Deep Borehole Disposal Safety Analysis

Fuel Cycle Research & Development

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

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FIGURES

TABLES

ACRONYMS

1-D	one-dimensional
2-D	two-dimensional
API	American Petroleum Institute
BOP	blowout preventer
BRC	Blue Ribbon Commission on America's Nuclear Future
CB	Characterization Borehole
CEDE	committed effective dose equivalent
CFR	Code of Federal Regulations
DBD	deep borehole disposal
DBFT	Deep Borehole Field Test
DOE	U.S. Department of Energy
DOE-NE	DOE Office of Nuclear Energy
DRZ	disturbed rock zone
EDZ	excavation disturbed zone
EPA	U.S. Environmental Protection Agency
EZ	emplacement zone
FCT	DOE-NE Fuel Cycle Technologies Program
FEPs	features, events, and processes
FoS	factor of safety
FTB	Field Test Borehole
HLW	high-level radioactive waste
IAEA	International Atomic Energy Agency
KTB	Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland (German Continental Deep Drilling Programme)
KURT	Korean Underground Research Tunnel
MCO	multicanister overpack
MDO	management and disposal organization
NDA	U.K. Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency
NEPA	National Environmental Policy Act
NWPA	Nuclear Waste Policy Act
NRC	U.S. Nuclear Regulatory Commission
NRDC	Natural Resources Defense Council

ACRONYMS (cont.)

NWTRB	U.S. Nuclear Waste Technical Review Board
OCRWM	Office of Civilian Radioactive Waste Management
OSHA	Occupational Safety and Health Administration
PA	performance assessment
PETSc	Portable Extensible Toolkit for Scientific Computation
QA	quality assurance
R&D	research and development
RCRA	Resource Conservation and Recovery Act
RD&D	research, development, and demonstration
RFP	request for proposal
RMEI	reasonably maximally exposed individual
SDWA	Safe Drinking Water Act
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SSCs	structures, systems, and components
SZ	seal zone
TBD	to be determined
TEDE	total effective dose equivalent
THCM	thermal, hydrologic, chemical, and mechanical
THCMBR	thermal, hydrologic, chemical, mechanical, biological, and radiological
TRL	technology readiness level
UBZ	upper borehole zone
UFD	DOE-NE Office of Used Nuclear Fuel Disposition Research and Development
UIC	Underground Injection Control
URL	underground research laboratory
USGS	U.S. Geological Survey
WESF	Waste Emplacement and Storage Facility
WF	waste form
WIPP	Waste Isolation Pilot Plant
WP	waste package

1. INTRODUCTION

This report presents a preliminary safety analysis for the deep borehole disposal (DBD) concept, using a safety case framework. A safety case is an integrated collection of qualitative and quantitative arguments, evidence, and analyses that substantiate the safety, and the level of confidence in the safety, of a geologic repository (Freeze et al. 2012, Section 1.1). This safety case framework for DBD follows the outline of the elements of a safety case and identifies the types of information that will be required to satisfy these elements. At this very preliminary phase of development, the DBD safety case focuses on the generic feasibility of the DBD concept. It is based on potential system designs, waste forms, engineering, and geologic conditions; however, no specific site or regulatory framework exists. It will progress to a site-specific safety case as the DBD concept advances into a site-specific phase, progressing through consent-based site selection and site investigation and characterization.

At this early phase of DBD development, the safety case framework provides an outline to organize and synthesize existing technical information and to identify unresolved issues and information gaps relevant to disposal of radioactive waste in deep boreholes. The issue and gap analysis will help prioritize future DBD research and development (R&D) activities with a focus on improving the defensibility of the safety case.

An overview of DBD is presented in Section 1.1. An overview of safety case development, including the individual elements of a safety case, is presented in Section 1.2. The remainder of the report, Sections 2 through 6, presents the current state of the safety case for DBD, with each section addressing a specific element of the safety case.

1.1 Deep Borehole Disposal Overview

1.1.1 History of Deep Borehole Disposal Research

DBD for the geologic isolation of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) has been considered for many years, beginning with evaluations of nuclear waste disposal options by the National Academy of Sciences in 1957 (NAS 1957). Efforts by the United States and the international community over the last half-century toward disposal of SNF and HLW (collectively referred to as high-activity waste[1]) have primarily focused on mined geological repositories. Nonetheless, evaluations of DBD have periodically continued in several countries. Selected references are listed in Table 1-1.

[1] The Nuclear Waste Policy Act (NWPA) defines “spent nuclear fuel” as “fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing” (NWPA 1983, Sec. 2(23)) and defines “high-level radioactive waste” as “(A) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (B) other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation” (NWPA 1983, Sec. 2(12)).

Table 1-1. DBD Publications by Country

Country / Region	References
Canada	Brunskill 2006; Jackson and Dormuth 2008, Section 9; Brunskill and Wilson 2011
East Asia	von Hippel and Hayes 2010; Chapman 2013
Japan	Tokunaga 2013
Germany	Bracke 2015; Schilling and Müller 2015
South Korea	Lee 2015
Sweden	Juhlin and Sandstedt 1989; Harrison 2000; Grundfelt 2013
Ukraine	Shestopalov et al. 2004
U.K.	Gibb 1999; Nirex 2004; Baldwin et al. 2008; Beswick 2008; Beswick et al. 2014
U.S.	O'Brien et al. 1979; Woodward-Clyde Consultants 1983; Sapiie and Driscoll 2009; Brady et al. 2009; Arnold et al. 2011; Vaughn et al. 2012; Arnold et al. 2013; Arnold et al. 2014; Bates 2015
U.S. (Excess Pu)	Ferguson 1994; Heiken et al. 1996; DOE 2014b, Section 5.2.5

In recent years, an updated conceptual evaluation of DBD and a preliminary performance assessment were completed (Brady et al. 2009), a reference design and operations methodology were developed using available drilling technology (Arnold et al. 2011), and site characterization methods were analyzed (Vaughn et al. 2012). These studies identified no fundamental flaws regarding safety or implementation of the DBD concept.

In 2012, the Blue Ribbon Commission on America's Nuclear Future (BRC) reviewed prior research on DBD, concluded that the concept may hold promise, and recommended further research, development, and demonstration (RD&D) to fully assess its potential (BRC 2012). In 2013, consistent with BRC recommendations, the U.S. Department of Energy (DOE) identified developing an R&D plan for DBD as a key strategy objective (DOE 2013).

In accordance with the BRC recommendations and the DOE strategy objective, the DOE Office of Nuclear Energy (DOE-NE) is currently investigating DBD as one alternative for the disposal of high-activity waste, along with R&D for mined repositories in salt, granite, and clay/shale, as part of the Fuel Cycle Technologies (FCT) Program, Office of Used Nuclear Fuel Disposition (UFD) R&D. A UFD RD&D roadmap was developed for DBD (Arnold et al. 2012) that emphasized a full-scale field demonstration project and defined a set of associated R&D activities. Further technical and logistical guidelines to advance the technical basis for the siting and implementation of the field demonstration project were developed by Arnold et al. (2013) and Arnold et al. (2014). The DBD concept is described further in Section 1.1.2. The field demonstration project, referred to as the Deep Borehole Field Test (DBFT), is described in Section 1.1.3.

1.1.2 Deep Borehole Disposal Concept

The DBD concept, illustrated in Figure 1-1, consists of drilling a large-diameter borehole into crystalline basement rock to a depth of about 5,000 m, emplacing waste packages in the lower, waste emplacement zone portion of the borehole, and sealing and plugging the upper portion of the borehole with a combination of bentonite, cement plugs, and cement/crushed rock backfill. As shown in Figure 1-1, waste in a DBD system is several times deeper than typical mined repositories (e.g., Onkalo and Waste Isolation Pilot Plant (WIPP)). The typical maximum depth of fresh groundwater resources is also shown in Figure 1-1, as indicated by the dashed blue line.

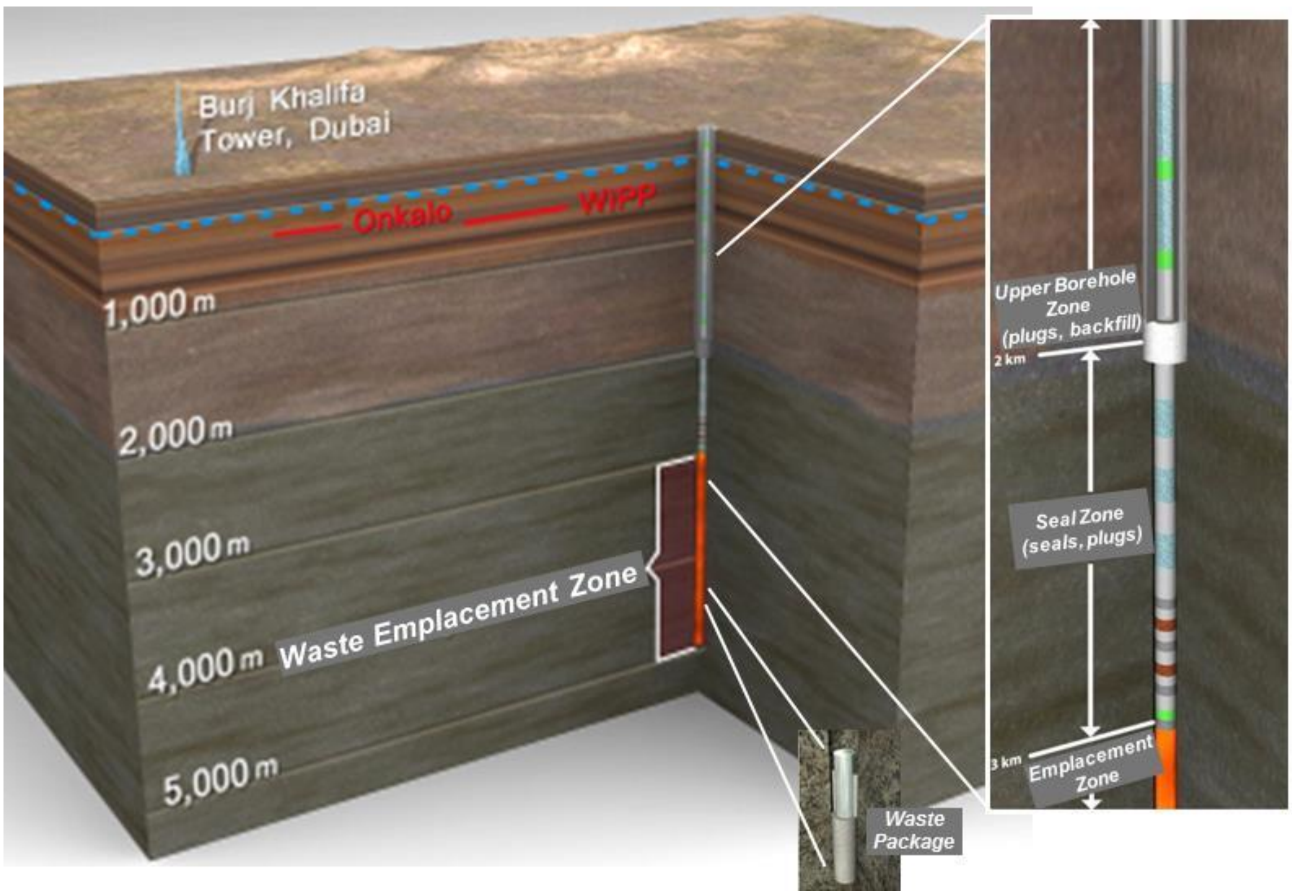


Figure 1-1. Generalized Schematic of the Deep Borehole Disposal Concept

Several design alternatives exist that satisfy the basic DBD concept, depending on a variety of factors, most notably the size and characteristics of the waste form and packaging. Initial DBD studies (e.g., Brady et al. 2009; Arnold et al. 2011; Arnold et al. 2012) proposed waste packages that contained commercial SNF. Specifically, the waste package was designed to encapsulate a single pressurized water reactor assembly, requiring a borehole with a bottom-hole diameter of approximately 0.43 m (17 in). More recently, DOE has recommended "a focused RD&D program addressing technologies relevant to deep borehole disposal of smaller DOE-managed waste forms" (DOE 2014a). For example, the smallest DOE-managed waste forms, cesium (Cs) and strontium (Sr) capsules, are all less than 0.09 m (3.5 in) in diameter (DOE 2014a), and could be emplaced in a borehole with a bottom-hole diameter on the order of 0.22 m (8.5 in).

Factors suggesting that the DBD concept is viable and safe have been summarized previously in Brady et al. (2009) and Arnold et al. (2011). Safety of the concept relies primarily on the natural barriers (the great depth of burial and the isolation provided by the deep natural geological environment), and, to a lesser extent, on the engineered barriers (the durability of the waste packages and waste forms and the integrity of the borehole seals). In contrast, mined geological repositories, with the possible exception of those located in extensive salt or argillaceous formations, rely on engineered barriers such as waste packages and/or buffer material to a greater degree.

