1.2.03.03 and 2.2.05.03).
- Mechanical degradation and seismic ground motion do not significantly affect backfilled underground systems (include FEP 2.1.07.03; exclude FEP 1.2.03.01; Table 1, Section 2.1.07.00; and FEP 2.1.11.04).
- Faulting does not affect the repository (potential slip on unrecognized faults is minor) (FEP 2.1.07.10).
- Igneous activity has very low probability of disrupting the repository (Table 1, Section 1.2.04.00).
- Other, long-term processes (tectonophysics, dissolution, astronomical) can be excluded (Table 1, Sections 1.2.01.00 and 1.5.00.00).
- Climate change (natural or anthropogenic; Table 1, Section 1.3.00.00) can be addressed in the base-case model by changing groundwater flow boundary conditions (FEP 2.2.08.03).
- Future human actions are limited to inadvertent human intrusion (Table 1, Section 1.4.00.00).
- Heterogeneity and co-location of the waste inventory (FEPs 2.1.01.03 and 2.1.01.04) can be addressed in the base case model by considering a range of age and burnup for commercial SNF without considering location in a repository.
- Cladding will be conservatively neglected in the base case (FEP 2.1.02.06) although partial credit for cladding containment may be taken in a more complete simulation case.
- Early waste package failure and modes of waste package corrosion are potentially significant for corrosion-resistant disposal overpacks, but much less so for corrosion allowance materials intended to have shorter corrosion lifetimes (FEPs 2.1.03.01 through 2.1.03.07).
- Evolution of flow pathways within failed packages can be neglected using a simplification that flow occurs within failed packages without restriction (FEP 2.1.03.08).
- Backfill is not degraded by mechanical or chemical processes (FEPs 2.1.04.01 and 2.1.07.04) although clay-based backfill and buffer materials may be eroded by groundwater flow (FEP 2.1.04.01).
- Radionuclide mobility is not affected by mechanical loading of waste forms, loading at interfaces, or other mechanical degradation processes in the EBS.

- Flow in the EBS can be represented using simplified approaches, accounting for possible changes (FEP 2.1.08.06), but unsaturated flow (FEPs 2.1.08.07 through 2.1.08.09) and flow through far-field plugs and seals (FEPs 2.1.05.01 and 2.1.08.04) require more detailed models (see simulation cases described in Section 3.2).
- Chemical processes in the EBS can affect the rates of waste package and waste form degradation, and radionuclide transport. Base case model simplification is recommended using bounding approximations to those rates, supported by sensitivity analyses (FEPs 2.1.09.01 through 2.1.09.12; FEP 2.1.11.14).
- Colloids do not contribute significantly to radionuclide transport because of limited mobility in low-permeability engineered and/or natural media (FEPs 2.1.09.55 through 2.1.09.61; FEPs 2.2.09.59 and 2.2.09.60).
- Thermal effects on flow and transport can be neglected (FEPs 2.1.11.02, 2.1.11.04, 2.1.11.05, and 2.1.11.08 through 2.1.11.13) as relatively brief transients that occur before most radionuclide releases. A minor exception is elevated waste package temperature from insulation by backfill, which may affect degradation of the disposal overpack, but can be readily evaluated in the base case using simple models.
- Disposal overpacks are resistant to thermally driven degradation, or provide corrosion allowance (FEP 2.1.11.07).
- Seals and plugs are located outside the influence of heating (FEP 2.1.11.09).
- Gas generation from corrosion of steels is a second-order influence on radionuclide mobility and transport for the base case (Table 1, Section 2.1.12.00).
- Radiation effects in the disposal environment (e.g., radiolysis, radiation damage) can be taken into account by adjusting degradation rates and solubilities (Table 1, Section 2.1.13.00).
- For the base case, in-package nuclear criticality (Table 1, Section 2.1.14.00) may be excluded based on insufficient water accumulation to flood breached waste packages (FEP 2.1.08.02) and/or the presence of neutron absorbers (e.g., borate or chloride) in the influent water (FEP 2.1.09.02).
- Criticality in the EBS or near field (FEP 2.1.14.02) is very unlikely because of homogeneous hydrochemical conditions that promote dissipation rather than concentration of fissile radionuclides, and/or moderator exclusion and the presence of neutron absorbers.
- Far-field flow and transport in the host rock formation and other units are substantially unchanged by repository excavation, mechanical effects, unsaturated flow processes, dehydration, surface water discharge, and thermally driven processes (FEP 2.2.05.03; Table 1, Section 2.2.07.00; FEPs 2.2.08.04 and 2.2.08.05; FEPs 2.2.08.07 and 2.2.08.08).
- Chemical processes in the far field can be neglected (or do not discriminate direct disposal of DPCs) if simplified bounding approaches to radionuclide transport are used (FEPs 2.2.09.01 through 2.2.09.04; FEPs 2.2.09.57 and FEPs 2.2.09.58).

- Isotope dilution of ^{129}I by stable ^{127}I in the geosphere does not affect dose calculations, i.e., the total iodide concentration is so small that all iodide ingested is absorbed (FEP 2.2.09.63).
- Biological processes do not significantly affect radionuclide transport in the far field (Table 1, Section 2.2.10.00).
- Thermal processes, gas generation, and nuclear criticality are not significant in the far field (Table 1, Sections 2.2.11.00, 2.2.12.00 and 2.2.14.00).
- Surface characteristics and surficial mechanical, hydrologic, chemical, biological and thermal processes do not discriminate direct disposal of DPCs (Table 1, Section 2.3.00.00).
- Human behavior and biosphere characteristics do not discriminate direct disposal of DPCs (Table 1, Sections 2.4.00.00 and 3.0.00.00).

The base case described here and in Table 1 is intended to represent the three disposal concepts identifed in Section 1:

- Salt Concept
- Hard Rock Backfilled Open Concept
- Sedimentary Backfilled Open Concept

with the following features in common: 1) corrosion allowance waste packaging (e.g., low-alloy steel); 2) saturated, low-permeability host medium; 3) emplacement drift backfill; 4) disturbed rock zone (DRZ) development; 5) advective and diffusive transport of radionuclides; 6) insignificant colloid and biocolloidal radionuclide mobility; and 7) no significant effects on radionuclide mobility from thermally driven processes or repository introduced materials. Various FEPs such as those representing multi-phase thermally driven processes, corrosion-resistant packaging, and consequences from seismic ground motion, may be added to represent the other concepts discussed in Section 1.

The base case approach will represent various FEPs using abstracted component models with input parameter settings based on judgment, supporting analyses, and/or analyses from previous studies. Processes to be represented this way in the nominal scenario include waste package and waste form degradation, solubility controls, sorption, and radionuclide transport (head gradient, conductivity, diffusion or flow area, path length).

3.2 Simulation Cases

The simulation cases described here identify the types of models that could provide addtional process-level detail for DPC PA. Additional FEPs that could be included for this purpose are listed in Table 1. The additional detail could be abstracted to augment the base case model, or an entirely different approach could be used. For example, integrated disposal system performance could be represented by merging component models with a “host” multi-physics simulator (Hardin 2012).

Lumped Parameter Model for Near-Field Chemistry – A “mixing cell” approach for modeling water chemistry in the near-field EBS is appropriate for non-advecting or slowly advecting conditions. This simulation case would be used to investigate the relationship between quantity of SNF (Section 3) and advective transport conditions. The composition of influx may be represented by formation waters (FEPs 2.1.08.01 and 2.1.09.01). Near-field waters interact with engineered materials, corrosion products, the waste form, and released radionuclides (FEPs 2.1.09.05 through 2.1.09.10, and 2.1.09.53). The near-field EBS water composition (FEPs 2.1.09.02 through 2.1.09.04) serves as a concentration boundary condition for diffusive transport (FEP 2.1.09.52) and as the composition of advective outflux (FEP 2.1.09.51), for example, associated with human intrusion.

Backfill Options – This simulation case could be used to quantify the relationship between quantity of SNF (Section 3) and radionuclide transport, for alternative backfill materials and schemes for plugging and sealing (FEPs 2.1.08.01, 2.1.08.02, 2.1.08.03 and 2.1.08.06). Functions assigned to backfill may include isolating waste packages by limiting radionuclide diffusive and advective transport, and stabilizing openings in the host rock. Low-permeability mixtures of swelling clay with sand or crushed rock have been studied extensively (SKB 2010), but emplacing such materials remotely, in a radiological environment, as would be necessary for some DPC direct disposal concepts, presents technical challenges for implementation and verification (Hardin and Voegele 2013). If the backfill function is limited to stabilizing openings (limiting further development of the DRZ after closure) then other materials, such as sand or non-swelling clay, could be used in conjunction with plugs and seals that compartmentalize emplacement areas. However, a more permeable backfill could promote advective transport, particularly in the human intrusion scenario (Section 4).

Thermally Driven Coupled Processes – The hotter conditions of DPC direct disposal could be important if thermally driven processes cause long-duration changes in the EBS or host medium. Changes such as fracture or matrix porosity changes, dewatering, bulk rock shrinkage, mineral alteration, reduction of surface area, etc., could affect flow into and within the EBS (FEPs 2.1.11.10 and 2.1.11.11). Numerical simulation of coupled chemical processes in the host rock and backfill can produce localized alteration of conditions affecting EBS performance and radionuclide transport (FEPs 2.1.04.01, 2.1.08.06, 2.1.08.09, 2.1.09.01, 2.1.09.03, 2.1.09.06 and 2.1.11.13). Beyond the influence of repository heating, for example in the far field where plugs and seals are installed, this simulation case would not discriminate direct disposal of DPCs.

Waste Package Degradation Mechanisms and Partial Containment – Containment lifetime is an objective for disposal concepts that protect SNF from the disposal environment for 10^4 years or longer to lower the probability of certain FEPs (e.g., postclosure criticality FEP 2.1.14.01). For example, containment is a key function of the waste package for the hard rock unsaturated concept, and corrosion-resistant materials would be used (Pierce et al. 2013). Corrosion-resistant disposal overpacks are also identified as an option for other DPC disposal concepts depending on site-specific and/or regulatory factors. Containment integrity for these concepts may be impacted by several processes such as general corrosion, stress corrosion cracking, localized corrosion, and microbially influenced corrosion (FEPs 2.1.03.02 through 2.1.03.05). These processes depend on temperature and other environmental conditions, and thus, may discriminate direct disposal of DPCs.

A simple model enhancement could represent total containment followed by time-dependent breach (instead of a fixed containment lifetime) caused by a single, dominant corrosion mechanism. A more complex simulation case could include multiple corrosion mechanisms, accounting for spatially variable corrosion over the surface of each package, and gradual degradation after initial breach. Also, it could account for restriction of water movement within or through degraded packages (FEP 2.1.08.02).

Seismic Ground Motion and Drift Collapse – For the unbackfilled DPC direct disposal concepts (Section 1) rockfall and drift collapse will eventually degrade the emplacement openings, potentially impacting engineered barriers such as the waste package (FEPs 2.1.07.01, 2.1.07.02, 2.1.07.05 and 2.1.07.06). Seismic initiation will increase the frequency of rockfall and drift collapse, depending on the seismic hazard (FEP 1.2.03.01), so static and seismically induced drift degradation should be modeled together. In particular, where waste package containment lifetime is an important part of the performance strategy with unbackfilled emplacement drifts, rockfall and drift collapse are potentially important to waste isolation performance (e.g., DOE 2008, Section 2.3.4).

Modeling approaches similar to those used in the past for the hard-rock unsaturated concept (e.g., distinct element; SNL 2004) can be used for static and dynamic (seismic initiation) analysis. Extensive seismic response calculations were performed for the Yucca Mountain license application (SNL 2007). These showed that: 1) corrosion resistant waste packages in open drifts can accumulate damage (e.g., residual stress); and 2) waste packages surrounded by fill (e.g., rockfall debris, or engineered buffer or backfill) sustain little or no damage from seismic ground motion. Dynamic calculations generally have not included in-package structural response (FEPs 1.2.03.01 and 2.1.07.10). In open drifts the potential for dynamic damage to cladding leads to an assumption that all cladding is breached, while for concepts that have corrosion-allowance overpacks in backfilled drifts the physical condition of the overpack, canister, basket, and fuel cladding is highly uncertain after degradation.

Unsaturated Flow in the Host Rock – For comparison of DPC disposal with alternative concepts in the unsaturated zone, multi-phase flow and thermally driven flow processes are potentially important. The controlling FEPs are the same as for saturated flow (e.g., FEPs 2.1.08.1, 2.1.08.02, 2.2.08.01 and 2.2.08.02) but the conceptual, mathematical and numerical models are different. Simulation can be accomplished using existing thermal-hydrology process models, coupled as necessary with chemical and mechanical processes.

Degradation of Far-Field Plugs and Seals – Degradation of far-field engineered barriers could change groundwater flow patterns and facilitate advective transport of radionuclides through or along repository openings (FEPs 2.1.05.01 and 2.1.08.04). Although these far-field components are not (by location) affected by heat, their performance may be important in relation to the Quantity of SNF issue (Section 2) if there is significant advective transport of radionuclides. Simulation of plug and seal performance can be accomplished using groundwater flow codes taking into account flow contributions from backfill, the DRZ, undisturbed host rock, and other flow features that may be active.

4. Scenarios

The overall assessment of risk may combine probabilistically independent scenarios by summing the consequences calculated for each. As independent scenarios they depend only on the initial state of the system (common to all scenarios) and the class of events or event sequences that is unique to the scenario. In principle one event class could modify the nominal state of the system prior to an initiating event of a different class. However, the probability of each independent disruptive scenario is low enough that conjoint events need not be considered.

The nominal scenario is the starting point for building a total system performance assessment. It describes projected performance without disruptive events, and is required to include features and processes (except for disruptive events) that can significantly contribute to system performance. The possibility that one or more waste packages could be defective leads to the early failure component of the nominal scenario (FEP 2.1.03.01). There are many different ways that defects could arise, and predicting many of them is problematic, so an early failure component may be added based on a conservative, probability weighted consequence.

Human intrusion is a required part of the performance assessment, using a separate, stylized scenario to represent the dose consequence from future drillers inadvertently intersecting one or more waste packages and exposing the contents to transport by groundwater (e.g., 40CFR191 App. C). The stylized scenario is defined by regulation, independently from other scenarios including seismic ground motion and postclosure criticality. The potential for changes in the probability of human intrusion associated with direct disposal of DPCs, is evaluated in Appendix A for repositories for SNF, using large waste packages such as would be used for DPC direct disposal, in salt and hard rock geologic settings. The results indicate that the expected number of intersections is greater than 1, particularly for the salt case (and other sedimentary settings by analogy), and for horizontal waste package orientation.

Previous studies (Pratt et al. 1979; SNL 2007) have shown that seismic ground motion has no significant effect on backfilled underground facilities. Also, faulting of the host rock has been excluded or limited in previous performance assessments (SNL 2008; SKB 2011). For a backfilled repository that is situated where there are limited seismic and fault displacement hazards, it is reasonable to anticipate that seismic ground motion and its consequences (FEPs 1.2.03.01, and 2.1.07.01 through 2.1.07.04) could be excluded from PA so that no seismic scenario would be needed. For an unbackfilled repository subject to seismic hazard of sufficient likelihood, a mechanistic representation of ground motion effects would be needed to support a seismic consequence model.

Postclosure criticality is treated as a separate scenario that can be formulated, for example, based on an event tree approach (Rechard et al. 1996). Since the probability of volcanic disruption of the repository is assumed for the present study to be less than 10^{-8} per year, seismicity is the only other disruptive event that might have a high enough joint probability with a criticality event, for the combination to be included in PA. However, seismic FEPs can be excluded for backfilled repositories (see above; FEPs 1.2.03.01 and 2.1.07.01, so its consequences are limited, and criticality can likely be considered in a separate scenario from seismic events (if neither moderator exclusion or groundwater salinity is effective as discussed in Section 3.1).

5. Numerical Implementation

In a previous study Wang et al. (2011) assessed the state of the art in numerical simulation of coupled processes, including numerical simulation codes. They identified a dichotomy between simple PA models and process-level models that incorporate coupled physics and numerical simulation grids. The base case model described in this report is such a simple PA model, that can be implemented using off-the-shelf modeling software. The “simulation cases” would use process-level models adapted as input to PA, to capture coupled processes.

A set of simple PA models was developed by Vaughn et al. (2011) for repositories in clay/shale media, salt, crystalline rock and deep boreholes. In particular, the clay/shale model is structured and versatile, and runs entirely within the GoldSim® software application (a trademark of GoldSim Technology Group). This software was developed to represent systems with both engineered and natural components, incorporating uncertainty and applying Monte Carlo methods. It is the result of extensive development activities, which for many years were driven by the Yucca Mountain repository project.

The clay/shale model from Vaughn et al. (2011) includes "mixing cells" for waste form, waste package, a second engineered barrier, a DRZ, and the far field (Figure 2). Multiple cells are used to discretize these features, and the cells are connected by advective-diffusive pathways. Waste form and waste package degradation parameters (waste quantity and degradation rate, package lifetime, temperature dependence), groundwater flow parameters (flow area and path length, flux, velocity) and radionuclide transport parameters (representing diffusion and sorption) are input as uncertainty distributions. Parameters are used to tailor individual elements and the connectivity between them, to represent different disposal concepts. The 2-D far-field part of the model can be used to represent axial and radial variation of a DRZ (Figure 2). With appropriate development of inputs the approach is suitable for modeling the base case described in this report, especially with emphasis on comparisons between DPC direct disposal and alternative concepts involving repackaging.

The base case will use abstracted inputs such as uncertainty distributions for transport path lengths, velocities, and transport properties for radionuclides. It will use temperature histories from supporting calculations, as input to waste form and waste package degradation components, and to assign damage conditions to engineered barriers and the DRZ. It will use functions to represent waste package corrosion damage and waste form degradation. Most of these inputs will be developed separately for different concepts. The simulation cases discussed here can use the same GoldSim software, with additional effort applied to evaluating and abstracting inputs (e.g., the approach used for DOE 2008). To avoid too much complexity leading to loss of transparency, enhancements for each simulation case can be implemented in separate GoldSim input files.

A more advanced numerical model architecture was described previously (Hardin 2012) and is the ultimate goal of model development. It would replace the off-the-shelf modeling software, such as GoldSim, with a detailed numerical grid and multi-physics simulation algorithms that could include multi-phase nonisothermal flow and reactive chemical transport. The idea is to avoid abstractions to the extent possible, and to run all model components together simultaneously in a high-performance computing environment. In this approach the PA model would always use such a numerical "host" simulation for the natural system, although it might have limited dimensionality and could even be 1-D if that satisfies the application requirements. The EBS would be represented as a subdomain for each waste package within the host simulation, where multi-physics couplings are activated, specific to local processes such as corrosion of metallic components, evolution of EBS flow paths, sorption on corrosion products, etc. Uncertainty and successive realizations of the model would be managed at runtime using a shell such as DAKOTA (Freeze and Vaughn 2012).

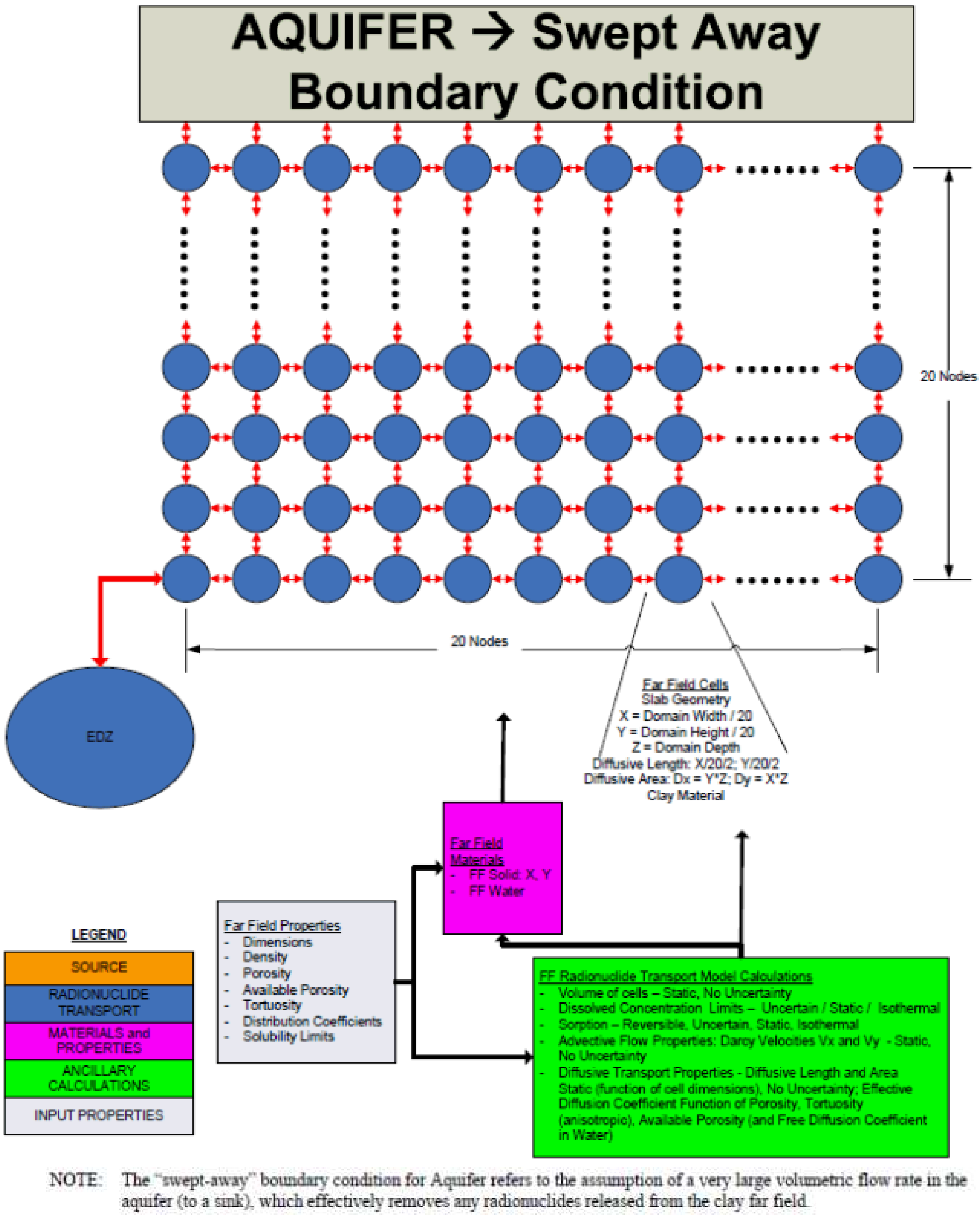

Figure 2. Schematic of Clay/Shale Model Far Field (Figure 3.3-9 from Vaughn et al. 2011)

6. Summary

Performance assessments will be used to evaluate the dose consequences of DPC direct disposal. The reduced set of disposal concepts for which representative DPC direct disposal will be evaluated consists of:

- Salt Concept
- Hard Rock Backfilled Open Concept
- Sedimentary Backfilled Open Concept

These concepts are further described elsewhere (Hardin and Voegele 2013). PAs will evaluate both the waste isolation performance of these three concepts for DPC direct disposal, and the differences in performance if the DPCs are repackaged, so that the same SNF is emplaced in purpose-built waste packages in the same geologic setting. A base case PA is proposed, and a set of simulation cases that would use increased model complexity and additional process-level simulations to address particular questions. Working with a previously described set of generic FEPs (Freeze et al. 2011), the FEPs that would be included in a base case, and a set of simulation cases, are identified (Table 1).

The recommended FEPs to be included are sufficient to address a set of topics representing potentially important differences between DPC direct disposal and disposal of the same SNF in purpose-built packages that are likely to be smaller. The topics identified in Section 3 are: emplacement mode and EBS design, thermal effects (comparing DPC direct disposal to other open modes), thermal effects (comparing to enclosed modes), quantity of SNF, and inner canister design.

The proposed base case would include: 1) corrosion allowance waste packaging (e.g., low-alloy steel); 2) saturated, low-permeability host medium; 3) emplacement drift backfill; 4) disturbed rock zone (DRZ) development; 5) advective and/or diffusive transport of radionuclides; 6) insignificant colloid and biocolloidal mobility; and 7) no significant effects on radionuclide mobility from thermally driven processes or repository introduced materials. The base case would represent backfilled openings and therefore does not need to consider rockfall, collapse, or effects from seismic ground motion.

More advanced simulation cases suggested in this report include additional model refinements to represent:

- Lumped parameter model for near-field chemistry
- Backfill options
- Thermally driven coupled processes
- Waste package degradation mechanisms and partial containment
- Consequences from seismic ground motion and drift collapse

These cases would require modeling capabilities such as integrated or abstracted geochemistry models, fully coupled multi-physics simulations, high-resolution waste package degradation and flow models, ground motion histories representing seismic hazard, and dynamic simulation of the effects of ground motion in open drifts and the surrounding rock.

A review of scenarios needed to implement total system PA shows that the base case representation of (backfilled) concepts would need: 1) nominal scenario; 2) human intrusion scenario; and 3) criticality scenario (unless postclosure criticality FEPs 2.1.14.01 and 2.1.14.02 are excluded).

Finally, a suggested approach for numerical implementation of the base case model is to use off-the-shelf software to model waste form and engineered barrier degradation and radionuclide transport, incorporating uncertainty and applying Monte Carlo methods to generate successive realizations of total system performance. The base case would use abstracted inputs such as temperature histories from supporting calculations, functions to represent waste package and waste form degradation, and uncertainty distributions for radionuclide transport parameters. Most of these inputs will be developed separately for different concepts. The simulation cases discussed here could either use the same off-the-shelf software, but with greater effort applied to evaluating and abstracting inputs, or the entire system could be represented in a numerical simulator.

Table 1. Features, Events and Processes Identified for Assessment of DPC Disposal Safety

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
0.0.00.00	0. ASSESSMENT BASIS								
0.1.02.01	Timescales of Concern		√	√	√			√	√
0.1.03.01	Spatial Domain of Concern		√	√	√			√	√
0.1.09.01	Regulatory Requirements and Exclusions		Note 1						
0.1.10.01	Model Issues	- Conceptual model - Mathematical implementation - Geometry and dimensionality - Process coupling - Boundary and initial conditions	Note 1	Note 1	Note 1			√	√
0.1.10.02	Data Issues	- Parameterization and values - Correlations - Uncertainty	Note 1		Note 1			√	√
1.0.00.00	1. EXTERNAL FACTORS								
1.1.00.00	1. REPOSITORY ISSUES								
1.1.01.01	Open Boreholes	- Site investigation boreholes (open, improperly sealed) - Preclosure and postclosure monitoring boreholes - Enhanced flow pathways from EBS			Note 1				
1.1.02.01	Chemical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock	- Water contaminants (explosives residue, diesel, organics, etc.) - Water chemistry different than host rock (e.g., oxiding) - Undesirable materials left - Accidents and unplanned events				√			√
1.1.02.02	Mechanical Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock	- Creation of excavation-disturbed zone (EDZ) - Stress relief - Boring and blasting effects - Rock reinforcement effects (drillholes) - Accidents and unplanned events - Enhanced flow pathways [see also Evolution of EDZ in 2.2.01.01]				√			√
1.1.02.03	Thermal-Hydrologic Effects from Preclosure Operations - In EBS - In EDZ - In Host Rock	- Site flooding - Preclosure ventilation - Accidents and unplanned events							√
1.1.08.01	Deviations from Design and Inadequate Quality Control	- Error in waste emplacement (waste forms, waste packages, waste package support materials) - Error in EBS component emplacement (backfill, seals, liner) - Inadequate excavation / construction (planning, schedule, implementation) - Aborted / incomplete closure of repository - Material and/or component defects							
1.1.10.01	Control of Repository Site	- Active controls (controlled area) - Retention of records - Passive controls (markers)							
1.1.13.01	Retrievability					√			
1.2.00.00	2. GEOLOGICAL PROCESSES AND EFFECTS								
1.2.01.00	2.01. LONG-TERM PROCESSES								
1.2.01.01	Tectonic Activity – Large Scale	- Uplift - Folding							
1.2.01.02	Subsidence								
1.2.01.03	Metamorphism	- Structural changes due to natural heating and/or pressure							

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
1.2.01.04	Diagenesis	- Mineral alteration due to natural processes							
1.2.01.05	Diapirism	- Plastic flow of rocks under lithostatic loading - Salt / evaporates - Clay							
1.2.01.06	Large-Scale Dissolution								
1.2.03.00	2.03.SEISMIC ACTIVITY								
1.2.03.01	Seismic Activity Impacts EBS and/or EBS Components	- Mechanical damage to EBS (from ground motion, rockfall, drift collapse, fault displacement) [see also Mechanical Impacts in 2.1.07.04, 2.1.07.05, 2.1.07.06, 2.1.07.07, 2.1.07.08, and 2.1.07.10]			Note 1	√			√ Concepts open after closure
1.2.03.02	Seismic Activity Impacts Geosphere - Host Rock - Other Geologic Units	- Altered flow pathways and properties - Altered stress regimes (faults, fractures) [see also Alterations and Impacts in 2.2.05.01, 2.2.05.02, 2.2.05.03, 2.1.07.01, and 2.1.07.02]			Note 1				
1.2.03.03	Seismic Activity Impacts Biosphere - Surface Environment - Human Behavior	- Altered surface characteristics - Altered surface transport pathways - Altered recharge							
1.2.04.00	2.04. IGNEOUS ACTIVITY								
1.2.04.01	Igneous Activity Impacts EBS and/or EBS Components	- Mechanical damage to EBS (from igneous intrusion) - Chemical interaction with magmatic volatiles - Transport of radionuclides (in magma, pyroclasts, vents) [see also Mechanical Impacts in 2.1.07.04, 2.1.07.05, 2.1.07.06, 2.1.07.07, and 2.1.07.08]			Note 1				
1.2.04.02	Igneous Activity Impacts Geosphere - Host Rock - Other Geologic Units	- Altered flow pathways and properties - Altered stress regimes (faults, fractures) - Igneous intrusions - Altered thermal and chemical conditions [see also Alterations and Impacts in 2.2.05.01, 2.2.05.02, 2.2.05.03, 2.1.07.01, 2.1.07.02, 2.2.09.03, 2.2.11.06 and 2.2.11.07]			Note 1				
1.2.04.03	Igneous Activity Impacts Biosphere - Surface Environment - Human Behavior	- Altered surface characteristics - Altered surface transport pathways - Altered recharge - Ashfall and ash redistribution							
1.3.00.00	3. CLIMATIC PROCESSES AND EFFECTS								
1.3.01.01	Climate Change - Natural - Anthropogenic	- Variations in precipitation and temperature - Long-term global (sea level,...) - Short-term regional and local - Seasonal local (flooding, storms,...) [see also Human Influences on Climate in 1.4.01.01] [contributes to Precipitation in 2.3.08.01, Surface Runoff and Evapotranspiration in 2.3.08.02]			Note 1			See FEP 2.2.08.03	See FEP 2.2.08.03
1.3.04.01	Periglacial Effects	- Permafrost - Seasonal freeze/thaw						See FEP 2.2.08.03	See FEP 2.2.08.03