1.1.3 Deep Borehole Field Test

The full-scale DBFT is designed to develop the logistics and advance the technical basis for the siting and implementation of a DBD facility. The overall goal of the DBFT is to demonstrate and evaluate technologies necessary for determining the safety and feasibility of the DBD concept, but without the use or disposal of actual radioactive waste. The overall goal of the DBFT can be achieved by completing the following objectives:

- Demonstration of drilling technology and borehole construction to 5,000 m depth in crystalline basement rock with sufficient diameter for cost-effective waste disposal;
- Evaluation of downhole scientific analyses to characterize the thermal-hydrologic-chemical-mechanical (THCM) conditions at a representative location that control waste stability and containment;
- Evaluation of package and seal materials at representative temperature, pressure, salinity, and geochemical conditions;
- Development and testing of engineering methods for test package loading, shielded surface operations, and test package emplacement and retrieval;
- Development and testing of sealing designs and seal emplacement methods; and
- Demonstration of pre-closure and post-closure safety.

The plan for the DBFT (SNL 2014a; SNL 2016a) consists of siting and drilling two 5,000 m deep boreholes into crystalline basement rock in a geologically stable continental location. First, a Characterization Borehole (CB) with approximately an 8.5-in (0.22 m) bottom-hole diameter will be drilled and constructed to facilitate downhole scientific testing (e.g., examination of THCM characteristics of the near-borehole host rock and groundwater). The scientific testing and analysis activities will identify the critical downhole measurements that must be made to determine if conditions favorable to long-term isolation of high-activity waste exist at depth. When sufficient drilling experience and information on site-specific subsurface conditions has been acquired in the CB, a decision will be made whether to proceed with a second, larger-diameter borehole – the Field Test Borehole (FTB), with approximately a 17-in (0.43 m) bottom-hole diameter. The FTB will be drilled and constructed to facilitate proof-of-concept of engineering activities using surrogate test packages. The engineering analysis will evaluate the feasibility of package emplacement operations by determining performance envelopes for drilling, package handling, and package emplacement and retrieval. In addition, borehole sealing materials and designs will be examined through laboratory testing.

These DBFT objectives and scope specifically address key technologies and data necessary to evaluate the feasibility of the DBD concept, particularly any unproven or especially critical components (e.g., collecting diagnostic geochemical signatures from deep low-permeability crystalline rocks at possibly elevated temperatures). However, this is a lesser scope than would be needed to fully characterize an actual DBD facility. Some activities required for DBD have a high technology readiness level (TRL) and therefore do not require explicit demonstration in the DBFT. To focus DBFT resources on key activities needed to build confidence in the DBD concept, these high-TRL activities are not included or in some cases minimally included in the DBFT scope.

1.2 Safety Case Overview

A widely accepted approach for documenting the basis for the understanding of a geologic disposal system, describing the key justifications for its safety, and acknowledging the unresolved uncertainties and their safety significance is a structured document, or set of documents, known as a safety case. The formal concept of a safety case for the long-term disposal of SNF and HLW in an engineered facility located in a deep geologic formation was first introduced by the Nuclear Energy Agency (NEA) (NEA 1999a). Initial discussion and documentation on the topic continued in NEA (2002), NEA (2004), and IAEA (2006). More recently, there have been a number of international symposia, conferences, working groups, and summary papers devoted to understanding, developing, and/or summarizing the nature, purpose, context, and elements of safety cases (e.g., NEA 2008; NEA 2009; IAEA 2011; IAEA 2012; NEA 2012; and NEA 2013). In these recent summary and overview reports, it is observed that there is notable convergence in the understanding and development of safety case documents published by national and international organizations. In parallel, UFD has published safety case overviews relevant to geologic disposal in the U.S. (Freeze et al. 2013a) and specific to the DBD concept (Arnold et al. 2013, Appendix A; Freeze et al. 2013a). The following excerpt from NEA (2012, Section 3.1) provides a definition of a safety case that is current and consistent with the aforementioned documents:

> *The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety of the geological disposal facility and the associated level of confidence.*

A central part of the safety case is the safety assessment. There are some differences in the use of the term safety assessment across national programs and over time; the definition used in this report is:

- *Safety Assessment* – An iterative set of assessments for evaluating the performance of a repository system and its potential impact that aims to provide reasonable assurance that the repository system will achieve sufficient safety and meet the relevant requirements for the protection of humans and the environment over a prolonged period. The role of a safety assessment, in a safety case, is (i) to quantify the repository system performance for all selected situations and (ii) to evaluate the level of confidence (taking into account of the identified uncertainties) in the estimated performance of the system (NEA 2013, Section 5.1). This encompasses all aspects that are relevant for the safety of the development, operation and closure of the disposal facility, including qualitative aspects, non-radiological issues, and organizational and managerial aspects (IAEA 2012, Section 4.41).

The scope of this definition has broadened recently to include not just quantitative analyses, but also a broad range of complementary qualitative evidence and arguments that support the reliability of the quantitative analyses (NEA 2013, Section 1). In this report, the quantitative components of a safety assessment are referred to as "pre-closure safety analysis" and "post-closure performance assessment"; the qualitative component is referred to as "confidence enhancement". These three components are defined in more detail in Section 1.2.1.4.

Like most geologic repository programs, the development and implementation of a DBD project is expected to take place over a period of years or decades. The project lifetime can be defined by three periods:

- Pre-Operational – Activities during this period commonly include (IAEA 2012, Section 2):
    - Development of the disposal concept and the safety strategy
    - Site evaluation (selection, characterization, environmental impacts)
    - Development of the facility design
    - Development of plans for research and development and monitoring
    - Licensing (to construct, to operate)
    - Construction
- Operational – This period begins when waste is first received at the facility and continues up to the final closure of all parts of the facility (IAEA 2012, Section 2). This period is subject to pre-closure safety analyses for radiation protection and occupational safety. Activities during this period commonly include:
    - Construction (in parts of the facility away from waste emplacement)
    - Transportation
    - Surface operations (waste receipt and handling)
    - Subsurface operations (waste emplacement)
    - Licensing (to close)
    - Closure (stepwise in parts of the facility, and the facility as a whole)
- Post-Closure – This period begins after the facility is closed. This period is subject to post-closure performance assessment. Activities during this period commonly include (IAEA 2012, Section 2):
    - Active institutional controls (e.g., performance confirmation monitoring, post-closure maintenance)
    - Passive institutional controls (e.g., land use restrictions, records maintenance)

The safety case is an essential management and communication tool throughout the project lifetime, in particular during the following key phases: site selection, site characterization and facility design, licensing, construction, operations, closure, and post-closure. Two primary roles of the safety case are (MacKinnon et al. 2012, Section 3, adapted from National Research Council 2003, Section 2.2):

1. As a management tool to guide the work of the implementer (e.g., DOE) through the various phases of repository development, and;
2. To communicate the understanding of safety to a broad audience of stakeholders (e.g., the public, Congress, state and local governments).

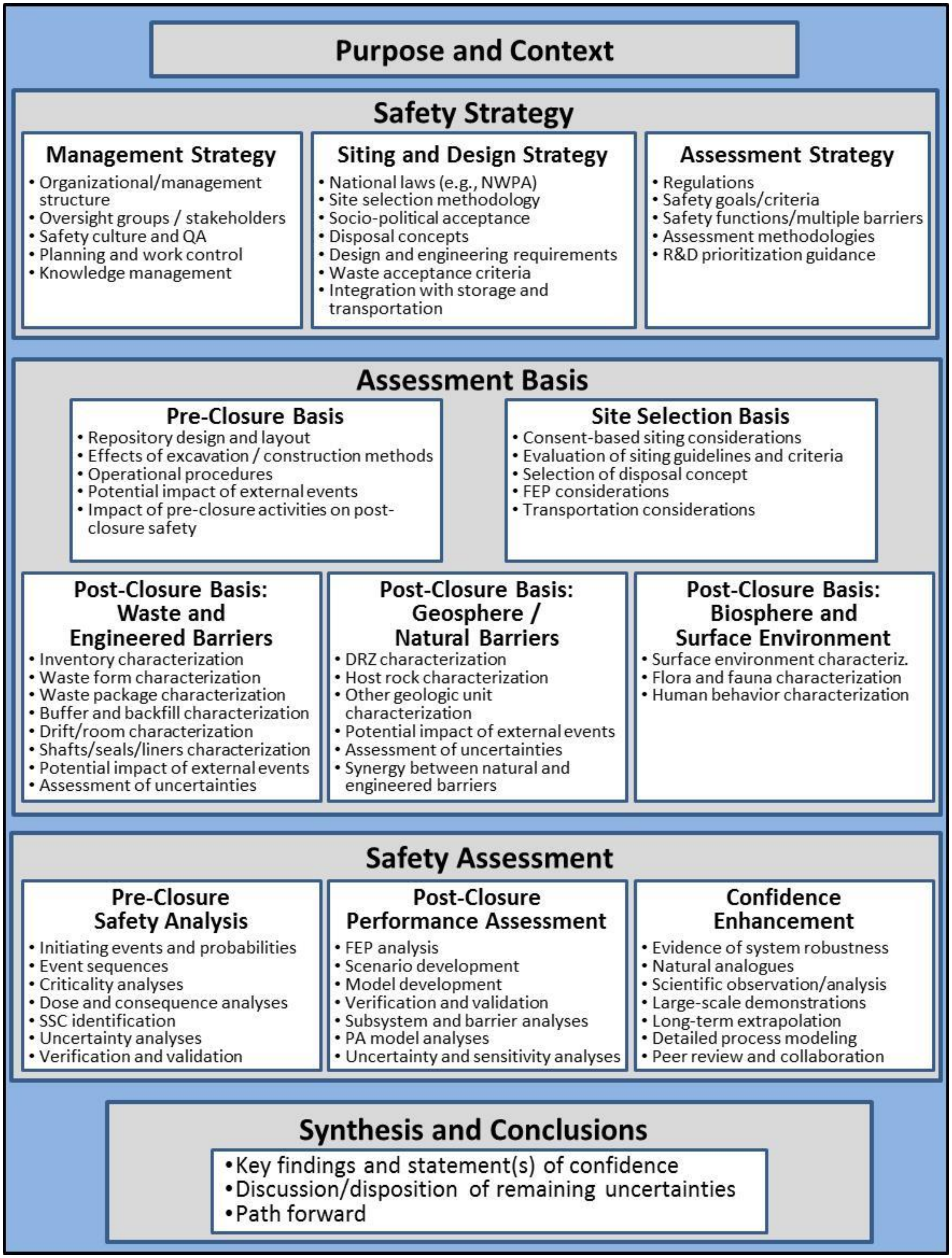
With regard to the role of management for the implementer, the safety understanding and basis of a safety case will evolve over time. The iterative evolution of the safety case assists in organizing and synthesizing existing knowledge and prioritizing the future R&D work, in order to reduce uncertainties and enhance the confidence in safety. As the disposal program evolves from siting to licensing and operations to closure, the required level of completeness and rigor increases and the associated safety case becomes iteratively more detailed with the addition of data from site characterization, system design, and safety assessment activities. For example, early safety cases might rely on rather generic assumptions about the properties of a host rock, its geological environment, and the repository design and layout, whereas the safety case for construction authorization would need sufficient factual basis and detail to provide the necessary confidence for the regulator to determine that the repository would be safe (NEA 2013, Section 2).

With regard to the role of communication to stakeholders, the background to major decisions generally needs to be explained to, and discussed with, diverse audiences, such as the national regulator, political and legal decision makers, and other stakeholders. The safety case provides a platform for informed discussion whereby interested parties can assess their own levels of confidence in a project, and identify the issues that may be a cause for concern or on which further work may be performed with a likelihood of providing meaningful information (NEA 2013, Section 2).

Additional details of the elements of a safety case are provided in Section 1.2.1.

1.2.1 Elements of the Safety Case

A number of elements contribute to, and must be described in, the safety case. A general set of safety case elements includes (NEA 2013, Section 1 and Figure 2.1; NEA 2004, Figure 1): purpose and context; safety strategy; assessment basis; safety assessment, evidence, and arguments; and synthesis into a safety case. These general safety case elements have been adapted for the purposes of developing safety cases supporting geologic disposal in the U.S. (MacKinnon et al. 2012, Figure A-1; Freeze et al. 2012, Figure 1-1; Freeze et al. 2013b, Figure 1-1; Sevougian and MacKinnon 2014, Fig. 2; and MacKinnon et al. 2015, Fig. 3). The safety case elements used in this report are shown in Figure 1-2.



Modified from MacKinnon et al. (2015, Fig. 3) and NEA (2013, Figure 2.1)

Figure 1-2. Key Elements of a Safety Case

Overviews of the key safety elements shown in Figure 1-2 are provided in the following subsections.

1.2.1.1 Purpose and Context

The purpose and context of the safety case is specific to the given phase of development of the disposal system. The purpose and context includes the role to be played by the repository in the overall waste management strategy and the current step or decision point within the program against which the safety case is presented. This sets the context in which the current strength of the safety case and the importance of remaining uncertainties can be judged. (NEA 2013, Section 2).