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
1.3.05.01	Glacial and Ice Sheet Effects	- Glaciation - Isostatic depression - Melt water			Note 1			See FEP 2.2.08.03	See FEP 2.2.08.03
1.4.00.00	4. FUTURE HUMAN ACTIONS								
1.4.01.01	Human Influences on Climate - Intentional - Accidental	- Variations in precipitation and temperature - Global, regional, and/or local - Greenhouse gases, ozone layer failure [contributes to Climate Change in 1.3.01.01]			Note 1			See FEP 2.2.08.03	See FEP 2.2.08.03
1.4.02.01	Human Intrusion - Deliberate - Inadvertent	- Drilling (resource exploration, …) - Mining / tunneling - Unintrusive site investigation (airborne, surface-based, …) [see also Control of Repository Site in 1.1.10.01]	Note 1	Note 1	Note 1			√	√
1.4.11.01	Explosions and Crashes from Human Activities	- War - Sabotage - Testing - Resource exploration / exploitation - Aircraft							
1.5.00.00	5. OTHER								
1.5.01.01	Meteorite Impact	- Cratering, host rock removal - Exhumation of waste - Alteration of flow pathways							
1.5.01.02	Extraterrestrial Events	- Solar systems (supernova) - Celestial activity (sun - solar flares, gamma-ray bursters; moon – earth tides) - Alien life forms							
1.5.03.01	Earth Planetary Changes	- Changes in earth's magnetic field - Changes in earth's gravitational field (tides) - Changes in ocean currents							
2.0.00.00	2. DISPOSAL SYSTEM FACTORS								
2.1.00.00	1. WASTES AND ENGINEERED FEATURES								
2.1.01.00	1.01. INVENTORY								
2.1.01.01	Waste Inventory - Radionuclides - Non-Radionuclides	- Composition - Enrichment / Burn-up	√	√	√	√	√	√	√
2.1.01.02	Radioactive Decay and Ingrowth	- Decay chains - Decay products - Neutron activation	√	√	√		√	√	√
2.1.01.03	Heterogeneity of Waste Inventory - Waste Package Scale - Repository Scale	- Composition - Enrichment / Burn-up - Damaged Area	Note 1	√	Note 1			√	√
2.1.01.04	Interactions Between Co-Located Waste								
2.1.02.00	1.02. WASTE FORM								
2.1.02.01	SNF (Commercial, DOE) Degradation - Alteration / Phase Separation - Dissolution / Leaching - Radionuclide Release	Degradation is dependent on: - Composition - Geometry / Structure - Enrichment / Burn-up - Surface Area - Gap and Grain Fraction - Damaged Area - THC Conditions [see also Mechanical Impact in 2.1.07.06 and Thermal-Mechanical Effects in 2.1.11.06]	Note 1	Note 1	Note 1		√	√	√

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.1.02.02	HLW (Glass, Ceramic, Metal) Degradation - Alteration / Phase Separation - Dissolution / Leaching - Radionuclide Release	Degradation is dependent on: - Composition - Geometry / Structure - Surface Area - Damaged / Cracked Area - Mechanical Impact - THC Conditions [see also Mechanical Impact in 2.1.07.07 and Thermal-Mechanical Effects in 2.1.11.06]	Note 1	Note 1	Note 1		√	Limited to commer-cial SNF	Limited to commer-cial SNF
2.1.02.03	Degradation of Organic/Cellulosic Materials in Waste	[see also Complexation in EBS in 2.1.09.54]							
2.1.02.04	HLW (Glass, Ceramic, Metal) Recrystallization								
2.1.02.05	Pyrophoricity or Flammable Gas from SNF or HLW	[see also Gas Explosions in EBS in 2.1.12.04]							
2.1.02.06	SNF Cladding Degradation and Failure	- Initial damage - General Corrosion - Microbially Influenced Corrosion - Localized Corrosion - Enhanced Corrosion (silica, fluoride) - Stress Corrosion Cracking - Hydride Cracking - Unzipping - Creep - Internal Pressure - Mechanical Impact				√	√		√
2.1.03.00	1.03. WASTE CONTAINER								
2.1.03.01	Early Failure of Waste Packages	- Manufacturing defects - Improper sealing [see also Deviations from Design in 1.1.08.01]			Note 1	√	√	√ Corrosion resistant packaging	√ Corrosion resistant packaging
2.1.03.02	General Corrosion of Waste Packages	- Dry-air oxidation - Humid-air corrosion - Aqueous phase corrosion - Passive film formation and stability			Note 1		√	√ Corrosion resistant packaging	√ Corrosion resistant packaging
2.1.03.03	Stress Corrosion Cracking (SCC) of Waste Packages	- Crack initiation, growth and propagation - Stress distribution around cracks			Note 1	√		√ Corrosion resistant packaging	√ Corrosion resistant packaging
2.1.03.04	Localized Corrosion of Waste Packages	- Pitting - Crevice corrosion - Salt deliquescence [see also 2.1.09.06 Chemical Interaction with Backfill]			Note 1			√ Corrosion resistant packaging	√ Corrosion resistant packaging
2.1.03.05	Hydride Cracking of Waste Packages	- Hydrogen diffusion through metal matrix - Crack initiation and growth in metal hydride phases			Note 1				√ Corrosion resistant packaging
2.1.03.06	Microbially Influenced Corrosion (MIC) of Waste Packages				Note 1			√ Corrosion resistant packaging	√ Corrosion resistant packaging
2.1.03.07	Internal Corrosion of Waste Packages Prior to Breach								√ Corrosion resistant packaging

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.1.03.08	Evolution of Flow Pathways in Waste Packages	- Evolution of physical form of waste package - Plugging of cracks in waste packages [see also Evolution of Flow Pathways in EBS in 2.1.08.06, Mechanical Impacts in 2.1.07.05, 2.1.07.06, and 2.1.07.07, Thermal-Mechanical Effects in 2.1.11.06 and 2.1.11.07]			Note 1	√	√		√
2.1.04.00	1.04. BUFFER / BACKFILL								
2.1.04.01	Evolution and Degradation of Backfill	- Alteration - Thermal expansion / Degradation - Swelling / Compaction - Erosion / Dissolution - Evolution of backfill flow pathways [see also Evolution of Flow Pathways in EBS in 2.1.08.06, Mechanical Impact in 2.1.07.04, Thermal-Mechanical Effects in 2.1.11.08, Chemical Interaction in 2.1.09.06]			Note 1	√	√	√ Including buffers; for non-DPC disposal compari-son	√ Including buffers; for non-DPC disposal compari-son
2.1.05.00	1.05. SEALS								
2.1.05.01	Degradation of Seals	- Alteration / Degradation / Cracking - Erosion / Dissolution [see also Mechanical Impact in 2.1.07.08, Thermal-Mechanical Effects in 2.1.11.09, Chemical Interaction in 2.1.09.08]			Note 1		√		√ Open concepts, saturated media without backfill
2.1.06.00	1.06. OTHER EBS MATERIALS								
2.1.06.01	Degradation of Liner / Rock Reinforcement Materials in EBS	- Alteration / Degradation / Cracking - Corrosion - Erosion / Dissolution / Spalling [see also Mechanical Impact in 2.1.07.08, Thermal-Mechanical Effects in 2.1.11.09, Chemical Interaction in 2.1.09.07]				√			√
2.1.07.00	1.07. MECHANICAL PROCESSES								
2.1.07.01	Rockfall	- Dynamic loading (block size and velocity) echanical Effects on Host Rock in 2.2.07.01]				√			√ Concepts open after closure
2.1.07.02	Drift Collapse	- Static loading (rubble volume) - Alteration of seepage - Alteration of EBS flow pathways - Alteration of EBS thermal environment [see also Evolution of Flow Pathways in EBS in 2.1.08.06, Chemical Effects of Drift Collapse in 2.1.09.12, and Effects of Drift Collapse on TH in 2.1.11.04, Mechanical Effects on Host Rock in 2.2.07.01]				√			√ Concepts open after closure
2.1.07.03	Mechanical Effects of Backfill	- Protection of other EBS components from rockfall / drift collapse				√		√	√
2.1.07.04	Mechanical Impact on Backfill	- Rockfall / Drift collapse - Hydrostatic pressure - Internal gas pressure [see also Degradation of Backfill in 2.1.04.01 and Thermal-Mechanical Effects in 2.1.11.08]				√			√

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.1.07.05	Mechanical Impact on Waste Packages	- Rockfall / Drift collapse - Waste package movement - Hydrostatic pressure - Internal gas pressure - Swelling corrosion products [see also Thermal-Mechanical Effects in 2.1.11.07]				√			√ Concepts open after closure, corrosion resistant packaging
2.1.07.06	Mechanical Impact on SNF Waste Form	- Drift collapse - Swelling corrosion products [see also Thermal-Mechanical Effects in 2.1.11.06]				√			√
2.1.07.07	Mechanical Impact on HLW Waste Form	- Drift collapse - Swelling corrosion products [see also Thermal-Mechanical Effects in 2.1.11.06]							
2.1.07.08	Mechanical Impact on Other EBS Components - Seals - Liner / Rock Reinforcement Materials - Waste Package Support Materials	- Rockfall / Drift collapse - Movement - Hydrostatic pressure - Swelling corrosion products [see also Thermal-Mechanical Effects in 2.1.11.09]				√			√
2.1.07.09	Mechanical Effects at EBS Component Interfaces	- Component-to-component contact (static or dynamic)	Note 1						
2.1.07.10	Mechanical Degradation of EBS	- Floor buckling - Fault displacement - Initial damage from excavation / construction - Consolidation of EBS components - Degradation of waste package support structure - Alteration of EBS flow pathways [see also Mechanical Effects from Preclosure in 1.1.02.02, Evolution of Flow Pathways in EBS in 2.1.08.06, Drift Collapse in 2.1.07.02, Degradation in 2.1.04.01, 2.1.05.01, and 2.1.06.01, and Mechanical Effects on Host Rock in 2.2.07.01]	Note 1			√			√
2.1.08.00	1.08. HYDROLOGIC PROCESSES								
2.1.08.01	Flow Through the EBS	- Saturated / Unsaturated flow - Preferential flow pathways - Density effects on flow - Initial hydrologic conditions - Flow pathways out of EBS [see also Open Boreholes in 1.1.01.01, Thermal-Hydrologic Effects from Preclosure in 1.1.02.03, Flow in Waste Packages in 2.1.08.02, Flow in Backfill in 2.1.08.03, Flow through Seals 2.1.08.04, Flow through Liner in 2.1.08.05, Thermal Effects on Flow in 2.1.11.10, Effects of Gas on Flow in 2.1.12.02]	Note 1		√		√	√	√
2.1.08.02	Flow In and Through Waste Packages	- Saturated / Unsaturated flow - Movement as thin films or droplets	Note 1		√		√	√	√
2.1.08.03	Flow in Backfill	- Fracture / Matrix flow	Note 1		√			√	√
2.1.08.04	Flow Through Seals	- Fracture / Matrix flow			Note 1		√		√
2.1.08.05	Flow Through Liner / Rock Reinforcement Materials in EBS							√ Bounding approach	√

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.1.08.06	Alteration and Evolution of EBS Flow Pathways	- Drift collapse - Degradation/consolidation of EBS components - Plugging of flow pathways - Formation of corrosion products - Water ponding [see also Evolution of Flow Pathways in WPs in 2.1.03.08, Evolution of Backfill in 2.1.04.01, Drift Collapse in 2.1.07.02, and Mechanical Degradation of EBS in 2.1.07.10]	Note 1		Note 1		√	√ Bounding approach	√ Concepts open after closure
2.1.08.07	Condensation Forms in Repository - On Tunnel Roof / Walls - On EBS Components	- Heat transfer (spatial and temporal distribution of temperature and relative humidity) - Dripping - Moisture movement [see also Heat Generation in EBS in 2.1.11.01, Effects on EBS Thermal Environment in 2.1.11.03 and 2.1.11.04]							
2.1.08.08	Capillary Effects in EBS	- Wicking - Capillary barrier - Osmotic binding							
2.1.08.09	Influx/Seepage Into the EBS	- Water influx rate (spatial and temporal distribution) [see also Open Boreholes in 1.1.01.01, Thermal Effects on Flow in EBS in 2.1.11.10, Flow Through Host Rock in 2.2.08.01, Effects of Excavation on Flow in 2.2.08.04]	Note 1		Note 1		√	√	√
2.1.09.00	1.09. CHEMICAL PROCESSES - CHEMISTRY								
2.1.09.01	Chemistry of Water Flowing into the Repository	- Chemistry of influent water (spatial and temporal distribution) [See also Chemistry in Host Rock 2.2.09.01]		Note 1			√		√
2.1.09.02	Chemical Characteristics of Water in Waste Packages	- Water composition (radionuclides, dissolved species, …) - Initial void chemistry (air / gas) - Water chemistry (pH, ionic strength, pCO2, ..) - Reduction-oxidation potential - Reaction kinetics - Influent chemistry (from tunnels and/or backfill) [see also Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04] - Evolution of water chemistry / interaction with waste packages			Note 1		√		√
2.1.09.03	Chemical Characteristics of Water in Backfill	- Water composition (radionuclides, dissolved species, …) - Water chemistry (pH, ionic strength, pCO2, ..) - Reduction-oxidation potential - Reaction kinetics - Influent chemistry (from tunnels and/or waste package) [see also Chemistry in Waste Packages in 2.1.09.02, Chemistry in Tunnels in 2.1.09.04] - Evolution of water chemistry / interaction with backfill			Note 1		√		√