At this early phase of DBD concept development, the purpose of this safety case is to provide a framework to organize and synthesize existing DBD science and identify unresolved issues and information gaps relevant to DBD. Additional details of the purpose and context for DBD are discussed in Section 2.

1.2.1.2 Safety Strategy

The safety strategy is the high-level approach adopted for achieving safe disposal of waste, focusing on radiological safety through the operational and post-closure periods. Pre-operational activities such as site characterization, facility design, and construction do not directly involve radiological hazards, but do provide initial conditions for operational and post-closure safety. Occupational safety and health considerations during construction are addressed outside the safety case.

The safety strategy must be sufficiently flexible to cope with unexpected site features or technical difficulties and uncertainties that may be encountered, as well as to take advantage of advances in scientific understanding and engineering techniques, as the repository program progresses (Freeze et al. 2012, Section 3).

Two important principles of the safety strategy are (i) public and stakeholder involvement in key aspects of siting, design, and assessment and (ii) alignment of the safety case with the existing legal and regulatory framework. Typically, a safety strategy becomes the basis for communications with stakeholders. Feedback from stakeholders on issues needing to be addressed may help more fully form the safety strategy (NEA 2013, Section 3).

The safety strategy includes:

- **Management Strategy** – The overall management of the various activities required for repository planning and implementation. The management strategy should address (MacKinnon et al. 2015, Fig. 3):
    - Organizational/management structure
    - Oversight groups/stakeholders
    - Safety culture and quality assurance (QA)
    - Planning and work control
    - Knowledge management (e.g., data, records)

- **Siting and Design Strategy** – The approach to select a site and to develop an implementable engineering design, consistent with the characteristics of the site and the waste forms to be disposed. It should be based on principles that favor robustness or defense-in-depth (e.g., multiple barriers contributing to the safety functions[2]) and minimize uncertainty. Societal acceptance is likely to be an important criterion and thus a site with a volunteer host community is likely to be seen as an important advantage (NEA 2013, Section 3). The siting and design strategy should address (MacKinnon et al. 2015, Fig. 3):
  - National laws (e.g., the Nuclear Waste Policy Act (NWPA))
  - Site selection methodology (e.g., consent-based siting, guidelines and/or criteria)
  - Socio-political acceptance
  - Disposal concepts
  - Design and engineering requirements
  - Waste acceptance criteria
  - Integration with storage and transportation

- **Assessment Strategy** – The approach to evaluate information, analyze the evolution of the system, perform quantitative safety assessments (i.e., pre-closure safety analyses and post-closure performance assessments), and collect complementary qualitative evidence and arguments. It must ensure that safety assessments capture, describe and analyze evidence and uncertainties that are relevant to safety, and investigate their effects, thereby enabling the safety assessments to provide the primary quantitative support, and reasonable assurance, for the safety case. The assessment strategy should address (MacKinnon et al. 2015, Fig. 3):
  - Regulations
  - Safety goals/criteria (pre-closure and post-closure)
  - Safety functions/multiple barriers
  - Assessment methodologies (pre-closure and post-closure)
  - R&D prioritization guidance

No formal safety strategy for DBD currently exists because the DBD concept is in the evaluation stage. However, considerations for the safety strategy for DBD are discussed in Section 2.1.

1.2.1.3 Assessment Basis

The assessment basis provides a link between the assessment strategy (described in Section 1.2.1.2) and the safety assessments (Section 1.2.1.4). The assessment basis describes the quantitative information necessary for site selection and to perform the pre-closure safety analyses and post-

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[2] Safety functions provide a basis for describing the contributions of the main system features/components to post-closure safety. The three main categories of safety functions are: stability/isolation; containment; and limited and delayed releases (European Commission 2011, Section 5). Post-closure safety should be provided by multiple safety functions and by multiple barriers. The performance of the barriers should be achieved by means of diverse physical and chemical processes together with various operation controls (IAEA 2011, Section 3).

closure performance assessments. The assessment basis information supporting the safety assessments includes (NEA 2013, Sections 2 and 4):

- a description of the repository location, layout, and design including (a) the features of engineered barriers and how they will be constructed and emplaced, (b) the main geological, hydrogeochemical, geomechanical and other features of the natural geologic system, and (c) how both engineered and natural barriers are expected to provide safety (typically in terms of safety functions);
- the scientific and technical information and understanding, including (a) descriptions of the various features, events and processes (FEPs) (and interactions between FEPs) that may affect the evolution and performance of the repository (i.e., the scenarios), based on multidisciplinary information, and (b) assessments of the uncertainties in scientific understanding.

In accordance with the safety case elements shown in Figure 1-2, this assessment basis information is categorized as follows:

- **Pre-Closure Basis –** A description of the design features (waste, engineered barriers and their interaction with the natural barriers), construction, operations, and site closure, including (MacKinnon et al. 2015, Fig. 3):
  - Repository design and layout (surface facilities, subsurface facilities and engineered barriers)
  - Effects of excavation and construction methods (including quality control) on operations and post-closure
  - Operational procedures (e.g., for surface waste handling, subsurface waste emplacement, and site closure)
  - Potential impact of external/disruptive events such as flooding, extreme weather, seismicity, and sabotage on the pre-closure activities
  - Potential impacts of any pre-closure activities on post-closure safety

- **Post-Closure Basis: Waste and Engineered Barriers** – Scientific information and understanding of the wastes (i.e., SNF and HLW) and engineered barriers (e.g., waste forms, waste packages, buffer, backfill, emplacement drifts/rooms, liners, shafts, and seals), including (MacKinnon et al. 2015, Fig. 3; MacKinnon et al. 2012, Appendix A):
  - Characteristics of the engineered barriers (e.g., design, layout)
  - Inventory characterization (characteristics and quantities of the potential radionuclide and chemotoxic inventory)
  - Waste form characterization (features, processes, and evolution over time – e.g., degradation and radionuclide release processes)
  - Waste package characterization (features, processes, and evolution over time – e.g., material degradation, coupled thermal-hydrologic-chemical-mechanical-biological-radiological (THCMBR) processes)
  - Buffer and backfill characterization (features, processes, and evolution over time –

e.g., degradation and radionuclide transport processes)
    - Drift/room characterization (features, processes, and evolution over time – e.g., radionuclide transport processes)
    - Shafts, seals, and liners characterization (features, processes, and evolution over time – e.g., degradation and radionuclide transport processes)
    - Potential impact of external events such as seismicity, igneous activity, and human intrusion on the performance of the engineered barriers
    - Assessment of uncertainties, including how uncertainties vary over time

- **Post-Closure Basis: Geosphere/Natural Barriers** – Scientific information and understanding of the natural barriers (the host rock and any surrounding formations out to the accessible biosphere), including (MacKinnon et al. 2015, Fig. 3; MacKinnon et al. 2012, Appendix A):
    - Characteristics of the natural barriers (e.g., location, geologic setting)
    - Disturbed rock zone (DRZ) characterization (features, processes, and evolution over time – e.g., fluid flow, geochemical, and radionuclide transport processes and interaction with engineered barriers)
    - Host rock characterization (features, processes, and evolution over time – e.g., fluid flow, geochemical, and radionuclide transport processes)
    - Other geologic unit characterization (features, processes, and evolution over time – e.g., fluid flow, geochemical, and radionuclide transport processes)
    - Potential impact of external events such as climate change, glaciation, seismicity, igneous activity, and human intrusion on the performance of the natural barriers
    - Assessment of uncertainties, including how uncertainties vary over time
    - Discussion of how the engineered and natural barriers will function synergistically (i.e., the multiple-barrier concept)

- **Post-Closure Basis: Biosphere and Surface Environment –** Scientific information and understanding of the biosphere and surface environment, including (MacKinnon et al. 2015, Fig. 3):
    - Surface environment characterization (location, features, and characteristics)
    - Flora and fauna characterization
    - Human behavior characterization (receptor location, receptor characteristics)

In addition to the pre-closure and post-closure bases described above, in the earliest phases of a repository program there is also a need for a site selection basis. The site selection basis supports the siting and design strategy and the site selection methodology introduced in Section 1.2.1.2. Section 3.2.1 summarizes the siting strategy and special considerations related to site selection.

- **Site Selection Basis -** Site characterization information that supports the site selection process (e.g., provides comparison to siting guidelines or criteria). It typically focuses on a preliminary understanding of the natural barriers, similar to the geosphere/natural barrier information listed above, and on socio-political considerations. The site selection basis should address (modified from MacKinnon et al. 2015, Fig. 3):

- Consent-based siting considerations
- Evaluation of siting guidelines and criteria
- Selection of disposal concept
- FEP considerations
- Transportation considerations

The components of the assessment basis for DBD are discussed in Section 4.

1.2.1.4 Safety Assessment

Safety assessments provide quantitative indicators of potential safety consequences (e.g., radiological) associated with a range of possible evolutions of the repository system over time (i.e., for a range of scenarios) both before and after closure. Due to uncertainties in predicting future events, reasonable assurance needs to be provided that the repository system will perform as it is designed and that compliance with safety criteria will be achieved. The results of the safety assessments provide the necessary technical input to support decision making and form a central part of the safety case (NEA 2013, Section 5). As noted in Section 1.2, in this report the quantitative evaluation of safety before repository closure will be referred to as a pre-closure safety analysis, while the quantitative evaluation of safety after repository closure will be referred to as a post-closure performance assessment. In addition to these quantitative evaluations, available qualitative information is used to provide further assurance for the safety case in the form of confidence enhancement. These three types of safety assessments, which are performed and updated iteratively throughout the phases of the repository project, are summarized below.

- **Pre-Closure Safety Analysis –** A quantitative evaluation of the potential natural and operational hazards for the pre-closure period, which includes operations up until closure. The implementation of the pre-closure safety analysis methodology includes (MacKinnon et al. 2012, Section 3.1):
    - Transportation safety analysis – a description and evaluation of potential waste forms, potential transportation routes, potential risks of transporting these wastes, and potential transportation accidents and consequences
    - Operational safety analysis – a description of the surface and subsurface facilities, their operation, and a comparison with safety standards that includes (i) identifying initiating events and event probabilities, (ii) identifying and categorizing event sequences, (iii) performing criticality analyses, (iv) performing radiological dose and consequence analyses, (v) identifying the structures, systems, and components (SSCs) and procedural safety controls intended to prevent or reduce the probability of an event sequence or mitigate the consequences of an event sequence, should it occur, (vi) uncertainty analyses, and (vii) verification and validation (MacKinnon et al. 2012, Section 4.4; DOE 2008, Chapter 1)

- **Post-Closure Performance Assessment –** A quantitative evaluation of the long-term, post-closure performance of the repository for all potential system evolutions (i.e., scenarios), analysis of the associated uncertainties in this prediction of performance, and comparison with the relevant design requirements and safety standards (MacKinnon et al. 2012, Section 4.5; NEA 2013, Section 5). Outside of the U.S., a "post-closure performance assessment" is commonly referred to as a "post-closure safety assessment" or sometimes just as a "safety assessment". In this report, and consistent with the definitions in Section 1.2, the term post-closure performance assessment (PA) is used. A quantitative post-closure PA is performed as part of an overarching PA methodology. The implementation of a post-closure PA includes (MacKinnon et al. 2015, Fig. 3):
    - FEP analysis
    - Scenario development
    - Model development (conceptual, mathematical, computational models, and integrated PA model)
    - Software verification and model validation
    - Subsystem and barrier/safety function analyses
    - PA model analyses
    - Uncertainty and sensitivity analyses

- **Confidence Enhancement –** Qualitative information that provides additional support for evaluations of pre-closure and post-closure safety of the repository system. It includes evidence and arguments related to the intrinsic robustness of the site and design, insights gained from the behavior of natural and anthropogenic analogues, and an account of measures taken to assure the quality of the safety evaluations (Mackinnon et al. 2012, Section 3.1; NEA 2013, Section 2). Examples of types of qualitative information that may provide confidence enhancement include (NEA 2013, Box 6.2; European Commission 2011, Section 6.4; MacKinnon et al. 2015, Fig. 3):
    - Independent evidence for the intrinsic robustness of the system, including passive safety features and consistency of site-specific features and processes with observations in nature
    - Comparison with natural and/or anthropogenic analogues of a repository system (e.g., natural uranium deposits) or one or more of its components
    - Scientific observation and analysis including: natural isotope profiles in some host rocks; groundwater ages and paleohydrogeological information in general; thermodynamic (e.g., waste package metal stability in deep groundwater) and/or kinetic (e.g., iron corrosion rate) arguments; and mass-balance arguments (e.g., showing that there is only a limited amount of reactant so that the extent of a detrimental reaction must be limited)
    - Site monitoring and performance confirmation
    - Large-scale demonstrations (e.g., underground research laboratories (URLs))
    - Long-term extrapolation of short-term experiments and observations
    - Detailed process modeling studies
    - Peer review and international collaboration

The application of these three types of safety assessments for DBD is summarized in Section 5.