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.1.09.04	Chemical Characteristics of Water in Tunnels	- Water composition (radionuclides, dissolved species, …) - Water chemistry (pH, ionic strength, pCO2, ..) - Reduction-oxidation potential - Reaction kinetics - Influent chemistry (from near-field host rock) - Initial chemistry (from construction / emplacement) [see also Chemical Effects from Preclosure in 1.1.02.01, Chemistry of Water Flowing in 2.1.09.01, Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03] - Evolution of water chemistry / interaction with seals, liner/rock reinforcement materials, waste package support materials			Note 1				√
2.1.09.05	Chemical Interaction of Water with Corrosion Products - In Waste Packages - In Backfill - In Tunnels	- Corrosion product formation and composition (waste form, waste package internals, waste package) - Evolution of water chemistry in waste packages, in backfill, and in tunnels [contributes to Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]					√		√
2.1.09.06	Chemical Interaction of Water with Backfill - On Waste Packages - In Backfill - In Tunnels	- Backfill composition and evolution (bentonite, crushed rock, ...) - Evolution of water chemistry in backfill, and in tunnels - Enhanced degradation of waste packages (crevice formation) [contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04, Localized Corrosion of WPs in 2.1.03.04]		Note 1			√		√
2.1.09.07	Chemical Interaction of Water with Liner / Rock Reinforcement and Cementitious Materials in EBS - In Backfill - In Tunnels	- Liner composition and evolution (concrete, metal, ...) - Rock reinforcement material composition and evolution (grout, rock bolts, mesh, ...) - Other cementitious materials composition and evolution - Evolution of water chemistry in backfill, and in tunnels [contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]		Note 1					√
2.1.09.08	Chemical Interaction of Water with Other EBS Components - In Waste Packages - In Tunnels	- Seals composition and evolution - Waste Package Support composition and evolution (concrete, metal, ...) - Other EBS components (other metals (copper), ...) - Evolution of water chemistry in backfill, and in tunnels [contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]					√		√
2.1.09.09	Chemical Effects at EBS Component Interfaces	- Component-to-component contact (chemical reactions) - Consolidation of EBS components							
2.1.09.10	Chemical Effects of Waste-Rock Contact	- Waste-to-host rock contact (chemical reactions) - Component-to-host rock contact (chemical reactions)							
2.1.09.11	Electrochemical Effects in EBS	- Enhanced metal corrosion							

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.1.09.12	Chemical Effects of Drift Collapse	- Evolution of water chemistry in backfill and in tunnels (from altered seepage, from altered thermal-hydrology) [contributes to Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]							
2.1.09.13	Radionuclide Speciation and Solubility in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Dissolved concentration limits - Limited dissolution due to inclusion in secondary phase - Enhanced dissolution due to alpha recoil [controlled by Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]	Note 1	Note 1	Note 1		√	√	√
2.1.09.50	1.09. CHEMICAL PROCESSES - TRANSPORT								
2.1.09.51	Advection of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Flow pathways and velocity - Advective properties (porosity, tortuosity) - Dispersion - Saturation [see also Gas Phase Transport in 2.1.12.03]	Note 1		√		√	√	√
2.1.09.52	Diffusion of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Gradients (concentration, chemical potential) - Diffusive properties (diffusion coefficients) - Flow pathways and velocity - Saturation		Note 1	√		√	√	√
2.1.09.53	Sorption of Dissolved Radionuclides in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Surface complexation properties - Flow pathways and velocity - Saturation [see also Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]		Note 1	√		√	√	√
2.1.09.54	Complexation in EBS	- Formation of organic complexants (humates, fulvates, organic waste) - Enhanced transport of radionuclides associated with organic complexants [see also Degradation of Organics in Waste in 2.1.02.03, see Radionuclide Speciation in 2.1.09.13 for inorganic complexation]							
2.1.09.55	Formation of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Formation of intrinsic colloids - Formation of pseudo colloids (host rock fragments, waste form fragments, corrosion products, microbes) - Formation of co-precipitated colloids - Sorption/attachment of radionuclides to colloids (clay, silica, waste form, FeOx, microbes)							
2.1.09.56	Stability of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Chemical stability of attachment (dependent on water chemistry) - Mechanical stability of colloid (dependent on colloid size, gravitational settling)							
2.1.09.57	Advection of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Flow pathways and velocity - Advective properties (porosity, tortuosity) - Dispersion - Saturation - Colloid concentration							

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.1.09.58	Diffusion of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Gradients (concentration, chemical potential) - Diffusive properties (diffusion coefficients) - Flow pathways and velocity - Saturation - Colloid concentration							
2.1.09.59	Sorption of Colloids in EBS - In Waste Form - In Waste Package - In Backfill - In Tunnel	- Surface complexation properties - Flow pathways and velocity - Saturation - Colloid concentration [see also Chemistry in Waste Packages in 2.1.09.02, Chemistry in Backfill in 2.1.09.03, Chemistry in Tunnels in 2.1.09.04]							
2.1.09.60	Sorption of Colloids at Air-Water Interface in EBS								
2.1.09.61	Filtration of Colloids in EBS	- Physical filtration or trapping (dependent on flow pathways, colloid size) - Electrostatic filtration							
2.1.09.62	Radionuclide Transport Through Liners and Seals	- Advection - Dispersion - Diffusion - Sorption [contributes to Radionuclide release from EBS in 2.1.09.63]			Note 1				√
2.1.09.63	Radionuclide Release from the EBS - Dissolved - Colloidal - Gas Phase	- Spatial and temporal distribution of releases to the host rock (due to varying flow pathways and velocities, varying component degradation rates, varying transport properties) [contributions from Dissolved in 2.1.09.51/52/53, Colloidal in 2.1.09.57/58/59, Gas Phase in 2.1.12.03, Liners and Seals in 2.1.09.62]		Note 1	Note 1			√	√
2.1.10.00	1.10. BIOLOGICAL PROCESSES								
2.1.10.01	Microbial Activity in EBS - Natural - Anthropogenic	- Effects on corrosion - Formation of complexants - Formation of microbial colloids - Formation of biofilms - Biodegradation - Biomass production - Bioaccumulation [see also Microbiallly Influenced Corrosion in 2.1.03.06, Complexation in EBS in 2.1.09.54, Radiological Mutation of Microbes in 2.1.13.03]							
2.1.11.00	1.11. THERMAL PROCESSES								
2.1.11.01	Heat Generation in EBS	- Heat transfer (spatial and temporal distribution of temperature and relative humidity) [see also Thermal-Hydrologic Effects from Preclosure in 1.1.02.03, Waste Inventory in 2.1.01.01]				√	√	√	√
2.1.11.02	Exothermic Reactions in EBS	- Oxidation of SNF - Hydration of concrete							
2.1.11.03	Effects of Backfill on EBS Thermal Environment	- Thermal blanket - Condensation					√	√	√
2.1.11.04	Effects of Drift Collapse on EBS Thermal Environment	- Thermal blanket - Condensation				√			√
2.1.11.05	Effects of Influx (Seepage) on Thermal Environment	- Temperature and relative humidity (spatial and temporal distribution) [see also Influx/Seepage into EBS in 2.1.08.09]							

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.1.11.06	Thermal-Mechanical Effects on Waste Form and In-Package EBS Components	- Alteration - Cracking - Thermal expansion / stress			Note 1			√	√
2.1.11.07	Thermal-Mechanical Effects on Waste Packages	- Thermal sensitization / phase changes - Cracking - Thermal expansion / stress / creep			Note 1			√	√
2.1.11.08	Thermal-Mechanical Effects on Backfill	- Alteration - Cracking - Thermal expansion / stress	Note 1		Note 1	√			√
2.1.11.09	Thermal-Mechanical Effects on Other EBS Components - Seals - Liner / Rock Reinforcement Materials - Waste Package Support Structure	- Alteration - Cracking - Thermal expansion / stress			Note 1	√			√
2.1.11.10	Thermal Effects on Flow in EBS	- Altered influx/seepage - Altered saturation / relative humidity (dry-out, resaturation) - Condensation			Note 1		√		√
2.1.11.11	Thermally-Driven Flow (Convection) in EBS	- Convection					√		√
2.1.11.12	Thermally-Driven Buoyant Flow / Heat Pipes in EBS	- Vapor flow					√		√
2.1.11.13	Thermal Effects on Chemistry and Microbial Activity in EBS						√		√
2.1.11.14	Thermal Effects on Transport in EBS	- Thermal diffusion (Soret effect) - Thermal osmosis			Note 1				√
2.1.12.00	1.12. GAS SOURCES AND EFFECTS								
2.1.12.01	Gas Generation in EBS	- Repository Pressurization - Mechanical Damage to EBS Components - He generation from waste from alpha decay - H_2 generation from waste package corrosion - CO_2, CH_4, and H_2S generation from microbial degradation - Vaporization of water	Note 1						√
2.1.12.02	Effects of Gas on Flow Through the EBS	- Two-phase flow - Gas bubbles [see also Buoyant Flow/Heat Pipes in 2.1.11.12]							√
2.1.12.03	Gas Transport in EBS	- Gas phase transport - Gas phase release from EBS	Note 1						√
2.1.12.04	Gas Explosions in EBS	[see also Flammable Gas from Waste in 2.1.02.05]							
2.1.13.00	1.13. RADIATION EFFECTS								
2.1.13.01	Radiolysis - In Waste Package - In Backfill - In Tunnel	- Gas generation - Altered water chemistry							
2.1.13.02	Radiation Damage to EBS Components - Waste Form - Waste Package - Backfill - Other EBS Components	- Enhanced waste form degradation - Enhanced waste package degradation - Enhanced backfill degradation - Enhanced degradation of other EBS components (liner/rock reinforcement materials, seals, waste support structure)				√			√
2.1.13.03	Radiological Mutation of Microbes								
2.1.14.00	1.14. NUCLEAR CRITICALITY								
2.1.14.01	Criticality In-Package	- Formation of critical configuration				√			√

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.1.14.02	Criticality in EBS or Near-Field	- Formation of critical configuration				√			√
2.2.00.00	2. GEOLOGICAL ENVIRONMENT								
2.2.01.00	2.01. EXCAVATION DISTURBED ZONE (EDZ)								
2.2.01.01	Evolution of EDZ	- Lateral extent, heterogeneities - Physical properties - Flow pathways - Chemical characteristics of groundwater in EDZ - Radionuclide speciation and solubility in EDZ - Thermal-mechanical effects - Thermal-chemical alteration [see also Mechanical Effects of Excavation in 1.1.02.02]		Note 1	√	√		√	√
2.2.02.00	2.02. HOST ROCK								
2.2.02.01	Stratigraphy and Properties of Host Rock	- Rock units - Thickness, lateral extent, heterogeneities, discontinuities, contacts - Physical properties - Flow pathways [see also Fractures in 2.2.05.01 and Faults in 2.2.05.02]	Note 1	Note 1	√			√	√
2.2.03.00	2.03. OTHER GEOLOGIC UNITS								
2.2.03.01	Stratigraphy and Properties of Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Rock units - Thickness, lateral extent, heterogeneities, discontinuities, contacts - Physical properties - Flow pathways [see also Fractures in 2.2.05.01 and Faults in 2.2.05.02]	Note 1	√				√	√
2.2.05.00	2.05. FLOW AND TRANSPORT PATHWAYS								
2.2.05.01	Fractures - Host Rock - Other Geologic Units	- Rock properties [see also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01]		Note 1				√	√
2.2.05.02	Faults - Host Rock - Other Geologic Units	- Rock properties [see also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01]		Note 1				√	√
2.2.05.03	Alteration and Evolution of Geosphere Flow Pathways - Host Rock - Other Geologic Units	- Changes In rock properties - Changes in faults - Changes in fractures - Plugging of flow pathways - Changes in saturation [see also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01, Fractures in 2.2.05.01, and Faults in 2.2.05.02] [see also Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07]	Note 1		Note 1				√
2.2.07.00	2.07. MECHANICAL PROCESSES								
2.2.07.01	Mechanical Effects on Host Rock	- From subsidence - From salt creep - From clay deformation - From granite deformation (rockfall / drift collapse into tunnels) - Chemical precipitation / dissolution - Stress regimes [see also Subsidence in 1.2.02.01, Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07]				√			√

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.2.07.02	Mechanical Effects on Other Geologic Units	- From subsidence - Chemical precipitation / dissolution - Stress regimes [see also Subsidence in 1.2.02.01, Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07]							
2.2.08.00	2.08. HYDROLOGIC PROCESSES								
2.2.08.01	Flow Through the Host Rock	- Saturated flow - Fracture flow / matrix imbibition - Unsaturated flow (fingering, capillarity, episodicity, perched water) - Preferential flow pathways - Density effects on flow - Flow pathways out of Host Rock [see also Influx/Seepage into EBS in 2.1.08.09, Alteration of Flow Pathways in 2.2.05.03, Thermal Effects on Flow in 2.2.11.01, Effects of Gas on Flow in 2.2.12.02]	Note 1	Note 1				√	√
2.2.08.02	Flow Through the Other Geologic Units - Confining units - Aquifers	- Saturated flow - Fracture flow / matrix imbibition - Unsaturated flow (fingering, capillarity, episodicity, perched water) - Preferential flow pathways - Density effects on flow - Flow pathways out of Other Geologic Units [see also Alteration of Flow Pathways in 2.2.05.03, Thermal Effects on Flow in 2.2.11.01, Effects of Gas on Flow in 2.2.12.02]		Note 1				√	√
2.2.08.03	Effects of Recharge on Geosphere Flow - Host Rock - Other Geologic Units	- Infiltration rate - Water table rise/decline [see also Infiltration in 2.3.08.03]			Note 1			√	√
2.2.08.04	Effects of Repository Excavation on Flow Through the Host Rock	- Saturated flow (flow sink) - Unsaturated flow (capillary diversion, drift shadow) - Influx/Seepage into EBS (film flow, enhanced seepage) [see also Influx/Seepage into EBS in 2.1.08.09]							
2.2.08.05	Condensation Forms in Host Rock	- Condensation cap - Shedding [see also Thermal Effects on Flow in Geosphere in 2.2.11.01]							
2.2.08.06	Flow Through EDZ	- Saturated / Unsaturated flow - Fracture / Matrix flow		Note 1	√			√	√
2.2.08.07	Mineralogic Dehydration	- Dehydration reactions release water and may lead to volume changes			Note 1				√
2.2.08.08	Groundwater Discharge to Biosphere Boundary	- Surface discharge (water table, capillary rise, surface water) - Flow across regulatory boundary	Note 1		Note 1				
2.2.08.09	Groundwater Discharge to Well	- Human use (drinking water, bathing water, industrial) - Agricultural use (irrigation, animal watering)	Note 1		Note 1			√	√

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.2.09.00	**2.09.CHEMICAL PROCESSES - CHEMISTRY**								
2.2.09.01	Chemical Characteristics of Groundwater in Host Rock	- Water composition (radionuclides, dissolved species, …) - Water chemistry (temperature, pH, Eh, ionic strength …) - Reduction-oxidation potential - Reaction kinetics - Interaction with EBS - Interaction with host rock [see also Chemistry in Tunnels in 2.1.09.04, Chemical Interactions and Evolution in 2.2.09.03] [contributes to Chemistry of Water Flowing into Repository in 2.1.09.01]	Note 1		Note 1				√
2.2.09.02	Chemical Characteristics of Groundwater in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Water composition (radionuclides, dissolved species, …) - Water chemistry (temperature, pH, Eh, ionic strength …) - Reduction-oxidation potential - Reaction kinetics - Interaction with other geologic units [see also Chemical Interactions and Evolution in 2.2.09.04]							
2.2.09.03	Chemical Interactions and Evolution of Groundwater in Host Rock	- Host rock composition and evolution (granite, clay, salt ...) - Evolution of water chemistry in host rock - Chemical effects on density - Interaction with EBS - Reaction kinetics - Mineral dissolution/precipitation - Redissolution of precipitates after dry-out [contributes to Chemistry in Host Rock in 2.2.09.01]			Note 1				√
2.2.09.04	Chemical Interactions and Evolution of Groundwater in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Host rock composition and evolution (granite, clay, salt ...) - Evolution of water chemistry in host rock - Chemical effects on density - Reaction kinetics - Mineral dissolution/precipitation - Recharge chemistry [contributes to Chemistry in Other Geologic Units in 2.2.09.02]							
2.2.09.05	Radionuclide Speciation and Solubility in Host Rock	- Dissolved concentration limits [controlled by Chemistry in Host Rock in 2.2.09.01]			√			√	√
2.2.09.06	Radionuclide Speciation and Solubility in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Dissolved concentration limits [controlled by Chemistry in Other Geologic Units in 2.2.09.02]	√	√				√	√
2.2.09.50	**2.09. CHEMICAL PROCESSES - TRANSPORT**								
2.2.09.51	Advection of Dissolved Radionuclides in Host Rock	- Flow pathways and velocity - Advective properties (porosity, tortuosity) - Dispersion - Matrix diffusion - Saturation [see also Gas Phase Transport in 2.2.12.03]	√	√	√			√	√

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.2.09.52	Advection of Dissolved Radionuclides in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Flow pathways and velocity - Advective properties (porosity, tortuosity) - Dispersion - Matrix diffusion - Saturation [see also Gas Phase Transport in 2.2.12.03]	√	√				√	√
2.2.09.53	Diffusion of Dissolved Radionuclides in Host Rock	- Gradients (concentration, chemical potential) - Diffusive properties (diffusion coefficients) - Flow pathways and velocity - Saturation	√	√	√			√	√
2.2.09.54	Diffusion of Dissolved Radionuclides in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Gradients (concentration, chemical potential) - Diffusive properties (diffusion coefficients) - Flow pathways and velocity - Saturation	√	√				√	√
2.2.09.55	Sorption of Dissolved Radionuclides in Host Rock	- Surface complexation properties - Flow pathways and velocity - Saturation [see also Chemistry in Host Rock in 2.2.09.01]	Note 1	√	√			√	√
2.2.09.56	Sorption of Dissolved Radionuclides in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Surface complexation properties - Flow pathways and velocity - Saturation [see also Chemistry in Host Rock in 2.2.09.01]	√	√				√	√
2.2.09.57	Complexation in Host Rock	- Presence of organic complexants (humates, fulvates, carbonates, …) - Enhanced transport of radionuclides associated with organic complexants [see Radionuclide Speciation in 2.2.09.05 for inorganic complexation]							
2.2.09.58	Complexation in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Presence of organic complexants (humates, fulvates, carbonates, …) - Enhanced transport of radionuclides associated with organic complexants [see Radionuclide Speciation in 2.2.09.06 for inorganic complexation]							
2.2.09.59	Colloidal Transport in Host Rock	- Flow pathways and velocity - Saturation - Advection - Dispersion - Diffusion - Sorption - Colloid concentration							
2.2.09.60	Colloidal Transport in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Flow pathways and velocity - Saturation - Advection - Dispersion - Diffusion - Sorption - Colloid concentration							
2.2.09.61	Radionuclide Transport Through EDZ	- Advection - Dispersion - Diffusion - Sorption		Note 1	√			√	√
2.2.09.62	Dilution of Radionuclides in Groundwater - Host Rock - Other Geologic Units	- Mixing with uncontaminated groundwater - Mixing at withdrawal well [see also Groundwater Discharge to Well in 2.2.08.09]	Note 1		Note 1			√	√

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.2.09.63	Dilution of Radionuclides with Stable Isotopes - Host Rock - Other Geologic Units	- Mixing with stable and/or naturally occurring isotopes of the same element							
2.2.09.64	Radionuclide Release from Host Rock - Dissolved - Colloidal - Gas Phase	- Spatial and temporal distribution of releases to the Other Geologic Units or to the Biosphere (due to varying flow pathways and velocities, varying transport properties) [contributions from Dissolved in 2.2.09.51/53/55, Colloidal in 2.2.09.59, Gas Phase in 2.2.12.03, EDZ in 2.2.09.61]	Note 1	Note 1	√			√	√
2.2.09.65	Radionuclide Release from Other Geologic Units - Dissolved - Colloidal - Gas Phase	- Spatial and temporal distribution of releases to the Biosphere (due to varying flow pathways and velocities, varying transport properties) [see also Groundwater Discharge to Biosphere Boundary in 2.2.08.08, Groundwater Discharge to Well in 2.2.08.09, Recycling of Accumulated Radionuclides in 2.3.09.55] [contributions from Dissolved in 2.2.09.52/54/56, Colloidal in 2.2.09.60, Gas Phase in 2.2.12.03]	Note 1	Note 1				√	√
2.2.10.00	2.10. BIOLOGICAL PROCESSES								
2.2.10.01	Microbial Activity in Host Rock	- Formation of complexants - Formation and stability of microbial colloids - Biodegradation - Bioaccumulation [see also Complexation in Host Rock in 2.2.09.57]							
2.2.10.02	Microbial Activity in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers	- Formation of complexants - Formation and stability of microbial colloids - Biodegradation - Bioaccumulation [see also Complexation in Other Geologic Units in 2.2.09.58]							
2.2.11.00	2.11. THERMAL PROCESSES								
2.2.11.01	Thermal Effects on Flow in Geosphere - Repository-Induced - Natural Geothermal	- Altered saturation / relative humidity (dry-out, resaturation) - Altered gradients, density, and/or flow pathways - Vapor flow - Condensation							
2.2.11.02	Thermally-Driven Flow (Convection) in Geosphere	- Convection							
2.2.11.03	Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere	- Vapor flow							
2.2.11.04	Thermal Effects on Chemistry and Microbial Activity in Geosphere	- Mineral precipitation / dissolution - Altered solubility [contributes to Chemistry in 2.2.09.01 and 2.2.09.02]							
2.2.11.05	Thermal Effects on Transport in Geosphere	- Thermal diffusion (Soret effect) - Thermal osmosis							
2.2.11.06	Thermal-Mechanical Effects on Geosphere	- Thermal expansion / compression - Altered properties of fractures, faults, rock matrix							

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.2.11.07	Thermal-Chemical Alteration of Geosphere	- Mineral precipitation / dissolution - Altered properties of fractures, faults, rock matrix - Alteration of minerals / volume changes - Formation of near-field chemically altered zone (rind)							
2.2.12.00	2.12. GAS SOURCES AND EFFECTS								
2.2.12.01	Gas Generation in Geosphere	- Degassing (clathrates, deep gases) - Microbial degradation of organics - Vaporization of water							√
2.2.12.02	Effects of Gas on Flow Through the Geosphere	- Altered gradients and/or flow pathways - Vapor/air flow - Two-phase flow - Gas bubbles [see also Buoyant Flow/Heat Pipes in 2.2.11.03]							
2.2.12.03	Gas Transport in Geosphere	- Gas phase transport - Gas phase release from Geosphere							
2.2.14.00	2.14. NUCLEAR CRITICALITY								
2.2.14.01	Criticality in Far-Field	- Formation of critical configuration							
2.3.00.00	3. SURFACE ENVIRONMENT								
2.3.01.00	3.01. SURFACE CHARACTERISTICS								
2.3.01.01	Topography and Surface Morphology	- Recharge and discharge areas							
2.3.02.01	Surficial Soil Type	- Physical and chemical attributes							
2.3.04.01	Surface Water	- Lakes, rivers, springs - Dams, reservoirs, canals, pipelines - Coastal and marine features - Water management activities							
2.3.05.01	Biosphere Characteristics	- Climate - Soils - Flora and fauna - Microbes - Evolution of biosphere (natural, anthropogenic – e.g., acid rain) [see also Climate Change in 1.3.01.01, Surficial Soil Type in 2.3.02.01, Microbial Activity in 2.3.10.01]		Note 1	Note 1			√	√
2.3.07.00	3.07. MECHANICAL PROCESSES								
2.3.07.01	Erosion	- Weathering - Denudation - Subsidence [see also Subsidence in 1.2.02.01, Periglacial Effects in 1.3.04.01, Glacial Effects in 1.3.05.01, Surface Runoff in 2.3.08.02, and Soil and Sediment Transport in 2.3.09.53]							
2.3.07.02	Deposition	- Weathering							
2.3.07.03	Animal Intrusion into Repository								
2.3.08.00	3.08. HYDROLOGIC PROCESSES								
2.3.08.01	Precipitation	- Spatial and temporal distribution [see also Climate Change in 1.3.01.01] [contributes to Infiltration in 2.3.08.03]							

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.3.08.02	Surface Runoff and Evapotranspiration	- Runoff, impoundments, flooding, increased recharge - Evaporation - Condensation - Transpiration (root uptake) [see also Climate Change in 1.3.01.01, Erosion in 2.3.07.01] [contributes to Infiltration in 2.3.08.03]							
2.3.08.03	Infiltration and Recharge	- Spatial and temporal distribution - Effect on hydraulic gradient - Effect on water table elevation [see also Topography in 2.3.01.01, Surficial Soil Type in 2.3.02.01] [contributes to Effects of Recharge in 2.2.08.03]							
2.3.09.00	3.09. CHEMICAL PROCESSES - CHEMISTRY								
2.3.09.01	Chemical Characteristics of Soil and Surface Water	- Altered recharge chemistry (natural) - Altered recharge chemistry (anthropogenic – e.g., acid rain) [contributes to Chemical Evolution of Groundwater in 2.2.09.04]							
2.3.09.02	Radionuclide Speciation and Solubility in Biosphere	- Dissolved concentration limits							
2.3.09.03	Radionuclide Alteration in Biosphere	- Altered physical and chemical properties - Isotopic dilution	Note 1						
2.3.09.50	3.09. CHEMICAL PROCESSES - TRANSPORT								
2.3.09.51	Atmospheric Transport Through Biosphere	- Radionuclide transport in air, gas, vapor, particulates, aerosols - Processes include: wind, plowing, degassing, precipitation							
2.3.09.52	Surface Water Transport Through Biosphere	- Radionuclide transport and mixing in surface water - Processes include: lake mixing, river flow, spring discharge, overland flow, irrigation, aeration, sedimentation, dilution [see also Surface Water in 2.3.04.01]							
2.3.09.53	Soil and Sediment Transport Through Biosphere	- Radionuclide transport in or on soil and sediments - Processes include: fluvial (runoff, river flow), eolian (wind), saltation, glaciation, bioturbation (animals) [see also Erosion in 2.3.07.01, Deposition in 2.3.07.02]							
2.3.09.54	Radionuclide Accumulation in Soils	- Leaching/evaporation from discharge (well, groundwater upwelling) - Deposition from atmosphere or water (irrigation, runoff)							
2.3.09.55	Recycling of Accumulated Radionuclides from Soils to Groundwater	[see also Radionuclide Release in 2.2.09.65]							
2.3.10.00	3.10. BIOLOGICAL PROCESSES								
2.3.10.01	Microbial Activity in Biosphere	- Effect on biosphere characteristics - Effect on transport through biosphere							
2.3.11.00	3.11. THERMAL PROCESSES								
2.3.11.01	Effects of Repository Heat on Biosphere								

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
2.4.00.00	4. HUMAN BEHAVIOR								
2.4.01.00	4.01. HUMAN CHARACTERISTICS								
2.4.01.01	Human Characteristics	- Physiology - Metabolism - Adults, children [contributes to Radiological Toxicity in 3.3.06.02]							
2.4.01.02	Human Evolution	- Changing human characteristics - Sensitization to radiation - Changing lifestyle							
2.4.04.00	4.04. LIFESTYLE								
2.4.04.01	Human Lifestyle	- Diet and fluid intake (food, water, tobacco/drugs, etc.) - Dwellings - Household activities - Leisure activities [see also Land and Water Use in 2.4.08.01] [contributes to Ingestion in 3.3.04.01, Inhalation in 3.3.04.02, External Exposure in 3.3.04.03]	Note 1						
2.4.08.00	4.08. LAND AND WATER USE								
2.4.08.01	Land and Water Use	- Agricultural (irrigation, plowing, fertilization, crop storage, greenhouses, hydroponics) - Farms and Fisheries (feed, water, soil) - Urban / Industrial (development, energy production, earthworks, population density) - Natural / Wild (grasslands, forests, bush, surface water)							
2.4.08.02	Evolution of Land and Water Use	- New practices (agricultural, farming, fisheries) - Technological developments - Social developments (new/expanded communities)							
3.0.00.00	3. RADIONUCLIDE / CONTAMINANT FACTORS (BIOSPHERE)								
3.1.00.00	1. CONTAMINANT CHARACTERISTICS								
3.2.00.00	2. RELEASE / MIGRATION FACTORS								
3.3.00.00	3. EXPOSURE FACTORS								
3.3.01.00	3.01. RADIONUCLIDE / CONTAMINANT CONCENTRATIONS								
3.3.01.01	Radionuclides in Biosphere Media	- Soil - Surface Water - Air - Plant Uptake - Animal (Livestock, Fish) Uptake - Bioaccumulation [contributions from Radionuclide Release from Geologic Units in 2.2.09.65, Transport Through Biosphere in 2.3.09.51/52/53/54/55]							

UFD FEP Number	Description	Associated Processes	GDSM Salt	GDSM Xtal.	GDSM Clay	EBS - UFD Roadmap[2]	EBS Base[3]	Base Case	Sim. Case
3.3.01.02	Radionuclides in Food Products	- Diet and fluid sources (location, degree of contamination, dilution with uncontaminated sources) - Foodstuff and fluid processing and preparation (water filtration, cooking techniques) [see also Land and Water Use in 2.4.08.01, Radionuclides in Biosphere Media in 3.3.01.01]	Note 1						
3.3.01.03	Radionuclides in Non-Food Products	- Dwellings (location, building materials and sources, fuel sources) - Household products (clothing and sources, furniture and sources, tobacco, pets) - Biosphere media [see also Land and Water Use in 2.4.08.01, Radionuclides in Biosphere Media in 3.3.01.01]							
3.3.04.00	3.04. EXPOSURE MODES								
3.3.04.01	Ingestion	- Food products - Soil, surface water	Note 1					√	√
3.3.04.02	Inhalation	- Gases and vapors - Suspended particulates (dust, smoke, pollen)							
3.3.04.03	External Exposure	- Non-Food products - Soil, surface water							
3.3.06.00	3.06. TOXICITY / EFFECTS								
3.3.06.01	Radiation Doses	- Exposure rates (ingestion, inhalation, external exposure) - Dose conversion factors - Gases and vapors - Suspended particulates (dust, smoke, pollen)	Note 1	Note 1				√	√
3.3.06.02	Radiological Toxicity and Effects	- Human health effects from radiation doses							
3.3.06.03	Non-Radiological Toxicity and Effects	- Human health effects from non-radiological toxicity							

[1] From Vaughn et al. (2011). Any FEP that is reported as partially included has "Note 1" inserted here. This generally includes FEPs that could be implemented by changing parameter values based on judgment or other input, but which were not necessarily addressed in the Vaughn et al. (2011) generic PA models.
[2] FEPS identified as high priority by Nutt (2011), with potential to distinguish DPC direct disposal from other disposal concepts.
[3] From Hardin (2012), these are recommendations for EBS model implementation, to address repository design related questions.