1.2.1.5 Synthesis and Conclusions

The conclusions of the safety case summarize the key findings and provide a statement of confidence with respect to the current phase of repository development (i.e., with respect to the purpose and context). The conclusions are based on a synthesis of the safety assessments, evidence, and arguments, and should (i) highlight the principal grounds on which the statement of confidence in the safety case is made, (ii) identify limitations of the presented quantitative and qualitative information, (iii) include a discussion of completeness to ensure that no important issues have been overlooked, and (iv) discuss and analyze any lines of evidence that are not supportive of the safety case.

The conclusions and statement of confidence should recognize the existence of open issues and residual uncertainties, and perspectives about how they can be addressed in the next phase(s) of the repository development (e.g., through future R&D), if they are considered to be important to establishing safety (Mackinnon et al. 2012, Section 3.1).

The synthesis and conclusions for this preliminary DBD are summarized in Section 6.

2. PURPOSE AND CONTEXT

The overall DOE strategy for management and disposal of high-activity waste (DOE 2013), which responds to the recommendations made by the BRC (BRC 2012), includes “a phased, adaptive, and consent-based approach to siting and implementing a comprehensive management and disposal system” that integrates transportation, interim storage, and geologic disposal under a new management and disposal organization (MDO). The safety case for DBD is a part of this overarching DOE strategy.

The disposal of commercial SNF and HLW is governed by the Nuclear Waste Policy Act of 1982, as amended (NWPA 1983). The NWPA (NWPA 1983, Section 8(b)) also provides for two possible pathways for the disposal of “high-level radioactive waste resulting from atomic energy defense activities” (referred to as Defense HLW), as summarized in DOE (2015a): (i) in one or more common repositories (referred to as NWPA Repositories), or (ii) in a separate Defense HLW Repository[3], based on a Presidential finding that considers six factors (cost efficiency, health and safety, regulation, transportation, public acceptability, and national security). In 2014, DOE provided an assessment of options (DOE 2014a) for the permanent disposal of DOE-managed SNF and HLW, which included consideration of whether DOE-managed SNF and HLW should be commingled with, or separate from, commercial SNF and HLW. The report considered three options (DOE 2014a):

1. Disposal of all HLW and SNF, regardless of origin, in a common repository. This option is essentially unchanged from the approach taken by the DOE since the mid-1980s; it calls for disposing of all DOE-managed HLW and SNF together with commercial SNF in one or more repositories. If more than one repository is ultimately required to accommodate the full inventory of commercial SNF, as envisioned in the NWPA, this option carries an implicit assumption that at least one repository would include a broad representation of all the waste types, both DOE-managed and commercial.
2. Disposal of some DOE-managed HLW and SNF in a separate mined repository. Flexible disposal options that allow for disposing of some DOE-managed HLW and SNF in a separate repository could lead to benefits in repository cost or performance based on different characteristics of the HLW and SNF such as thermal output, chemical characteristics, and fissile mass loading. For example, there could be advantages to separating thermally cooler DOE-managed SNF from thermally hotter DOE-managed SNF (e.g., hotter naval SNF) and disposing of the thermally cooler DOE-managed SNF with DOE-managed HLW.
3. Disposal of smaller waste forms in deep boreholes. Some DOE-managed waste forms are small enough to be candidates for disposal in deep boreholes drilled using currently available commercial drilling technology, as an alternative to emplacement in mined repositories. Preliminary evaluations of deep borehole disposal indicate a high potential for robust isolation of the waste, and the concept could offer a pathway for earlier disposal of some wastes than might be possible in a mined repository.

[3] The presidential finding is only necessary for separate disposal of Defense HLW. The NWPA does not limit the separate disposal of Defense SNF, or HLW or SNF resulting from R&D activities. Therefore, the Defense HLW Repository could include all DOE-managed SNF and HLW that is not of commercial origin.

The report (DOE 2014a, Section 3.4) recommended that "DOE pursue options for disposing of some DOE-managed HLW and SNF separately from commercial SNF and HLW. Specifically, it recommends that DOE pursue options that allow for flexibility in disposing of HLW and cooler DOE-managed SNF (potentially including cooler naval SNF) in one repository, while disposing of other DOE-managed wastes, including HLW and SNF of commercial origin and naval SNF with relatively higher heat output, in another repository with commercial SNF and HLW. The report also recommends that DOE retain the flexibility to consider options for disposal of smaller DOE-managed waste forms in deep boreholes rather than in a mined repository, and that DOE conduct the deep borehole field test needed to confirm the safety and feasibility of the concept."

This recommendation was confirmed in DOE (2015a), which concluded that, "A geologic repository for permanent disposal of Defense HLW could be sited, licensed, constructed, and operated more quickly than a Common NWPA Repository and would provide valuable experience to reduce the cost of a future repository and the time needed to develop it. In consideration of the six statutory factors cumulatively, this report concludes that a strong basis exists to find that a Defense HLW Repository is required". Based on the conclusion in DOE (2015a), President Obama issued a finding that "the development of a repository for the disposal of high-level radioactive waste resulting from atomic energy defense activities only is required" (Obama 2015).

As noted in Section 1.1.1, current research into the disposal of high-activity waste, being performed by the DOE-NE UFD Campaign, is examining multiple disposal concepts for geologic repositories: mined repositories in salt, granite, and clay/shale, as well as DBD in crystalline basement rock. These concepts have broad applicability to both a NWPA Repository and a Defense HLW Repository.

Within this overarching national strategy for the management and disposal of high-activity waste, the current emphasis for deep boreholes is the disposal of smaller DOE-managed waste forms, which would make a DBD facility a type of Defense HLW Repository and not be subject to the provisions of the NWPA (NWPA 1983, Section 8(c)).

This preliminary iteration of a DBD safety case focuses on a generic safety case of the feasibility of the DBD concept; there is no site, system design studies are just beginning, and the regulatory framework is unclear and lacks focus for this method of disposal. Therefore, at this early phase of DBD concept development, the purpose of this safety case for DBD is to provide a framework to organize and synthesize existing science and identify unresolved issues and information gaps relevant to DBD. Crystalline basement rock is the current focus as a DBD host rock, but other geologies are not excluded. Further, the early emphasis is on post-closure safety (both the technical bases and the safety assessments), but most safety case elements are addressed in at least some minimal fashion.

The DBFT (Section 1.1.3) is expected to significantly enhance the DBD knowledge base, for both pre-closure and post-closure safety. Although radioactive waste disposal is not planned for the DBFT, the subsurface characteristics and emplacement demonstration operations are likely to be representative of an actual DBD facility. This information, together with the issue and gap analysis from the safety case, will help prioritize future DBD R&D activities.

2.1 Regulatory Considerations

The safety standards and the implementing regulations governing the management and disposal of radioactive waste in a geologic repository are the fundamental technical requirements that are addressed in a safety case. In the U.S., such standards are promulgated by the U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (NRC). Safety standards and guidance are also available from national programs in other countries and from international organizations (e.g., IAEA 2011).

The current regulatory framework for radioactive waste management in the U.S. focuses on mined geologic repositories and was not intended to be applied to the long-term performance of DBD facilities. Site-specific regulations for Yucca Mountain (10 CFR 63 (NRC) and 40 CFR 197 (EPA)), first promulgated in 2001, are not applicable to a Defense HLW Repository. Existing general regulations for disposal of high-activity wastes in geologic repositories (10 CFR 60 (NRC) and 40 CFR 191 (EPA)), first promulgated in 1983 and 1985, respectively, remain in effect, and could be applied to disposal of nuclear waste in deep boreholes, as written (EPA 2015). However, these existing regulations would likely be superseded, since they were developed more than 30 years ago and are not consistent with the more recent thinking on regulating geologic disposal concepts that embraces a risk-informed, performance-based approach (NRC 2004), such as that represented in the site-specific regulations for Yucca Mountain (Arnold et al. 2013, Appendix A). Also, 10 CFR 60 is for a geologic repository sited, constructed, or operated in accordance with the NWPA (although it pre-dates the 1987 amendments to the NWPA).

Despite these uncertainties, it is likely that regulations for a DBD facility, classified as a non-NWPA Defense HLW Repository, would be strongly informed by the current regulations. Therefore, the preliminary safety case framework for DBD is developed based on assumptions about the potential regulatory environment. These assumptions are based on inferences from:

- relevant portions of the existing general standards (10 CFR 60 and 40 CFR 191),
- anticipated updates consistent with the risk-informed approach in 10 CFR 63 and 40 CFR 197, and
- generic standards that incorporate dose or risk metrics recognized internationally to be important to establishing repository safety (e.g., IAEA 2011; IAEA 2012).

As the safety case and regulations evolve, these assumptions will be updated, and will eventually reflect applicable regulations.

Relevant portions of the aforementioned regulations that might provide insights to future DBD regulations are excerpted in Appendix A. Key considerations are summarized in the following subsections. Section 2.1.1 describes regulatory assumptions related to pre-closure, Section 2.1.2 describes regulatory assumptions related to post-closure, and Section 2.1.3 describes additional regulatory topics requiring clarification. These regulatory assumptions address radiological safety through the use of annual dose limits, which include the effects of both internal doses from radioactive materials and external radiation exposures. Appendix A contains specific details of various dose calculations (e.g., effective dose equivalent, committed effective dose equivalent (CEDE), and total effective dose equivalent (TEDE)), however, a detailed understanding of these differences is not necessary for the summary discussions presented in the following subsections, where the term "annual dose" is generally used.

Included in Section 2.1.3 is a discussion of the potential applicability of EPA regulations for the Underground Injection Control (UIC) program (40 CFR 144 through 148) and the Resource Conservation and Recovery Act (RCRA) (40 CFR 261) to DBD; these regulations address the potential for contamination of drinking water from hazardous waste (including liquid radioactive waste). Section 2.1.3 also includes a brief mention of transportation safety. Transportation safety needs consideration as part of either the national policy or as part as this specific DBD safety case, however, it is not further addressed in this preliminary iteration of the DBD safety case.

Other regulations that need to be considered as part of a repository lifecycle include non-radiological environmental impacts under the National Environmental Policy Act (NEPA) (40 CFR 1500 through 1508) and non-radiological construction and operational safety under the Occupational Safety and Health Administration (OSHA) standards (29 CFR 1910). However, these regulations are considered beyond the scope of this DBD safety case.

2.1.1 Pre-Closure Regulatory Assumptions

The pre-closure regulatory assumptions for this iteration of the DBD safety case focus on the operational safety analysis outlined in Section 1.2.1.4. Pre-closure activities regulated for radiological safety include: surface operations (waste receipt and handling), subsurface operations (waste emplacement), and closure (borehole sealing, decommissioning of surface facilities).

2.1.1.1 Pre-Closure Performance Objectives

Pre-closure performance objectives are specified in 10 CFR 60.111 and 10 CFR 63.111 for (i) occupational dose from on-site radiation levels and radiological exposures, and (ii) dose to the public from off-site releases of radioactive materials.

On-Site Occupational Dose

10 CFR 60.111(a) and 10 CFR 63.111(a)(1) both state that the pre-closure occupational dose limit in the geologic repository operations area (i.e., on-site) until permanent closure has been completed must meet the requirements of 10 CFR 20. 10 CFR 20.1201(a) limits the occupational dose to individual adults to:

- the more limiting of (i) an annual dose (TEDE) ≤ 5 rem/yr, or (ii) the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than the lens of the eye ≤ 50 rem/yr,
- a lens dose equivalent ≤ 15 rem/yr, and
- a shallow-dose equivalent to the skin ≤ 50 rem/yr.

Off-Site Dose to Members of the Public

10 CFR 63.111(a)(2) states that the annual dose (TEDE) to any member of the public located beyond the site boundary (i.e., off-site) must meet the pre-closure standard at 10 CFR 63.204. 10 CFR 63.204 (which is consistent with 40 CFR 197.4) limits the annual dose to a member of the public, during normal operations and Category 1 event sequences (i.e., event sequences that are expected to occur one or more times before permanent closure), to:

- ≤ 15 mrem/yr.

10 CFR 60.111(a) states that generally applicable environmental standards (such as EPA standards) must be met. For doses to members of the public as a result of transportation and storage of SNF and HLW at an NRC-regulated facility or a DOE disposal facility, 40 CFR 191.03 applies. 40 CFR 191.03(a) limits the annual dose to any member of the public in the general environment to:

- ≤ 25 mrem/yr to the whole body,
- ≤ 75 mrem/yr to the thyroid, and
- ≤ 25 mrem/yr to any other critical organ.