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Appendix A – Human Intrusion Scenarios for Spent Nuclear Fuel: Borehole/Waste Package Intersections

A.1 Introduction

In many spent nuclear fuel (SNF) repository concepts currently under consideration, a major contribution to dose could be human intrusion via inadvertent drilling into the subsurface repository. Parameters for assessing human intrusion describe the number of holes drilled through the repository, and the number of waste packages intersected. For hard rock (represented by crystalline rock in this analysis) the likelihood of drilling through the repository is lower, as discussed below. In sedimentary host rock (e.g., salt or shale) a repository is more likely to be situated proximal to economic resources such as oil and gas, coal, or potash. Gasda et al. (2004) evaluated well densities in the Alberta Basin, and found more than 200,000 wells over an area of 468,000 km^2, yielding an average frequency of 0.48 wells/km^2. In a similar study, Nicot (2009) documented oil and gas wells in Texas and found over 1.1 million, mostly in the Permian Basin and along the Gulf Coast. In the Gulf Coast more than 125,000 wells were identified in an area of approximately 50,000 km^2, yielding an average density of 2.4 wells/km^2. Note that with most oil and gas exploration and development the boreholes tend to be clustered, for example Nicot (2009) found local densities as high as 100 wells/km^2 near salt domes. This uncertainty is part of the reason for using stylized scenarios with borehole frequency or waste package intersection rates specified by regulation.

Recognizing the variability and uncertainty in drilling rates, 40 CFR 191 (Appendix C) "*Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High Level and Transuranic Radioactive Wastes*" states that:

> *...the likelihood of such inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer of repository area per 10,000 years for geologic repositories in proximity to sedimentary rock formations, or more than 3 boreholes per square kilometer per 10,000 years for repositories in other geologic formations.*

While 40 CFR 191 provides general regulations for assessing the frequency of human intrusion, these are generally superseded by site-specific regulations. The only existing site-specific regulation for a SNF repository in the U.S. is 10 CFR 63: "*Disposal of High Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada*." The stylized scenario described in this regulation considers the impact of one borehole intersecting a waste package. By comparison, regulations for the Waste Isolation Pilot Plant (WIPP), a repository for transuranic waste (40 CFR 194: "*Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations*") state that the frequency of boreholes drilled through the repository is more than 58 boreholes/km^2 per 10,000 years (DOE 2009).

This appendix assesses the number of borehole-waste package intersections expected to occur for SNF repositories sited in hard rock settings and in sedimentary basins, based on the borehole frequency limits quoted above from 40 CFR 191: 3 boreholes/km^2 per 10,000 years for crystalline rock (representing hard rock options for this analysis), and 30 boreholes/km^2 per 10,000 years for sedimentary basins (e.g., salt or shale). It also examines how the number of borehole/waste package intersections varies with waste package size (ranging up to packages containing 32-PWR size DPCs or BWR equivalent) and orientation (horizontal or vertical).

Whereas the human intrusion assessment for the WIPP considers "cavings and cuttings" of waste that would be transferred to the surface by drilling (DOE 2009), the approach described in 10 CFR 63 ignores this potential dose pathway because it would not show "…how well a particular repository site and design would protect the public at large" (10CFR63, 66 FR 55732, p. 55761, Supplementary Information, 3.10 Human Intrusion Standard). The approaches to license application safety analysis described in 10 CFR 63 are assumed to be applicable to DPC direct disposal (Miller et al. 2012). However, 10 CFR 63 is specific to the Yucca Mountain site, so for this analysis the borehole frequency is assumed to be described by 40 CFR 191. For details of the Yucca Mountain and WIPP assessments the reader is referred to separately published analyses (SNL 2008; DOE 2009).

Regardless of how dose is calculated, any regulatory framework will require estimates of the number of borehole/waste package intersections. In low permeability host media radionuclide releases would likely be insignificant unless waste packages are actually penetrated. This appendix provides a framework for estimating the potential number of borehole/waste package intersections from drilling.

A.2 Parameters Needed

To calculate the potential number of borehole/waste package intersections for a repository, several parameters are needed:

Borehole frequency—As noted above, the rates from 40 CFR 191 are used. These are specified over a time frame of 10,000 years, which is the time limit for considering a human intrusion event, according to both 10 CFR 60 and 10 CFR63 (the consequences of human intrusion may be considered beyond 10,000 years).

Waste package dimensions—Package length and diameter are used to calculate cross-sectional area for horizontal and vertical emplacement (Table A-1). Several different package sizes are compared in order to assess the effects of waste package size and capacity on the number of fuel assemblies exposed by borehole/waste package intersections.

Table A-1. Waste Package Dimensions

PWR/BWR	Length, m	Diameter, m	# WPs for a 140,000 MT repository
4/9	5	0.82	82,583
12/24	5	1.29	28,792
21/44	5	1.60	16,157
32/68	5	2.00	~10,000 (est)

Source: Hardin et al. (2012, Tables 1.4-1 & 4-1)

Borehole diameter—It is assumed for this analysis that:

- Waste packages are substantially degraded when drilling occurs, so that any borehole-waste package intersection will expose the entire inventory of that waste package.
- Waste package degradation does not change the overall dimensions of the waste package.

These assumptions are generally consistent with previous analyses (e.g., DOE 2009) and they simplify the calculation. The borehole location can be treated as a single point in X-Y space, if the dimensions of the waste package "target" are increased by the radius of the borehole (Figure A-1).

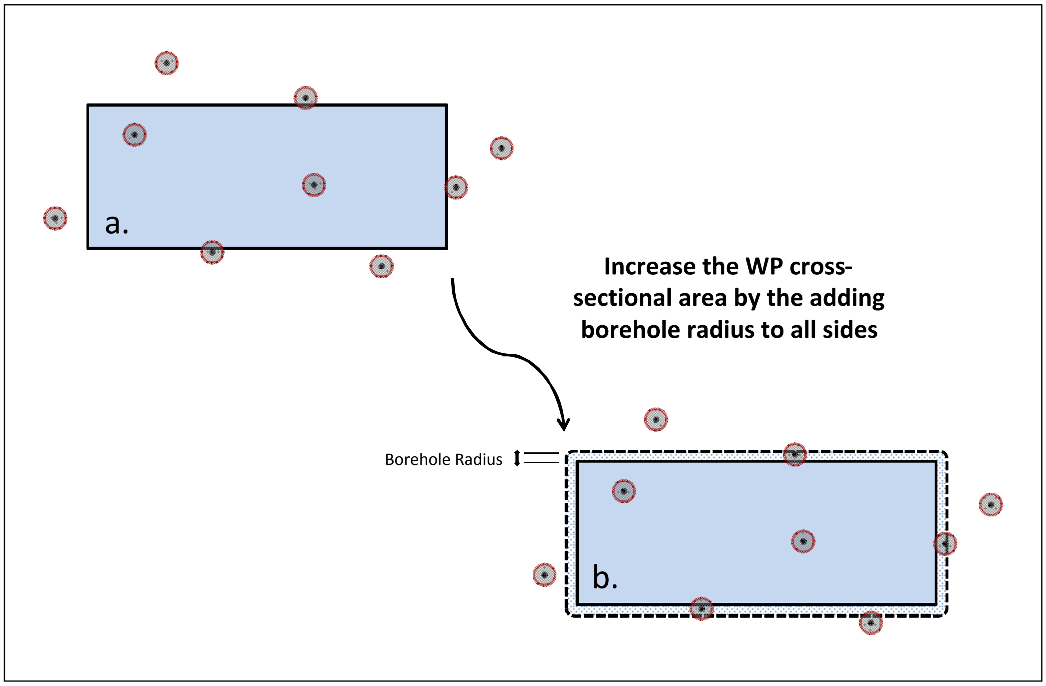


Figure A-1. Schematic of Borehole–Waste Package Intersection Geometry

Borehole diameter is treated parametrically over a range from 8 to 13 inches. This range encompasses the 11-inch diameter typical of oil and gas boreholes that penetrate the Salado salt formation in southeastern New Mexico.

Repository layout—The layout determines the layout area per waste package, and the total repository area. This scoping analysis assumes that waste packages in sedimentary host media (and particularly salt) will be emplaced on a 30 m × 30 m grid, or a single-package layout area of 900 m^2 per package. This area is appropriate for larger, hotter packages containing 32-PWR (or BWR equivalent) size DPCs (Hardin and Voegele 2013) and is greater than for previously described concepts with smaller packages (Hardin et al. 2012). For the hard rock repository, it is assumed that waste packages will be emplaced on a 20 m × 70 m grid, corresponding to a single-package layout area of 1,400 m^2 per package (Hardin and Voegele 2013).

A.3 Calculating the Number of Intersections

A.3.1 Expected Number of Intersections

In the simplest approach, the mean probability of intersection per package, at any given borehole frequency (boreholes/km^2), can be calculated from the cross-sectional plan area of a single waste package, regardless of the repository layout. It is given by the borehole frequency multiplied by the waste package cross-sectional area. Thus, for a sedimentary basin with a borehole frequency of 30 boreholes/km^2 and a waste package cross-sectional area of 10 m^2/package for each 32-PWR size package (Table A-1), the mean probability of intersection per package is 0.0003 (= 10 m^2 × 10^{-6} km^2/m^2 × 30 boreholes/km^2). Multiplying by the total number of waste packages in the repository (10,000 in this case) gives the expected number of borehole/waste package intersections per repository (= 3 in this case).

Equivalently, the mean predicted number of intersections for the entire repository is equal to the total waste package cross-sectional area (km^2) multiplied by the borehole frequency. For instance, in a 140,000 MT repository using 32-PWR size waste packages emplaced horizontally, the total waste package cross-sectional area is 0.1 km^2 (Table A-2). Thus, for an assumed sedimentary repository borehole frequency of 30 boreholes per km^2, one would expect three waste package intersections per repository, accessing 96 SNF PWR assemblies.

The expected number of borehole/waste package intersections at a borehole frequency of 1 borehole/km^2 is equal to the total cross-sectional area of waste packages in a square kilometer, divided by 1 km^2. The expected number of intersections at any borehole frequency can be found by multiplying the frequency (in boreholes per km^2) by this result. Thus, the expected number of intersections varies linearly with the borehole frequency.

These results illustrate three points: 1) the expected number of intersections is much lower for waste packages emplaced vertically; 2) smaller packages have a greater total cross-sectional area and thus a greater expected probability of intersection than larger packages; and 3) although the expected probability of intersection is lower for larger packages, the expected number of exposed fuel assemblies *increases*.

Table A-2. Total Plan Cross-Sectional Area of Waste Packages

Waste Package Dimensions				Footprint per WP, m^2		# of WPs*	Summed WP area, km^2	
PWR	BWR	Length, m	Diameter, m	Horizontal	Vertical		Horizontal	Vertical
4	**9**	5	0.82	4.10	0.53	82583	0.339	0.0436
12	**24**	5	1.29	6.45	1.31	28792	0.186	0.0376
21	**44**	5	1.60	8.00	2.01	16157	0.129	0.0325
32	**68**	5	2.00	10.0	3.14	~10000	0.100	0.0314

* For a 140,000 MT repository

The calculations in Table A-2 do not include the effect of the borehole diameter, which can be implemented by increasing the effective dimensions of the waste packages (Figure A-1). The total waste package cross-sectional areas accounting for boreholes from 8 to 13 inches in diameter are given in Table A-3 and illustrated in Figure A-2. The effect of borehole diameter is greater for the smaller waste packages because the relative change in the waste package cross-sectional area is greater. The effect is greater for vertical emplacement for the same reason. Including the borehole diameter significantly increases the waste package cross-sectional areas (adjusted or "apparent" areas in Figure A-2) and probabilities of intersection. For vertically-emplaced 4PWR/9BWR waste packages, the probability of intersection increases by 56% for the 8-inch boreholes and by 97% for 13-inch boreholes, relative to the unadjusted value (comparing Tables A-2 and A-3). For horizontally emplaced packages the increase is smaller. For 32-PWR size packages, including borehole diameter increases the probability of intersection by 21% (8-inch) to 36% (13-inch) for vertical emplacement, and 7.2% to 12% for horizontal emplacement.

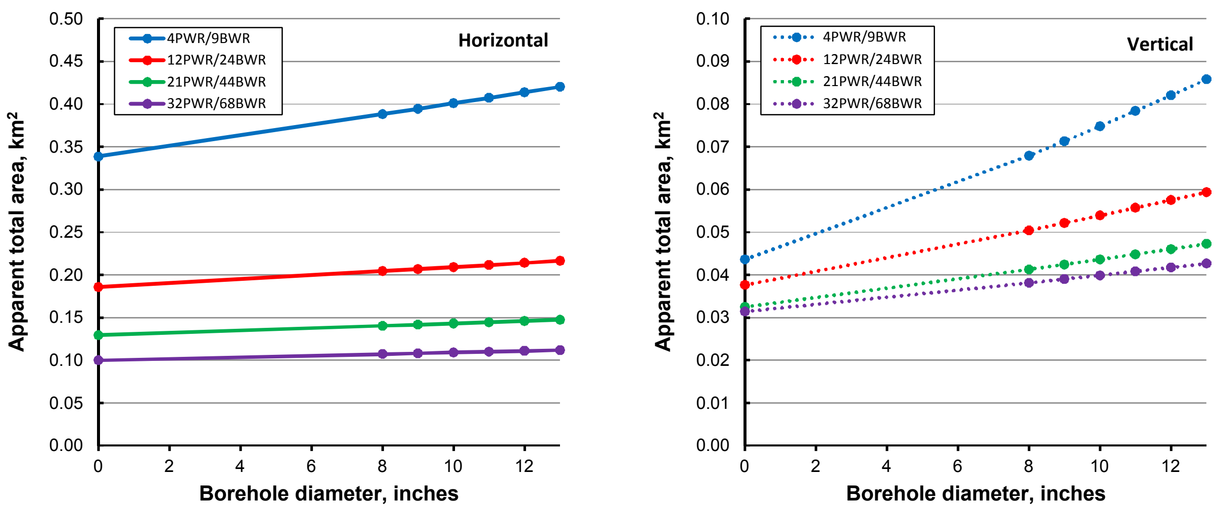


Figure A-2. Change in Total Waste Package Cross-Sectional Area ("Apparent") as a Function of Borehole Diameter: for (left) Horizontal Emplacement, and (right) Vertical Emplacement

Table A-3. Effect of Borehole Diameter Adjustment on Waste Package Cross-Sectional Area

Waste Package		# of WPs*	Borehole Diameter, in.	Adjusted Cross-Sectional Area, m^2/package		Total Adjusted Cross-Sectional Area, km^2	
PWR	BWR			Horizontal	Vertical	Horizontal	Vertical
4	**9**	82,583	0	4.10	0.53	0.339	0.044
			8	4.70	0.82	0.388	0.068
			9	4.78	0.86	0.395	0.071
			10	4.86	0.91	0.401	0.075
			11	4.93	0.95	0.407	0.078
			12	5.01	0.99	0.414	0.082
			13	5.09	1.04	0.420	0.086
12	**24**	28,792	0	6.45	1.31	0.186	0.038
			8	7.10	1.75	0.204	0.050
			9	7.18	1.81	0.207	0.052
			10	7.26	1.87	0.209	0.054
			11	7.35	1.93	0.212	0.056
			12	7.43	2.00	0.214	0.058
			13	7.52	2.06	0.216	0.059
21	**44**	16,157	0	8.00	2.01	0.129	0.032
			8	8.68	2.55	0.140	0.041
			9	8.77	2.63	0.142	0.042
			10	8.85	2.70	0.143	0.044
			11	8.94	2.77	0.144	0.045
			12	9.03	2.85	0.146	0.046
			13	9.12	2.93	0.147	0.047
32	**68**	10,000	0	10.00	3.14	0.100	0.031
			8	10.72	3.81	0.107	0.038
			9	10.81	3.90	0.108	0.039
			10	10.91	3.99	0.109	0.040
			11	11.00	4.08	0.110	0.041
			12	11.09	4.17	0.111	0.042
			13	11.18	4.26	0.112	0.043

* For a 140,000 MT repository

A.3.2 Statistical Distribution of the Number of Intersections

As noted above, for any given borehole frequency (boreholes/km^2) the expected number of borehole-waste package intersections is independent of repository size or layout. The expected value does not change with waste package spacing, because an increase in waste package spacing results in a proportionally larger repository footprint, hence, more boreholes are drilled (for a given borehole frequency).