Pre-Closure Design Objectives

In addition to the pre-closure on-site and off-site dose limits listed above, 10 CFR 63.111(b) also provides pre-closure design objectives in the form of dose limits. These dose limits are the same as above, with the additional requirement in 10 CFR 63.111(b)(2) that, taking into consideration a single Category 2 event sequence (i.e., an event sequence that has at least one chance in 10,000 of occurring before permanent closure), the dose limit to an individual on or beyond the site boundary (i.e., off-site) is:

- the more limiting of (i) an annual dose (TEDE) ≤ 5 rem/yr, or (ii) the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than the lens of the eye ≤ 50 rem/yr,
- a lens dose equivalent ≤ 15 rem/yr, and
- a shallow-dose equivalent to the skin ≤ 50 rem/yr.

This is the same as the 10 CFR 20 on-site occupational dose limit.

2.1.1.2 Pre-Closure Safety Analysis

In 10 CFR 63.102(f) pre-closure safety analysis is defined as “a systematic examination of the site; the design; and the potential hazards, initiating events and their resulting event sequences and potential radiological exposures to workers and the public. Initiating events are to be considered for inclusion in the preclosure safety analysis for determining event sequences only if they are reasonable (i.e., based on the characteristics of the geologic setting and the human environment, and consistent with precedents adopted for nuclear facilities with comparable or higher risks to workers and the public). The analysis identifies structures, systems, and components important to safety.”

The requirements for a pre-closure safety analysis are identified in 10 CFR 63.112. Key items to be included in a pre-closure safety analysis are:

- A description of the design, both surface and subsurface, of the geologic repository operations area, including:
    - the relationship between design criteria and the requirements specified by the pre-closure performance objectives, and
    - the design bases and their relation to the design criteria;
- An identification and systematic analysis of naturally occurring and human-induced hazards at the geologic repository operations area, including a comprehensive identification of potential event sequences;
- The technical basis for either inclusion or exclusion of specific, naturally occurring and human-induced hazards in the safety analysis;
- An analysis of the performance of the SSCs to identify those that are important to safety. This analysis identifies and describes the controls that are relied on to limit or prevent potential event sequences or mitigate their consequences.

2.1.2 Post-Closure Regulatory Assumptions

The post-closure regulatory assumptions for this iteration of the DBD safety case focus on the standards for the post-closure PA outlined in Section 1.2.1.4.

2.1.2.1 Post-Closure Performance Objectives

Post-closure performance objectives are specified in 10 CFR 60.112 and 10 CFR 63.113 for (i) radiological exposures to members of the public, and (ii) radiological releases to the accessible environment. These are reflected in separate standards for individual protection and for groundwater protection.

10 CFR 60.112 states that releases of radioactive materials to the accessible environment conform to generally applicable environmental standards (such as EPA standards) with respect to both anticipated processes and events and unanticipated processes and events. EPA standards are found at 40 CFR 191.15 for individual protection and 40 CFR 191.24 for groundwater protection.

10 CFR 63.113(b) states that, for individual protection, radiological exposures to a member of the public (referred to as the reasonably maximally exposed individual (RMEI)) are within the limits specified at 10 CFR 63.311. 10 CFR 63.113(c) states that, for groundwater protection, releases of radionuclides into the accessible environment are within the limits specified at 10 CFR 63.331.

Additional regulatory considerations (e.g., containment requirement/cumulative release limits, multiple barriers, retrievability, human intrusion), which require further clarification regarding their applicability to DBD, are discussed in Section 2.1.3.

Individual Protection Standards

For post-closure individual protection, 10 CFR 63.311(a) (which reflects 40 CFR 197.20) limits the annual dose to an individual (the RMEI) from releases from the undisturbed disposal system (i.e., "not affected by human intrusion" (10 CFR 63.302)) to:

- ≤ 15 mrem/yr for 10,000 years following disposal, and
- ≤ 100 mrem/yr after 10,000 years, but within the period of geologic stability (limited to the period within 1,000,000 years after disposal by 10 CFR 63.303(a)).

10 CFR 63.341 includes a requirement to calculate the peak dose that would occur after 10,000 years following disposal but within the period of geologic stability. No regulatory standard applies to the results; however, the results and their bases provide an indicator of long-term disposal system performance.

40 CFR 191.15(a) limits the annual dose (CEDE) to any member of the public in the accessible environment from undisturbed performance of the disposal system (i.e., “not disrupted by human intrusion or the occurrence of unlikely natural events” (40 CFR 191.12)) to:

- ≤ 15 mrem/yr for 10,000 years after disposal.

Groundwater Protection Standards

For post-closure groundwater protection, 10 CFR 63.331 (which reflects 40 CFR 197.30) limits the level of radioactivity in a representative volume of groundwater (defined in 10 CFR 63.332) in the accessible environment, due to releases of radionuclides from 10,000 years of undisturbed performance of the disposal system after disposal, to:

- ≤ 5 pCi/L from combined radium-226 and radium-228,
- ≤ 15 pCi/L from gross alpha activity (including radium-226 but excluding radon and uranium), and
- ≤ 4 mrem/yr (to the whole body or any organ, based on drinking 2 liters of water per day from the representative volume) from combined beta and photon emitting radionuclides.

40 CFR 191.24(a)(1) limits the levels of radioactivity in any underground source of drinking water, in the accessible environment, from 10,000 years of undisturbed disposal system performance after disposal, to the limits specified in 40 CFR 141 (the National Primary Drinking Water Regulations). Maximum contaminant levels for radionuclides are specified in 40 CFR 141.66 as:

- ≤ 5 pCi/L for combined radium-226 and radium-228,
- ≤ 15 pCi/L for gross alpha activity (including radium-226 but excluding radon and uranium),
- ≤ 4 mrem/yr (to the total body or any internal organ, based on drinking 2 liters of water per day) for combined beta particle and photon radioactivity, and
- ≤ 30 μg/L for uranium.

These are the same as the 10 CFR 63.331 limits, with the addition of uranium.

2.1.2.2 Post-Closure Performance Assessment

In 10 CFR 63.102(j) post-closure PA is defined as "a systematic analysis that identifies the features, events, and processes (i.e., specific conditions or attributes of the geologic setting, degradation, deterioration, or alteration processes of engineered barriers, and interactions between the natural and engineered barriers) that might affect performance of the geologic repository; examines their effects on performance; and estimates the radiological exposures to the reasonably maximally exposed individual. The features, events, and processes considered in the performance assessment should represent a wide range of both beneficial and potentially adverse effects on performance (e.g., beneficial effects of radionuclide sorption; potentially adverse effects of fracture flow or a criticality event). Those features, events, and processes expected to materially affect compliance with § 63.113(b) or be potentially adverse to performance are included, while events (event classes or scenario classes) that are very unlikely (less than one chance in 10,000 over 10,000 years) can be excluded from the analysis. …Additionally, performance assessment methods are appropriate for use in demonstrating compliance with the postclosure performance objectives for ground-water protection and human intrusion …"

The requirements for a post-closure PA are identified in 10 CFR 63.114. Key items to be included in a post-closure PA through the period of geologic stability are:

- Data related to the geology, hydrology, and geochemistry (including disruptive processes and events) of the site, and the surrounding region (i.e., natural barriers), and information on the design of the engineered barriers used to define parameters and conceptual models used in the assessment;
- Uncertainties and variabilities in parameter values and the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment;
- Consideration of features, events, and processes (FEPs) consistent with the limits specified at 10 CFR 63.342:
    - shall not include consideration of very unlikely FEPs, i.e., those that are estimated to have less than one chance in 100,000,000 per year of occurring,
    - need not evaluate the impacts resulting from any FEPs or sequences of events and processes with a higher chance of occurring if the results of the performance assessments would not be changed significantly in the initial 10,000-year period after disposal,
    - shall project the continued effects of the FEPs beyond the 10,000-year post-disposal period through the period of geologic stability (with prescribed post-10,000-year consideration for seismic activity, igneous activity, climate change, and general corrosion on engineered barriers);
- The technical basis for either inclusion or exclusion of specific FEPs in the performance assessment. Specific FEPs must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the RMEI, or radionuclide releases to the accessible environment, for 10,000 years after disposal, would be significantly changed by their omission;
- The technical basis for models used to represent the 10,000 years after disposal in the performance assessment, such as comparisons made with outputs of detailed process-level

models and/or empirical observations (e.g., laboratory testing, field investigations, and natural analogs).

2.1.3 Additional Regulatory Considerations

As noted in Section 2.1, the current U.S. regulatory framework for the disposal of high-activity waste was not originally intended to be applied to DBD facilities. Specific regulatory topics that may benefit from clarification for DBD have been identified in a number of documents (Winterle et al. 2011; Arnold et al. 2013, Appendix A; Freeze 2015; EPA 2015; NWTRB 2016). These topics include:

- Post-Closure Performance Standards: Dose Limits vs. Cumulative Release Limits
- Reference Biosphere and Receptor
- Multiple Barriers / Subsystem Performance
- Retrievability
- Human Intrusion
- Licensing (Non-Phased Approach / Multiple Boreholes)
- Underground Injection Control
- RCRA
- Transportation

Additional regulatory considerations associated with each of these topics are discussed further in the following subsections.

2.1.3.1 Post-Closure Performance Standards

Post-closure performance standards for individual protection and groundwater protection that are common between 10 CFR 60 and 10 CFR 63 were summarized in Section 2.1.2. In addition to the common standards, there are also some differences between the post-closure requirements in 10 CFR 60 and 10 CFR 63.

10 CFR 60.112 includes an additional post-closure standard for containment. The containment requirements at 40 CFR 191.13(a) state that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal shall: (1) have a likelihood of less than one chance in 10 of exceeding the release limits; and (2) have a likelihood of less than one chance in 1,000 of exceeding ten times the release limits. The release limits, listed in Appendix A of 10 CFR 191, are radionuclide-specific limits expressed in units of cumulative radionuclide release (curies) per 1,000 metric tons of heavy metal (MTHM) of waste.

The 10,000-year cumulative release limits of the 40 CFR 191.13 containment requirements provide a different metric than the 10,000-year and 1,000,000-year dose limits at 10 CFR 63.311 and 40 CFR 191.15. Dose standards, which emphasize low annual dose/risk, can be open-ended in time and can benefit from gradual releases and biosphere dilution. Cumulative release limits, which emphasize waste isolation from the accessible environment for a specified time period, are normalized to the initial waste inventory and remove uncertainty associated with biosphere assumptions. Any new post-closure regulations are likely to be dose/risk-based standards to at least 1,000,000 years after closure, consistent with International Atomic Energy Agency (IAEA) guidelines (IAEA 2011) and with the National Academy of Sciences (NAS 1995) recommendations on Yucca Mountain standards.

2.1.3.2 Reference Biosphere and Receptor

The existing regulations prescribe post-closure dose limits for an individual (receptor) in the "accessible environment", which is defined in relation to the "controlled area". The controlled area is defined in 40 CFR 191.12 (and similarly in 10 CFR 63.302) to include the surface area and underlying subsurface that extends horizontally no more than 5 km in any direction from the outer boundary of the disposal system. Dose estimates further require specification of biosphere and receptor characteristics.

For mined repositories, radionuclide uptake by the receptor is typically assumed to occur from dissolved radionuclides that have migrated from the emplaced waste packages to a subsurface aquifer and are then pumped to the surface at a location on or near the 5 km boundary of the controlled area. Assumptions about the aquifer, the pumping rates, and the usage and/or ingestion of the well water at the surface are typically specified in the regulations (e.g., 10 CFR 63.312).

For a DBD system, the existing regulations, as written, would be applied in a similar manner with dose limits applied 5 km from the location of the borehole(s). If a new regulation is written, then some of these biosphere and receptor assumptions may need to be specified differently than for a mined repository.

2.1.3.3 Multiple Barriers

Existing regulations include requirements for multiple barriers and/or subsystem performance of specific barriers.

10 CFR 63.113(a) states that "The geologic repository must include multiple barriers, consisting of both natural barriers and an engineered barrier system". 10 CFR 63.115 requires identification of "those design features of the engineered barrier system, and natural features of the geologic setting, that are considered barriers important to waste isolation".

10 CFR 60.113(a) provides the following subsystem performance requirements for specific barriers:

- Containment of HLW within the waste packages will be substantially complete for a period … not less than 300 years nor more than 1,000 years after permanent closure.
- The release rate of any radionuclide from the engineered barrier system following the containment period shall not exceed one part in 100,000 per year of the inventory of that radionuclide calculated to be present at 1,000 years following permanent closure …. The calculated total release rate limit shall be taken to be one part in 100,000 per year of the inventory of radioactive waste, originally emplaced in the underground facility, that remains after 1,000 years of radioactive decay.
- … pre-waste emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years.

As described in Section 1.1.2, the safety of the DBD concept relies primarily on the great depth of burial and the isolation provided by the natural barriers, with a lesser reliance on the engineered barriers (the durability of the waste packages and waste forms and the integrity of the borehole seals). For example, corrosion-resistant and long-lived waste packages are not necessary to meet post-closure performance standards; preliminary DBD PA model results (see Section 5.2.6) show very limited radionuclide transport beyond the emplacement zone and into the seal zone, even with no credit taken for the durability of the waste packages or the waste forms.

Defense-in-depth design of the waste packages and/or seals would permit compliance with multiple barrier requirements of 10 CFR 63.113, but the more prescriptive subsystem performance requirements of 10 CFR 60 are largely inappropriate for the DBD concept and demonstrating compliance with them may pose unnecessary costs and complexities.

However, 10 CFR 60.113(b) states "On a case-by-case basis, the Commission may approve or specify some other radionuclide release rate, designed containment period or pre-waste-emplacement groundwater travel time, provided that the overall system performance objective, as it relates to anticipated processes and events, is satisfied." Therefore, one option for addressing the subsystem performance requirements (should they be retained in a DBD-specific regulation) could be to request an exception from the NRC on the basis that a DBD system meets the overall requirements by providing very robust geologic isolation (Arnold et al. 2013, Appendix A).

2.1.3.4 Post-Closure Retrievability

Existing regulations include requirements for post-closure retrievability of waste.

10 CFR 60.111(b)(1) and 10 CFR 63.111(e)(1) state "… the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after the waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission."

40 CFR 191.14(f) states that "Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal".

Additionally, 10 CFR 60.46(a)(1) states "… an amendment of the license shall be required … [for any] action which would make emplaced high-level radioactive waste irretrievable or which would substantially increase the difficulty of retrieving such emplaced waste."

The EPA noted when promulgating 40 CFR 191 in 1985 that "The intent of this provision was not to make recovery of waste easy or cheap, but merely possible in case some future discovery or insight made it clear that the wastes needed to be relocated" (40 CFR 191, 50 FR 38082). So, while DBD systems are a good choice for permanent and irreversible disposal, and traditional retrievability of emplaced waste may not be feasible, it may be possible to meet the "removal of most of the waste" requirement 40 CFR 191.14 and the EPA intent. For example, overcoring the waste emplacement region of a disposal borehole (e.g., containing narrower-diameter waste forms such as Cs and Sr capsules) appears to be technically possible using current technology, although is unlikely to be either "easy or cheap" (Arnold et al. 2013, Appendix A).

Also, although not addressed by the existing regulations, pre-closure retrievability (i.e., before the emplacement of borehole seals) from a cased deep borehole should be technically feasible.

And finally, NEA (2001) noted: "The introduction of provisions for retrievability must not be detrimental to long-term safety. Thus, for example, locating a repository at a depth that is less than optimum from a long-term safety perspective in order to facilitate retrieval is unlikely to be acceptable…". The application of retrievability requirements to DBD seems to be an example of this type of detrimental provision.

2.1.3.5 Human Intrusion

Existing regulations require consideration of human intrusion, which is assumed to be an inadvertent drilling intrusion.

In 10 CFR 63, human intrusion is evaluated with an analysis that is separate from the individual protection performance assessment. The human intrusion scenario (10 CFR 63.322) assumes a single intrusion borehole is drilled directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository, and that radionuclides are transported to the saturated zone (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the saturated zone); radionuclide exposure to the drillers is not considered.

In 10 CFR 60, human intrusion is evaluated as part of a performance assessment that considers all significant processes and events that may affect the disposal system. The human intrusion scenario (40 CFR 191 Appendix C) assumes that the likelihood of drilling is not more 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. The consequences of drilling are assumed to be not more severe than: (1) direct release to the land surface of ground water in the repository horizon (all ground water that would promptly flow to the surface, or release of 200 m^3 of ground water if pumped); and (2) creation of a ground water flow path with a permeability typical of a borehole filled by the soil or gravel that would normally settle into an open hole over time—not the permeability of a carefully sealed borehole.

Both of these human intrusion scenarios are specific to mined repositories, and would be difficult to apply to a DBD system. For a DBD site with a single borehole, the probability of an intrusion borehole intersecting the disposal borehole would likely be below the threshold for inclusion (Arnold et al. 2013, Appendix A); "less than one chance in 10,000 of occurring over 10,000 years" (40 CFR 191 Appendix C) or "less than one chance in 100,000 per year of occurring" (10 CFR 63.342(b)). A DBD site with multiple boreholes might require further analysis of intrusion probabilities.

2.1.3.6 Licensing (Non-Phased / Multiple Boreholes)

Existing regulations contain an implicit assumption that a repository will be licensed and constructed as a single unit, using a phased approach (i.e., license for construction, license to receive and possess waste, license for permanent closure).

For licensing a single borehole, the phased approach may not be applicable because construction, emplacement, and closure may take place over a few years, as opposed to decades for a mined repository (Winterle et al. 2011). Instead, DBD-specific regulations may need to permit a single license application for all phases of DBD development and operation.

For licensing multiple boreholes at a single site, it is not clear how the "single unit" paradigm would apply. Further regulatory guidance is needed from NRC to determine whether (i) each borehole would need a separate license application, and/or (ii) the full multi-borehole disposal system could be licensed prior to emplacing any waste, and/or (iii) licensing of individual but similar boreholes could follow a reactor licensing paradigm.

2.1.3.7 Underground Injection Control

EPA regulations for the UIC program (40 CFR 144 through 148) are promulgated under the Safe Drinking Water Act (SDWA). The SDWA required all States to submit an UIC program to the EPA for approval. 40 CFR 145 specifies the procedures the EPA will follow in approving, revising, and withdrawing State UIC programs, and 40 CFR 145.1(g)(1) allows States to adopt and enforce requirements that are more stringent or extensive than those set forth by the EPA.

These regulations address the potential for contamination of drinking water from hazardous waste (including liquid radioactive waste) injection wells; 40 CFR 144.6(a)(3) defines Class I injection wells as, "radioactive waste disposal wells which inject fluids below the lowermost formation containing an underground source of drinking water within one quarter mile of the well bore". The focus of the regulations is on subsurface injection of fluids, but they may have some application and/or informative value to DBD.

In a 1987 ruling (NRDC v. EPA 1987), the U.S. Court of Appeals, First Circuit concluded that "the primary disposal method being considered, underground repositories, would likely constitute an 'underground injection' under the SDWA." However, in its 1993 repromulgation of 40 CFR 191 following the Court remand (for issues other than the underground injection question), the EPA determined "that nuclear waste disposal systems should not be considered underground injection" (40 CFR 191, 58 FR 66407). Consistent with this decision, the DOE determined in 1996 that emplacement of waste in WIPP did not constitute "injection" (DOE 1996, Appendix BECR Section 8.2.2).

Further guidance from the EPA will be helpful in determining whether DBD of canistered solid or granular HLW falls under UIC regulations.

2.1.3.8 Resource Conservation and Recovery Act

RCRA authorizes the EPA to establish nationwide standards for the management of hazardous wastes. Regulations promulgated under RCRA in 40 CFR 261 include lists of designated hazardous wastes and methods for identifying wastes exhibiting hazardous characteristics. Some high activity wastes (e.g., unprocessed Cs and Sr capsules) also exhibit hazardous characteristics and are therefore prohibited from land disposal unless treated to meet the standards established by the EPA or a "no-migration" variance is obtained.

Since treatment of this waste is impractical, it appears DBD of this hazardous/mixed waste would require a RCRA no-migration variance prior to emplacement. In the case of the WIPP, Congress waived this requirement through legislation.

2.1.3.9 Transportation

The NRC recently published NUREG-2125, Spent Fuel Transportation Risk Assessment (NRC 2014). This report reconfirms that radiological impacts from spent fuel transportation conducted in compliance with NRC regulations are low. It is expected that nuclear waste transported for DBD will be shipped in accordance with NRC regulations and therefore, the risks have been studied and the conclusion is that regulations for transportation of radioactive materials are adequate to protect the public against unreasonable risk. However, further, more detailed analysis is required.

3. SAFETY STRATEGY

As noted in Section 2, the safety strategy for DBD will be developed within the larger context of the national strategy for management and disposal of high-activity waste, and will be informed by past U.S. and international experience. No formal safety strategy currently exists for DBD because (i) there has been no decision yet on DBD in the U.S. and (ii) the DBD concept is still in the evaluation stage. However, as described in Section 1.1, recent R&D gives a preliminary indication that DBD may a safe and viable waste management option.

Considerations in the development of a safety strategy for DBD include:

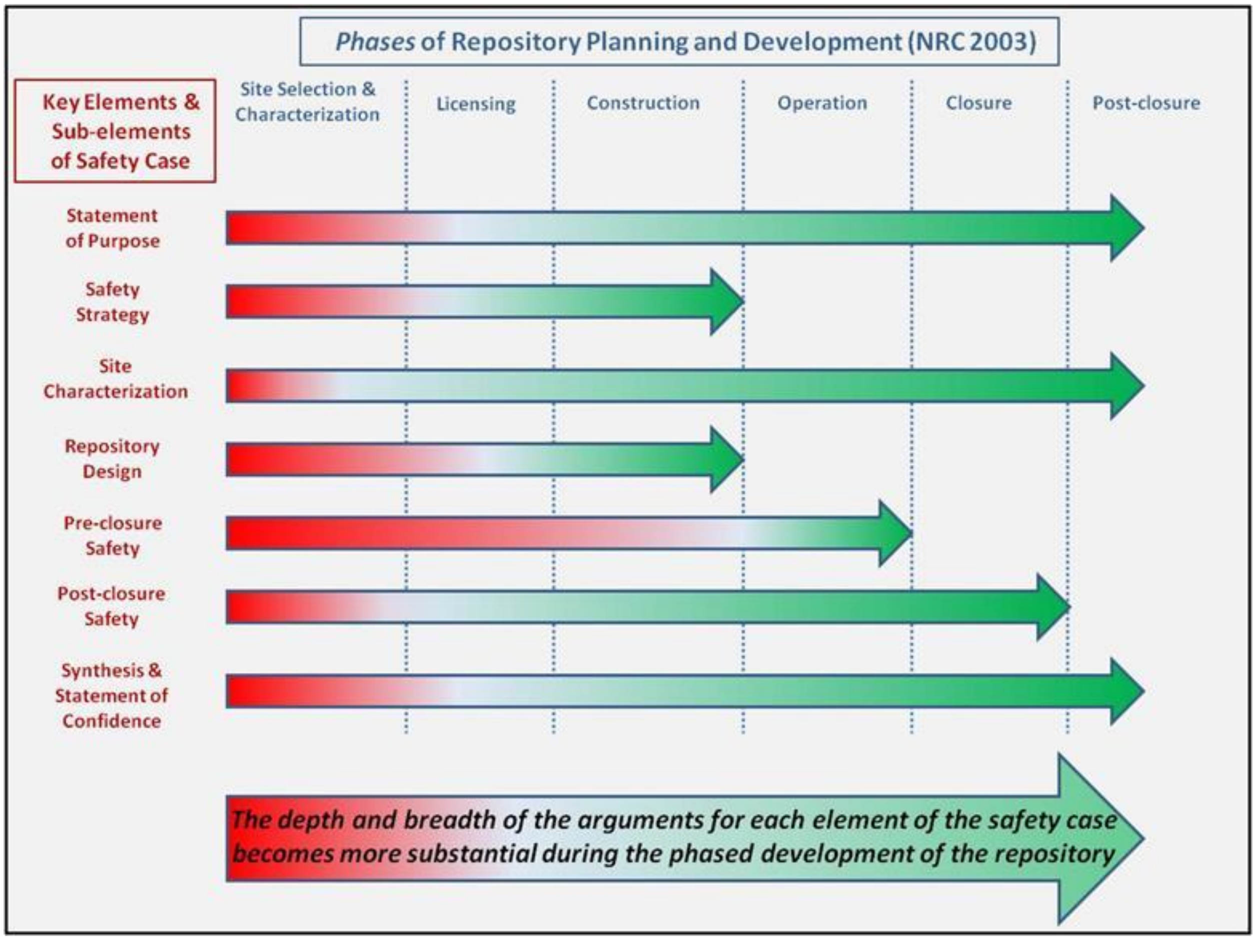
- **Waste -** DBD is for smaller DOE-managed waste forms. While there is no technical limitation to DBD of SNF (e.g., Brady et al. 2009; Arnold et al. 2011; Arnold et al. 2012), it is not the current focus of DBD in the U.S.
- **Regulations -** There is no regulatory framework for DBD. Existing regulations for mined geologic disposal of SNF and HLW disposal and their possible applicability or implications to DBD regulations were discussed in Section 2.1.
- **Siting -** A specific site has not been identified; instead, safety assessments are based on generic assumptions about crystalline basement rock and overlying sediments.
- **Design -** Preliminary design concepts have been examined, but no final design exists.

Specific considerations for the components of the safety strategy for DBD are discussed in the following subsections.

3.1 Management Strategy

The management strategy will outline the various activities required for planning and implementation of a DBD facility. It will build from sound management and engineering principles, which include a nuclear safety culture, QA, work controls (e.g., cost and schedule tracking), and records/data management. An important principle of the management strategy is stakeholder involvement in key aspects of siting, design, and assessment. Confidence on the part of stakeholders can be enhanced if there is a sense that the development of a geologic disposal facility and its safety case are able to address concerns as they are raised. If the development proceeds faster than stakeholders are able to raise concerns and have them addressed, there is a potential for loss of confidence in the program (Freeze et al. 2013a, Section 2.1.1).