While the *expected* number of intersections does not depend on repository size or layout, the spatial distribution of boreholes is random, and the statistical range of the number of intersections does depend on repository layout. For probabilistic performance assessment this range could be important, so the statistical distribution of the number of borehole/waste package intersections is developed here, based on a given number of boreholes drilled.

The approach uses the layout area assigned to each waste package in the repository (i.e., single-package layout area) and applies the binomial distribution. Thus, using the probability of intersection for a single borehole within the layout area for a single package (Table A-4), the binomial distribution represents the probability for a given number of intersections, for a specified number of boreholes drilled. The probability mass function (PMF) for a binomial distribution is defined as:

$$f(k; n, p) = \Pr(K = k) = \binom{n}{k} p^k (1-p)^{n-k} \qquad \text{Eq. A-1}$$

For $k = 0,1,2,\ldots n$, where

$$\binom{n}{k} = \frac{n!}{k!\,(n-k)!}$$

As applied here, n is the total number of boreholes within the repository footprint, and p is the probability of intersection for any one borehole drilled within the layout area for one waste package (Table A-4). The PMF provides the probability of getting k intersections for n boreholes. Note that n is an integer. It is not possible to drill a partial borehole, so the predicted number of intersections is conservatively rounded up. For small numbers of boreholes the effect of this rounding can be significant as discussed below.

As an example calculation, consider the statistical distributions for the number of intersections for the sedimentary case (single-package layout area = 900 m^2/package) and the hard rock case (1,400 m^2/package). The calculation is done for 32-PWR size packages, and boreholes with 8- and 13-inch diameter (bounding the range considered). The parameters used are shown in Table A-4. Figure A-3 shows PMFs for the number of intersections, using the maximum borehole frequencies from 40 CFR 191 (Section A.2 above). For the sedimentary repository case with horizontal emplacement the PMF peaks at 3 intersections, but 8 intersections will occur more than 1% of the time. For vertical emplacement the most probable number of intersections is 1, and greater than 4 intersections will occur less than 1% of the time. In the hard rock case the probability of no intersections is 72% for horizontal emplacement and 88% for vertical emplacement.

Table A-4. Parameters Used in Calculating the PMF for Number of Boreholes Intersecting a Waste Package

Waste Package Dimensions			Borehole Diameter		WP Cross-Sectional Area Adjusted for Borehole Dia., m^2		Layout Area per Package, m^2	Probability (p) of Intersection for a Single Borehole in the Layout Area for a Single Package		Total # of WPs	Total Repository Area, km^2
PWR/BWR	Length, m	Dia., m	in	m	Horizontal	Vertical		Horizontal	Vertical		
Salt Repository											
32/68	5	2	8	0.20	10.72	3.81	900	1.19E-02	4.24E-03	10,000	9
			13	0.33	11.18	4.26		1.24E-02	4.74E-03		
Hard Rock Repository											
32/68	5	2	8	0.20	10.72	3.81	1,400	7.66E-03	2.72E-03	10,000	14
			13	0.33	11.18	4.26		7.99E-03	3.05E-03		

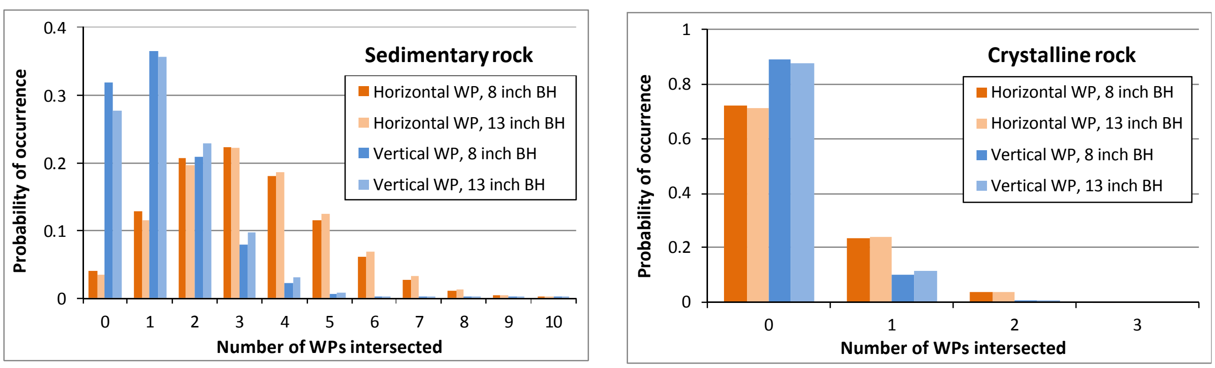
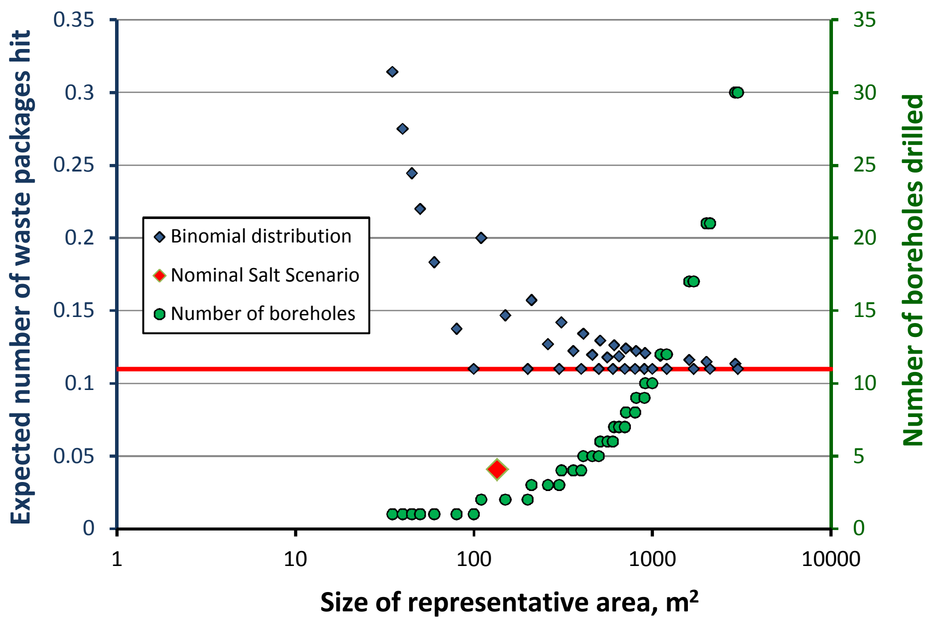


Figure A-3. Probability Mass Functions for the Number of Intersections with 32-PWR Size Packages, for: (left) the Sedimentary (Salt) Repository Case (30 boreholes/km^2), and (right) the Hard Rock (Crystalline) Repository Case (3 boreholes/km^2)

The expected number of intersections can be calculated from the PMFs by summing the product of the probability of occurrence (y-axis) multiplied by the number of waste packages intersected (x-axis):

$$\text{Expected number} = \sum_0^n f(k; n, p) \times k \qquad \text{Eq. A-2}$$

It might be anticipated that the expected number of intersections calculated this way would be equal to the simple estimates discussed in Section A.3.1 (Table A-3). This is true only when the total number of boreholes calculated from the repository footprint is an integer. In general, the calculated total number of boreholes will not be an integer and will have to be rounded up for use with the binomial distribution. Accordingly, the expected number of intersections from Eq. A-2 will not be equal to the expected numbers based on cross-sectional areas in Table A-3, but will vary as a function of the rounding error. The rounding effect can be quite significant for small numbers of boreholes. To illustrate this, the single-package layout area (for horizontally emplaced 32-PWR size packages, or BWR equivalent) was varied from 35 m^2 to 3000 m^2 with a borehole frequency of 1 borehole per km^2, to show the possible effect from rounding the number of boreholes (Figure A-4). The effect of rounding can be significant in a relative sense, for small numbers of boreholes drilled, but it decreases rapidly as the number of boreholes increases. Once the repository total layout area is large enough that the expected number of boreholes drilled is 10 or greater, the potential discrepancy in the expected number of intersections is 0.1 or less (Figure A-4). This threshold would be met many times over for a repository in sedimentary or hard rock, for the U.S. SNF inventory (e.g., Table A-4 which describes a repository for SNF in 32-PWR size packages).



Note: The red line represents the expected probability of intersection calculated from total cross-sectional area of the waste packages. Borehole frequency = 1 borehole/km^2. The representative area is the single-package layout area.

Figure A-4. Effect of Rounding Up the Number of Boreholes Drilled to the Next Integer for the Binomial Distribution.

A.3.3 Effect of Repository Layout Size

As noted earlier, for a given borehole frequency (boreholes/km^2) the expected number of intersections, which corresponds to the mean of the PMF, will not change with waste package spacing because an increase in waste package spacing results in a proportionally larger repository footprint, and hence, more boreholes drilled. The PMF, however, must change as the number of boreholes increases, because there is a non-zero probability that as many as all of the boreholes could intersect waste packages. Because the binomial distribution is a factorial function, the probability decreases rapidly for each additional intersection. As an example, consider the sedimentary repository case, in which the layout area for each waste package is

900 m^2. While holding the borehole frequency constant at 1 borehole/km^2, the single-package layout area for each waste package is varied, changing the repository footprint, and hence the number of boreholes intersecting the footprint (Table A-5). Single-package layout areas were chosen to result in an integer number of boreholes, to avoid the effect of rounding discussed in previously. As the number of boreholes changes from 1 to 64, the probability of intersecting 0 waste packages changes from 89.00% to 89.58%; the probability of intersecting one waste package changes from 11.00% to 9.87%; and the probability of intersecting 2 waste packages changes from 0% (for the 1 borehole case) to 0.54%. It is clear that changing the single-package layout area (i.e., spacings between waste packages) changes the number of boreholes drilled but will have only a minor effect on the shape of the PMF.

Table A-5. Effect of Repository Layout Size on the PMF for Borehole–Waste Package Intersections (1 borehole/km^2, 11 inch borehole diameter, horizontal emplacement, 32-PWR size packages).

Layout Area per WP, m^2	**100**	**200**	**400**	**800**	**1600**	**3200**	**6400**
Total Repository area, km^2	**1**	**2**	**4**	**8**	**16**	**32**	**64**
# of Boreholes (at 1 borehole/km^2)	**1**	**2**	**4**	**8**	**16**	**32**	**64**
# of Intersections (*n*)	**PMF: Probability of Intersecting *n* Packages**						
0	0.8900	0.8930	0.8945	0.8952	0.8955	0.8957	0.8958
1	0.1100	0.1039	0.1012	0.0998	0.0992	0.0988	0.0987
2		0.0030	0.0043	0.0049	0.0051	0.0053	0.0054
3			0.0001	0.0001	0.0002	0.0002	0.0002
4			5.71E-07	2.37E-06	3.74E-06	4.56E-06	5.00E-06
5				2.64E-08	6.21E-08	8.80E-08	1.03E-07
6				1.84E-10	7.88E-10	1.37E-09	1.75E-09
7				7.32E-13	7.79E-12	1.75E-11	2.49E-11
8				1.28E-15	6.07E-14	1.88E-13	3.06E-13
9					3.73E-16	1.73E-15	3.27E-15
10					1.81E-18	1.37E-17	3.10E-17

In a second example, consider the sedimentary and hard rock cases (Section A.2). If we assume the same borehole frequency of 1 borehole/km^2, then these two cases are equivalent except for waste package spacing and repository size; there will be 9 boreholes through the repository in the sedimentary case (9 km^2), and 14 boreholes for the hard rock case (14 km^2). The PMFs for the number of intersections are shown in Figure A-5. For the sedimentary case the most likely number of intersections is zero, and that will occur about 90% of the time for horizontal emplacement, and about 96% of the time for vertical emplacement. The second most probable number of intersections is 1, and there is a small chance of 2 intersections, especially for horizontally emplaced packages (~0.5%). Because the largest waste package is being evaluated, the effect of different borehole diameters is small. The results for the hard rock repository are almost identical to the sedimentary results, since as discussed earlier, the expected number of waste packages intersected, which corresponds to the mean of each distribution, must be the same. The change in the number of boreholes (from 9 to 14) slightly changes the shape of the curves, but the change is small. For instance, for horizontal emplacement in a hard rock repository, the probability of one intersection is 0.04% lower than in the corresponding sedimentary cases, and the probability of two intersections is about 0.02% greater. Small differences occur in the low-probability tails of the curves as well.

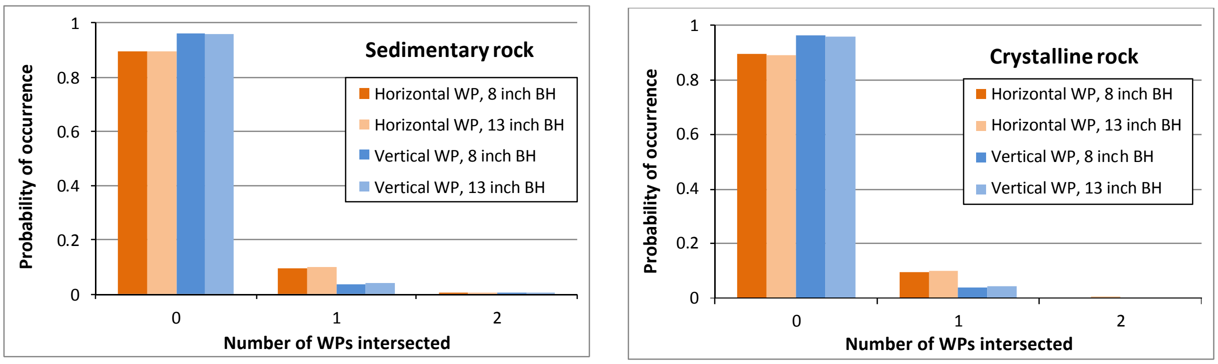


Figure A-5. Probability Mass Functions for the Number of Intersections at a Borehole Frequency of 1 borehole/km^2, for the Sedimentary (Salt) Repository Case

The foregoing sensitivity analysis of two parameters (borehole frequency and repository size), which could affect the number of boreholes drilled, shows that they have very different effects on the statistical distribution for the number of intersections. When the borehole frequency (boreholes/km^2) is increased, the PMFs for number of intersections shift to higher values and broaden (Figure A-3); however, when the repository size is increased without changing the borehole frequency there is little change in the PMF (Table A-5 and Figure A-5).