As described in Section 1.2, the planning and development of a DBD facility is expected to take place over a period of years or decades. The safety case is an essential management and communication tool as it evolves throughout the project lifetime. The relationship between the phases of repository development and the evolution of the safety case is illustrated in Figure 3-1. Typical phases (i.e., decision points) in the development of a repository are shown across the top of the figure, while key elements of the safety case are shown along the side. As the repository program evolves from siting to licensing to closure, the required level of completeness and rigor increases and the associated safety case becomes more detailed with the addition of more data supporting the assessment basis (e.g., from site characterization and repository design) and more analysis results from safety evaluations (e.g., from post-closure PAs).



Source: MacKinnon et al. 2012, Figure 1 (Repository Phases from National Research Council 2003)

Figure 3-1. Evolution of the Safety Case through the Phases of Repository Development

As noted in Section 2.1.3.6, within a planning and development period that may span a decade or two, the licensing, construction, operation (emplacement), and closure of a DBD site with only a single borehole may take place over a just a few years. In this case, the program evolution illustrated in Figure 3-1 may be accelerated, but the key activities are still relevant.

The management strategy informs these key activities as they combine to drive the iterative evolution of the safety case, wherein the safety assessment and remaining uncertainties from one phase inform site characterization, design, and modeling at the next phase. Public and other stakeholder participation are important in each phase, and contribute to the decision to proceed to the next phase of development. The management strategy should be flexible over the DBD planning and development lifecycle in recognition of the fact that the uncertainties (e.g., due to the scarcity of data about the geologic environment or the changing social and political environment) evolve over time (Freeze et al. 2012, Section 3.1).

3.2 Siting and Design Strategy

The siting and design strategy will outline the approach for site selection consistent with national laws, policies, and regulations outlined in Section 2. As noted in Section 1.2.1.2, the siting and design strategy should favor robustness and defense-in-depth (i.e., a multiple barrier concept), which is accomplished by the presence of both engineered and natural barriers. It will include a siting strategy (Section 3.2.1) that outlines a site selection methodology that considers technical (i.e., natural barrier characteristics) and socio-political aspects, and a design strategy (Section 3.2.2) that considers disposal concepts and engineered barrier designs that can function together with the natural barrier characteristics to meet regulatory criteria.

The siting and design strategy for DBD is part of the overall DOE strategy for management and disposal of high-activity waste that includes "a phased, adaptive, and consent-based approach to siting and implementing a comprehensive management and disposal system" that integrates transportation, interim storage, and geologic disposal (DOE 2013).

The siting and design strategy considers radiological risks and safety. The siting strategy is more focused on the geosphere and natural barriers, which are key factors in post-closure safety. Post-closure risks are associated with potential releases of radionuclides from the engineered barriers and transport through the natural barriers to the biosphere, generally in the far future. The design strategy is more focused on the engineered barriers and pre-closure safety, with consideration of synergy with the natural barriers and post-closure safety. Pre-closure risks include possible radiological accidents and exposures during operations, and the potential for operational failures (e.g., waste packages stuck in the borehole above the emplacement zone).

Geologic disposal of high-activity waste can contribute to national security and non-proliferation objectives (DOE 2013). Specific safeguards and security considerations are identified in SNL (2014b, Appendix D), but are not further addressed in this preliminary iteration of the DBD safety case.

3.2.1 Siting Strategy

The siting strategy develops the site selection methodology and the siting guidelines and/or criteria, which consider the national laws and policies along with the likelihood of encountering favorable characteristics for the natural barriers. DOE is in the initial stages of developing a consent-based siting methodology, which will integrate socio-political and technical considerations (Section 3.2.1.1). In the absence of a formal methodology, the preliminary siting strategy for DBD identifies a set of technical, logistical, and socio-political guidelines and criteria (Section 3.2.1.2), based on previous studies.

3.2.1.1 Consent-Based Siting

Siting of storage or disposal facilities has proven in several countries, including the U.S., to be the most contentious part of a radioactive waste management program (BRC 2012; Rechard et al. 2011). When countries began to search for repository sites in the late 1960s and early 1970s, the prevailing view on siting was that establishing technical suitability (i.e., "based on factors most related to the physical characteristics of the locations") would be more challenging than social acceptability (i.e., "based not only on choices made by the political estate but also on actions taken by various interested and affected nongovernmental parties") (NWTRB 2015). However, most of the failed efforts resulted from top-down, federally-mandated siting decisions, made over the objections of local authorities. Even when public participation mechanisms (e.g., public hearings and public comment processes) were established following the expression of public opposition, those efforts did not result in successful siting of a facility (Jenkins-Smith et al. 2013). As a result, siting efforts (e.g., potential repository locations in Finland, Sweden, and Canada) are moving in the direction of earlier and more meaningful public involvement and decision-making, in order to garner acceptance for building radioactive waste facilities (BRC 2012; Rechard et al. 2011).

Promising experiences in these other countries indicate that a consent-based process, developed through engagement with states, tribes, local governments, key stakeholders, and the public, offers a greater probability of success than a top down approach to siting (DOE 2013). In addition, the BRC has recommended "a new, consent-based approach to siting future nuclear waste management facilities" BRC (2012). Steps in this approach might include (BRC 2012):

- **Develop a set of basic initial siting criteria** – These criteria will ensure that time is not wasted investigating sites that are clearly unsuitable or inappropriate.
- **Encourage expressions of interest from a large variety of communities that have potentially suitable sites** – As these communities become engaged in the process, the implementing organization must be flexible enough not to force the issue of consent while also being fully prepared to take advantage of promising opportunities when they arise.

A DOE consent-based siting approach, which will apply to the siting of a DBD facility, is under development. The following excerpts from DOE (2013), informed by the recommendations from the BRC (2012), outline the current DOE thinking on consent-based siting:

> *The NWPA specified a process for evaluating sites for a repository. The Administration concurs with the conclusion of the BRC that a fundamental flaw of the 1987 amendments to the NWPA was the imposition of a site for characterization, rather than directing a siting process that is, as the BRC recommends, "explicitly adaptive, staged, and consent-based…" In practical terms, this means encouraging communities to volunteer to be considered to host a nuclear waste management facility while also allowing for the waste management organization to approach communities that it believes can meet the siting requirements. Under such an arrangement, communities could volunteer to provide a consolidated interim storage facility and/or a repository in expectation of the economic activity that would result from the siting, construction, and operation of such a facility in their communities.*
>
> *Defining consent, deciding how that consent is codified, and determining whether or how it is ratified by Congress are critical first steps toward siting [a pilot storage facility, a consolidated interim storage facility, and a repository]. As such, they are among the near-term activities to be undertaken by the Administration in consultation with Congress and others. Legislation recently under consideration by Congress includes requirements for consent at multiple levels, including Congressional ratification. The Department is currently gathering information from the siting of nuclear facilities in the U.S. and elsewhere in order to better understand critical success factors in these efforts and to facilitate the development of a future siting process for a repository and storage facilities.*

> *This Strategy endorses the proposition that prospective host jurisdictions must be recognized as partners. Public trust and confidence is a prerequisite to the success of the overall effort, as is a program that remains stable over many decades; therefore, public perceptions must be addressed regarding the program's ability to transport, store, and dispose of used nuclear fuel and high-level radioactive waste in a manner that is protective of the public's health, safety, and security and protective of the environment.*

In the development of a consent-based siting process, certain strategies seem to have been important ingredients in at least some of the countries that have successfully adopted such an approach. These strategies include (NWTRB 2015, Box 5):

- Beginning far in advance of a specific siting study, communicate and engage with interested and affected parties to discuss the overall goals and objectives of national radioactive waste-management programs.
- Use multiple techniques and approaches to communicate and directly engage with interested and affected parties.
- Embed the implementer's representatives within the community.
- Create clear rules—that are agreed to in advance—to govern the relationship between the implementer and the community.
- Establish a group that is broadly representative of the community, to foster ongoing interactions with the implementer.
- Specify the basis for when, why, and how a community can withdraw from the siting process.
- Provide sufficient funding to allow a community to participate fully in the process.
- Provide independent review of the implementer's technical arguments either by experts chosen by the community or by an ongoing external group.
- Encourage the implementer to be open and responsive to questions and challenges from the community.
- Create a partnership between the community and the implementer to support repository development if the former agrees to host the facility.
- Clearly articulate the benefits the community is likely to receive from hosting a deep-mined, geologic repository.

3.2.1.2 Siting Guidelines and Criteria

Siting guidelines provide a means to determine relatively quickly whether a site meets basic suitability requirements, and can inform decisions for proceeding to more detailed site investigation and site characterization studies (Rechard et al. 2011). The guidelines are intended to describe characteristics of the natural barriers that (i) contribute to long-term isolation of radionuclides in the deep geologic environment, and (ii) can facilitate an appropriate disposal concept and design. In cases where there are multiple communities and/or candidate sites (e.g., as part of a consent-based siting process), the siting guidelines provide a basis for evaluation and comparison of the relative merits.

The natural barriers include the following geosphere features and components (Freeze et al. 2014, Section 3.1):

- Host Rock – The geologic unit(s) containing the repository excavations and emplaced waste. For DBD, the repository excavation is the disposal borehole(s) and the host rock is the crystalline basement. The vertical extent of the host rock and the stratigraphic distinction between host rock and the overlying geologic units is site- and geology-specific. Components may include the DRZ and/or various stratigraphic units.
- Overlying Geologic Units – The geologic unit(s) not considered part of the host rock stratigraphy. Typically, the subsoil and rock that is not part of the biosphere (i.e., below the depth affected by normal human activities, in particular agriculture) (IAEA 2007). Components may include overlying sediments, aquifers, and/or unsaturated units.

Siting guidelines and criteria for high-activity waste repositories have been developed since the late 1970s (e.g., Ekren et al. 1974, IAEA 1977, NAS 1978, USGS 1980, DOE 1980). Following these early efforts, more formal siting guidelines and criteria for mined geologic repositories were published in the NWPA (NWPA 1983, Section 112(a)), 10 CFR 60, and 10 CFR 960.

In 10 CFR 60.122(a), the siting criteria state:

> *A geologic setting shall exhibit an appropriate combination of [favorable conditions] so that, together with the engineered barriers system, the favorable conditions present are sufficient to provide reasonable assurance that the performance objectives relating to isolation of the waste will be met.*

and

> *…potentially adverse conditions [if present,] may compromise the ability of the geologic repository to meet the performance objectives relating to isolation of the waste.*

In 10 CFR 960 (General Guidelines for the Preliminary Screening of Potential Sites for a Nuclear Waste Repository), technical guidelines were established for qualifying, favorable, potentially adverse, and, in some cases, disqualifying conditions for the characteristics, processes, and events that may influence the pre-closure suitability of a site and/or the post-closure performance of a repository system. 10 CFR 960 includes post-closure guidelines (in Subpart C) and pre-closure guidelines (in Subpart D) in the following categories:

Subpart C – Postclosure Guidelines: 10 CFR 960.4

- Geohydrology
- Geochemistry
- Rock characteristics
- Climatic changes
- Erosion
- Dissolution

- Tectonics
- Human interference
  - Natural resources
  - Site ownership and control

Subpart D – Preclosure Guidelines: 10 CFR 960.5

Preclosure Radiological Safety

- Population density and distribution
- Site ownership and control
- Meteorology
- Offsite installations and operations

Environment, Socioeconomics, and Transportation

- Environmental quality
- Socioeconomic impacts
- Transportation

Ease and Cost of Siting, Construction, Operation, and Closure

- Surface characteristics
- Rock characteristics
- Hydrology
- Tectonics

More specific details of these historical siting guidelines and criteria are presented in Appendix B.

Siting guidelines for DBD should encompass considerations that maximize the probability of successfully (i) drilling and completing a deep large-diameter borehole at a site with favorable geologic, hydrogeochemical, and geophysical conditions, (ii) building and maintaining the associated infrastructure, (iii) conducting surface handling, emplacement, and sealing operations, and (iv) demonstrating long-term post-closure safety (Freeze et al. 2015b, Section III). DBD siting guidelines should include potentially disqualifying factors – to identify sites that are clearly unsuitable or inappropriate. Examples of unfavorable features may include: presence of high-permeability connection(s) from the waste emplacement zone to the shallow subsurface, upward hydraulic gradients, young meteoric and/or oxidizing groundwater at depth, presence of economically exploitable natural resources at depth, high geothermal heat flow, and significant probability of future volcanic activity (Sassani and Hardin 2015; Freeze et al. 2015b, Section III).