A.3.4 Effect of Changing Waste Package Size

The foregoing analysis has shown that the repository layout size has little effect on the expected number of waste package intersections, and would have no effect at all, but for the discretization of the predicted number of boreholes, a step necessary to generate the PMF. (Note that this result is specific to the problem formulation where the borehole frequency is established *a priori*, for example by regulation.) Repository geometry also has little effect on the PMFs and cumulative distribution functions (CDFs) for the number of intersections. The parameters of importance to the number of intersections are the borehole frequency (boreholes/km^2) and the total cross-sectional area of the waste packages (adjusted to account for borehole diameter).

This section evaluates the effect from using different size waste packages in the sedimentary and hard rock cases while keeping all other parameters the same. A borehole frequency of 30 boreholes/km^2 is assumed for the sedimentary case, and 3 boreholes/km^2 for the hard rock case. Borehole diameter is assumed to be 11 inches. The single-package layout area is held constant, so comparisons are best limited to similar packages, for example, between 21- and 32-PWR sizes. Changing the waste package capacity while maintaining the same single-package layout area means that the total repository footprint area will change. Table A-6 lists the total area of the repository and the estimated number of boreholes drilled within the repository footprint at the assumed borehole frequency, for the sedimentary and hard rock cases.

The results for the sedimentary rock repository are shown in Figure A-6. As expected, the smaller and more numerous the waste packages, the more intersections are predicted. For vertical emplacement the expected number of intersections varies from 2.35 for 4-PWR size packages, to 1.17 for 32-PWR size waste packages. For horizontal emplacement the expected number of intersections varies from 12.2 for the 4-PWR package, to 3.50 for the 32-PWR package. The results for the hard rock repository are shown in Figure A-7. The expected number of intersections for vertical emplacement varies from 0.235 to 0.117, and for horizontal emplacement from 1.22 to 0.350, for the 4-PWR and 32-PWR size packages, respectively.

Table A-6. Total Repository Area for the Sedimentary (Salt) and Hard Rock Cases Assuming that the Single Waste Package Layout Area is the Same for Different Package Types

WP Size PWR/BWR	# of WPs	Host Rock Type	Single-Package Layout Area, m^2/WP	Total Repository Area, km^2	# Boreholes Drilled
4/9	82,583	Sed. (salt)	900	74.32	2,230
		Hard Rock	1,400	115.62	347
12/24	28,792	Sed. (salt)	900	25.91	778
		Hard Rock	1,400	40.31	121
21/44	16,157	Sed. (salt)	900	14.54	437
		Hard Rock	1,400	22.62	68
32/68	10,000	Sed. (salt)	900	9.00	270
		Hard Rock	1,400	14.00	42

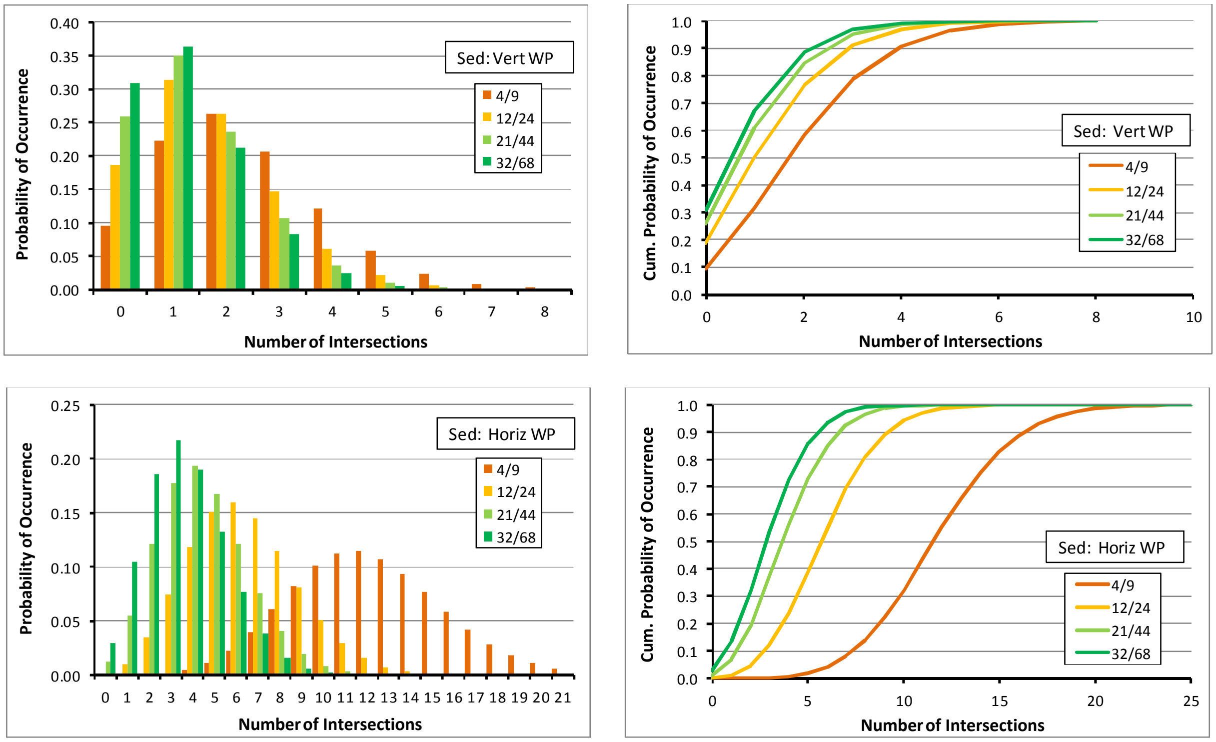


Figure A-6. Probability Mass Functions (left) and Cumulative Distributions (right) for the Sedimentary (Salt) Repository, with Waste Packages in: (upper) Vertical; or (lower) Horizontal Orientation

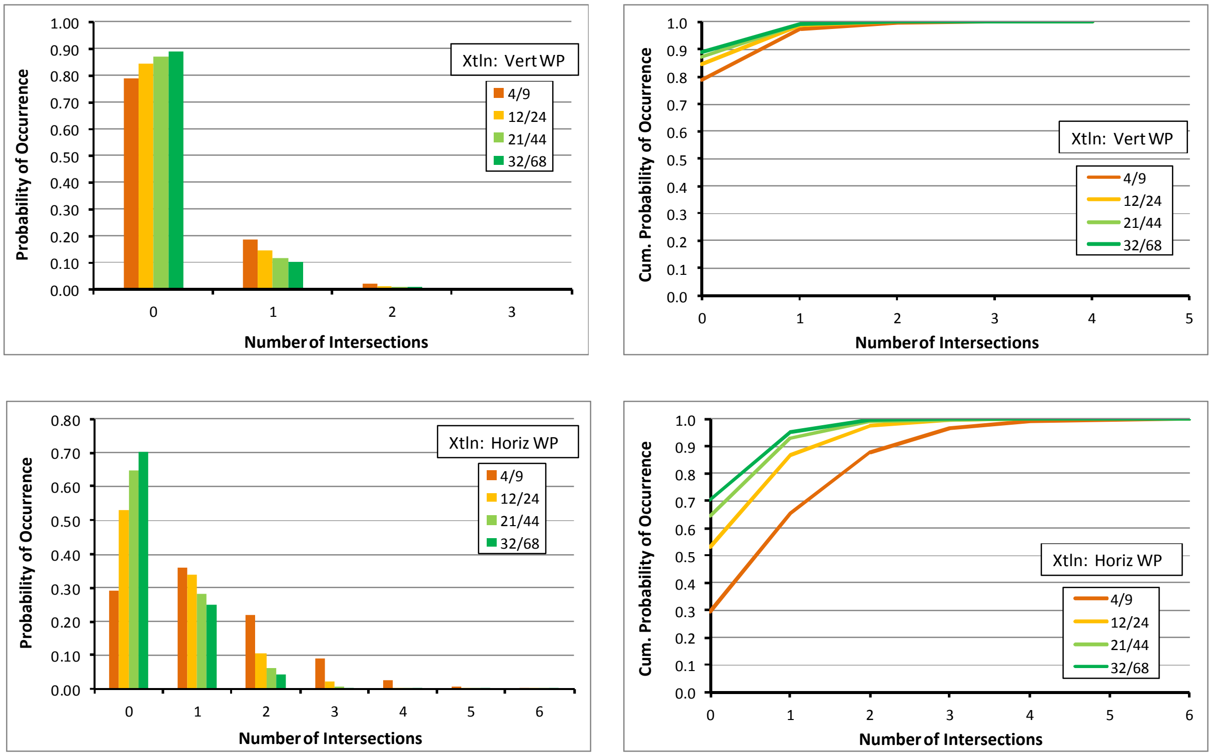


Figure A-7. Probability Mass Functions (left) and Cumulative Distributions (right) for the Hard Rock (Crystalline) Repository, with Waste Packages in: (upper) Vertical; or (lower) Horizontal Orientation

Larger waste packages result in fewer borehole/waste package intersections, other factors held constant. However, the different waste load of each container must also be considered. This is done by evaluating the expected number of SNF assemblies exposed in each case. This is equal to the sum of the products of the probabilities of a given number of waste packages being intersected and the number of assemblies in each waste package:

$$\text{Expected \# Assemblies Exposed} = \text{Expected Number of Intersections} \times \text{\# Assemblies per WP} \qquad \text{Eq. A-3}$$

The results for the sedimentary repository case are shown in Table A-7. Although the expected number of waste packages intersected decreases with increasing waste package size, more SNF assemblies are exposed. The results for the hard rock case (Table A-8) are consistent.

Table A-7. Expected Number of Fuel Assemblies Exposed by Borehole-Waste Package Intersection in the Sedimentary (Salt) Repository Case (30 boreholes/km^2)

WP Orientation	WP type	Expected # of WPs Intersected	Expected # of PWR Assemblies Exposed
Vertical	4/9	2.35	9.4
	12/14	1.67	20.0
	21/44	1.35	28.4
	32/68	1.17	37.4
Horizontal	4/9	12.22	48.9
	12/24	6.35	76.2
	21/44	4.34	91.1
	32/68	3.49	112

Table A-8. Expected Number of Fuel Assemblies Exposed by Borehole-Waste Package Intersection in the Hard Rock Repository Case (3 boreholes/km^2)

WP Orientation	WP type	# WPs Intersected	# PWR Assemblies Accessed
Vertical	4/9	0.235	0.94
	12/14	1.22	4.89
	21/44	0.167	2.01
	32/68	0.635	7.62
Horizontal	4/9	0.135	2.83
	12/24	0.434	9.12
	21/44	0.117	3.74
	32/68	0.350	11.2

Note that the relative importance of waste package intersection versus the number of assemblies exposed is not known, and may depend on radionuclide transport details of the human intrusion scenario, the timing of borehole intersection, and the waste isolation performance objectives given by regulation. If intersection of even a single waste package of any size is sufficient to exceed the performance objectives, then larger packages are beneficial. If the quantity of SNF exposed by borehole intersections is critical, then smaller packages are beneficial.

A.3.5 Other Repository Geometries

The general trends presented here are applicable to repository geometries, such as multi-level repositories, with modifications to account for single waste package layout area and total repository area. For instance, assume a two-level repository, for which two cases might be considered:

- Waste packages in each layer are interspersed between those in the other layer. This might be done to provide maximum spacing for thermal considerations. In this case, the single-package layout area and the repository footprint are smaller (half that for a single layer) but the summed waste package cross-sectional area is the same. For a given borehole frequency the expected number of intersections would be the same as for the single-layer case. However, there would be half as many boreholes so there would be slight differences in the PMF for the number of intersections (for example, Table A-6).
- Waste packages in each layer are aligned vertically. For instance, waste packages could be emplaced vertically in large-diameter boreholes (two to a borehole) drilled from underground galleries, with salt backfill between them. Here, the layout area for each pair of waste packages is the same as for one package in the single-layer case, and the repository footprint is half that of the single layer case. The total waste package cross-sectional area is also half that of the single-layer case. Hence, the calculated number of intersections would be half that of the single-layer case but each intersection would be with two packages, exposing twice as many fuel assemblies. Therefore, the expected number of package intersections (and the expected quantity of fuel exposed) would be exactly the same as for the single-layer case. The PMF would differ, however, so that the probability of zero intersections would be greater, and intersections with odd numbers of waste packages would not be predicted.

A.4 Conclusions

This analysis evaluates the number of waste packages that might be inadvertently intersected by boreholes, should SNF waste repositories be situated in sedimentary basins or hard rock (represented by crystalline rock for this analysis). The analysis is based on *a priori* borehole frequency, such as that specified in 40 CFR 191 for sedimentary and crystalline rock settings.

The expected number of borehole/waste package intersections at a borehole frequency of 1 borehole/km^2 is equal to the total cross-sectional area of waste packages in a square kilometer, divided by 1 km^2. The expected number of intersections at any borehole frequency can be found by multiplying the frequency (in boreholes per km^2) by this result.

For a given number of boreholes drilled within the repository footprint, a binomial distribution can be used to calculate the probability mass function for the number of intersections. However, the expected number of intersections calculated from the total waste package cross-sectional area is not preserved because of rounding of the total number of boreholes. This effect is significant only when small numbers of boreholes (e.g., fewer than 10) are considered.

The most important parameters affecting the number of waste package intersections are the borehole frequency (boreholes/km^2) and the waste package geometry (total waste package cross-sectional area). The expected number of intersections varies linearly with the borehole frequency. The waste package cross-sectional area defines the size of the “target” and is adjusted to account for borehole diameter (e.g., up to 13 inches). This results in significantly more intersections, especially for smaller waste packages. Minimizing waste package cross-sectional area by using vertical emplacement can substantially decrease the number of borehole intersections. For a given total repository inventory and borehole frequency, use of larger waste packages results in fewer borehole intersections. However, the quantity of SNF exposed by borehole intersections is greater with larger packages, other factors held constant.

It is notable that repository geometry has little impact on the expected number of borehole-waste package intersections. For a given borehole frequency (boreholes/km^2), increasing waste package spacing decreases the probability of intersecting a waste package within the single-package layout area assigned to that package, but this is exactly offset by the increase in total repository area, and hence, the total number of boreholes drilled. Increasing the repository area does have a slight effect on the probability mass function for the number of intersections.

It can be concluded that, for repositories in sedimentary rock (e.g., salt) the probability of at least one borehole/waste package intersection is significant. For hard rock (crystalline) repositories the probability is an order-of-magnitude less. Comparing the largest and smallest waste packages analyzed (32-PWR and 4-PWR sizes, or BWR equivalents) the expected number of intersections decreases for larger packages, but the expected quantity of fuel exposed increases (e.g., a factor of 2 greater).

Finally, it should be noted that this analysis has not considered the timing of human intrusion, or the pathway and processes by which radionuclides could be released to the environment.