Based on these DBD siting considerations, and insights provided by the historical guidelines and criteria for mined repositories, a set of siting guidelines for DBD have evolved over the past several years (Arnold et al. 2012, Section 8; Arnold et al. 2013, Section 2; Arnold et al. 2014, Section 2; Freeze et al. 2015a; Freeze et al. 2015b; DOE 2015b; DOE 2016). These DBD siting guidelines include the following technical, logistical, and socio-political factors:

Technical Factors – Geological, hydrogeochemical, and geophysical conditions potentially relevant to successfully drilling and constructing a DBD facility and demonstrating post-closure safety for a DBD system. Technical factors include:

- **Depth** – The depth to crystalline basement should be 2,000 m or less. This allows for a 2,000 m emplacement zone to be overlain by at least 1,000 m of seals within the crystalline basement.
- **Nature of Crystalline Basement Fabric and Stress State** – In the crystalline basement rocks, it is preferred to have (a) a lack of steeply dipping foliation or layering; and (b) a low differential horizontal stress. A large differential in horizontal stress at depth can be an indicator of potential difficulties in drilling a vertical hole and of borehole instability (e.g., extensive borehole breakouts and/or an enhanced DRZ around the borehole).
- **Regional Structures, Crystalline Basement Shear Zones, and Other Tectonic Features** – The absence of major regional structures, crystalline basement shear zones, or other tectonic features within 50 km of the site is preferred.
- **Groundwater Flow at Depth –** There should be a lack of fresh groundwater recharge at depth. Conditions/features might include, for example: lack of significant topographic relief that would drive deep recharge; evidence of ancient groundwater at depth; and/or data suggesting high-salinity groundwater at depth.
- **Geochemical Environment** – High salinity and geochemically-reducing conditions at depth are preferred. High salinity at depth indicates old groundwater and precludes use of deep groundwater as a drinking water source. Increasing salinity with depth promotes stable stratification based on fluid density, and tends to oppose thermal convection from waste heat. Geochemically-reducing conditions tend to reduce radionuclide mobility by decreasing solubility and increasing sorption.
- **Geothermal Heat Flux** – A heat flux at the site of less than 75 mW/m^2 is preferred. A high geothermal gradient or geothermal heat flux can be related to the potential for upward hydraulic gradients and is also related to the potential for geothermal drilling.
- **Seismic/Tectonic Activity** – Less than 2% probability within 50 years of peak ground acceleration greater than 0.16 g is preferred. This is generally indicative of an area of tectonic stability. A larger seismic hazard could increase risk during drilling and emplacement and is also a general indicator of tectonic activity, potential fault movement, and structural complexity.
- **Volcanism –** Distance to Quaternary age volcanism or faulting greater than 10 km is preferred. Quaternary-age faulting and volcanism is an indicator for potential future volcanism or tectonic activity.
- **Natural Resources Potential** – Absence of potential resources in the crystalline basement and sedimentary overburden is preferable. Resource exploration and/or production (e.g., drilling or mining for petroleum, minerals, or water) could lead to human intrusion into the deep borehole and/or impact the release of radionuclides to the overlying sediments.
- **Surface and Subsurface Usage** – There are no previous or current uses or conditions of the surface or subsurface near the site that could interfere with the pre-closure or post-closure performance of the DBD facility. Such uses or conditions might include, for example, wastewater disposal by deep well injection, CO_2 injection, oil and gas production, mining,

underground drinking water extraction, strategic petroleum reserve sites, or anthropogenic radioactive or chemical contamination.

Logistical Factors – Considerations relevant to successfully completing the construction and engineering operations associated with a DBD facility. Logistical factors include:

- **Site Area** – The site area should be sufficient to accommodate drilling operations, construction of surface facilities, surface waste handling, downhole emplacement operations, and site operation needs.
- **Site Access** – There should be reasonable access to roadways and/or railways for transportation of waste and other materials and for heavy equipment needs. Transportation costs could vary considerably depending on the DBD location relative to waste storage and/or nuclear power plant locations.
- **Wetlands/Flood Plains –** The site area should be outside of wetland areas and 100-year flood zones.
- **Regulations and Permitting** – Legal and regulatory requirements associated with permitting and pre-closure operations (i.e., drilling, construction of surface facilities, and waste handling and emplacement) should be achievable. The regulatory environment varies from state to state and for Federal versus private land.

Socio-political Factors – Considerations relevant to public opinion and acceptance. These considerations would be expected to be addressed as part of a consent-based siting process. Social and political factors include:

- **Proximity to Population Centers –** The site should be distant from major urban developments.
- **Public Opinion** – The support or opposition of state and local entities and other stakeholders towards nuclear facilities in general and DBD in particular. Early engagement with local and regional stakeholders is helpful, and engagement with scientific communities (e.g., state geological surveys and state university faculty) provides local and regional geoscientific knowledge. An ongoing stakeholder outreach and political engagement program is necessary.

Sites that exhibit stronger combinations of favorable attributes of the above DBD siting guidelines are more likely to provide long-term isolation of radionuclides in the deep geologic environment. However, it is not necessary, nor likely, for a site to meet all of the guidelines. A site that meets only certain guidelines may still be able to safely isolate waste.

In addition to the siting guidelines presented above, site screening typically also considers the attributes of the engineered components of the system (e.g., the design criteria, such as described in Section 3.2.2.2), and how they would be expected to function in conjunction with the site conditions.

3.2.2 Design Strategy

The design strategy outlines the approach to selecting a disposal concept and design, including the requirements for the engineered barriers. The design should satisfy pre-closure safety requirements and should work in conjunction with the surrounding natural barriers to satisfy post-closure safety requirements. In addition, the design strategy must consider potential impacts from the waste acceptance criteria and from integration with waste generators, interim storage/aging and/or transportation (e.g., timing and throughput of waste, waste package sizes and characteristics).

Based on the national strategy outlined in Section 2, the current emphasis of the DBD concept is the disposal of smaller DOE-managed waste forms. Section 3.2.2.1 describes this DBD disposal concept; Section 3.2.2.2 presents a preliminary set of design requirements.

3.2.2.1 Disposal Concept

The disposal concept for DBD of smaller DOE-managed waste forms builds from recent design studies for DBD disposal of SNF (Arnold et al. 2011; Arnold et al. 2012, Section 4). For DBD in crystalline basement rock a generic disposal concept (Figure 3-2) includes several engineered features and components that are important to pre-closure and/or post-closure safety.

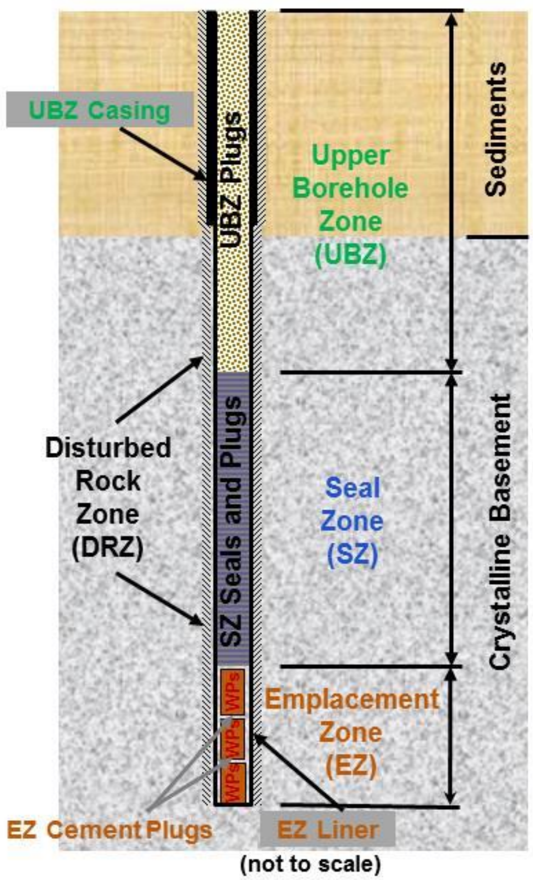


Figure 3-2. Schematic of the Deep Borehole Disposal Concept

DBD engineered features and components include:

- **Borehole and Casing** – The drilled excavation for waste disposal. The borehole depth, diameter, casing schedule, and waste loading are determined by the waste and host rock properties. The DBD reference design (Section 4.1.1) assumes steel casing.
- **Waste Form (WF)** – The bulk waste material containing the radionuclide inventory and the materials used to envelop or solidify the waste. The waste material (i.e., the waste form matrix) may be the result of treatment and/or conditioning (resulting in a solid product) and may be encapsulated in a waste canister. SNF typically is in the form of spent fuel pellets and cladding. HLW (such as smaller DOE-managed waste forms) can have a variety of forms (e.g., granular waste inside a waste canister, borosilicate glass). (Freeze et al. 2014, Section 3.1; SNL 2015, Section 2.6.7). For the DBD reference design, the waste form is CsCl and SrF_2 (Section 4.2.3).
- **Waste Package (WP)** – The sealed container used to package the waste form(s) for final disposal. The waste package may be fabricated with a corrosion-resistant outer layer and/or may be inserted into a disposal overpack. Waste package internal structures may include racks or inserts for structural support and waste form or canister stability and/or neutron absorbers for criticality control. (Freeze et al. 2013a, Section 2.2.3.1.1; Freeze et al. 2014, Section 3.1; SNL 2015, Section 2.6.7). For the DBD reference design, the waste package is carbon steel casing (Section 4.2.4) and includes the inner and outer shells of the Cs capsules (stainless steel) and Sr capsules (stainless steel or Hastelloy) as waste package internals (Section 4.2.3).
- **Emplacement Zone (EZ) Buffer/Backfill** – The material(s) placed in the void region of the borehole EZ between the waste packages and the EZ liner. This material serves the purpose of both a buffer (a material (e.g., bentonite) immediately surrounding a waste package and having some chemical and/or mechanical buffering role) and a backfill (a material (e.g., clay, cement, or crushed rock) used to refill excavated underground regions and/or to control mechanical, thermal, and/or chemical conditions in the repository) (Freeze et al. 2014, Section 3.1). For the DBD reference design, the EZ buffer/backfill material is a fluid (brine) (Section 4.2.5.1).
- **Emplacement Zone Cement Plugs** – Cement that has been poured or injected on top of a bridge plug (SNL 2016b, Section 2.7.4). For the DBD reference design, the EZ cement plugs are nominally 10-m thick and are emplaced between stacks of 40 waste packages (Section 4.2.5.2).
- **Emplacement Zone Liner** – For the DBD reference design, the EZ liner is assumed to be steel casing (Section 4.1.1), perforated to facilitate pre-closure waste emplacement and post-closure thermal expansion of EZ fluid (Section 4.2.5.3).
- **Seal Zone (SZ) Seals and Plugs** – The engineered materials placed in the borehole above the emplacement zone to limit entry of water and migration of contaminants, i.e., to isolate the emplaced waste from the accessible environment (Freeze et al. 2013a, Section 2.2.3.1.1). For DBD, the seal zone is in a borehole interval that is entirely within the crystalline basement rock. It will include multiple low-permeability materials (e.g., bentonite seals, cement plugs) and will also contain intermittent segments of ballast (sand and/or crushed rock) (see Sections 4.1.3.4 and 4.2.6). These seals and plugs will be emplaced directly against the borehole wall host rock/DRZ.

- **Upper Borehole Zone (UBZ) Plugs** – The materials placed in the borehole above the seal zone to limit entry of water and migration of contaminants. For DBD, the UBZ is in a borehole interval that is likely to be predominantly in the overlying sediments. It will primarily consist of cement plugs but may also include other low-permeability materials (e.g., sand and/or crushed rock ballast) and bridge plugs (see Sections 4.1.3.4 and 4.2.7). These plugs and backfill will be emplaced against the borehole casing.
- **Upper Borehole Zone Casing** – For the DBD reference design, the steel UBZ casing will be cemented (Sections 4.1.1 and 4.2.7).

In addition to the engineered features and components mentioned above, the DBD concept also includes the following pre-closure activities and SSCs that may be important to safety:

- **Borehole Drilling and Construction** – As noted in Section 1.2.1.2, borehole drilling activities, which are conducted during the pre-operational period, do not involve radiological hazards and are therefore beyond the scope of this DBD safety case. However, drilling methods and final borehole and casing dimensions and properties are important to the design of other features and components and to the pre-closure basis.
- **Surface Facility Construction** – As noted in Section 1.2.1.2, construction activities, which are conducted during the pre-operational period, do not involve radiological hazards and are therefore beyond the scope of this DBD safety case.
- **Transportation** – As noted in Section 1.2.1.4, transportation safety is part of the pre-closure safety analysis. However, it is not further addressed in this preliminary iteration of the DBD safety case.
- **Surface Facility Operations** – During the operational period, surface activities that involve radiological hazards will need to be evaluated. Surface activities specifically involving waste package handling are addressed in the next bullet.
- **Waste Package Surface Handling** – This includes activities and SSCs associated with on-site receipt of waste containers from transportation, transfer of waste to disposal waste packages (if necessary), and on-site surface transport of waste packages to the downhole emplacement components. Specific considerations include:
    - waste acceptance criteria (e.g., waste forms and characteristics)
    - interface/integration with waste generation and storage (Hanford) and transportation (e.g., timing and throughput of waste, waste package sizes and characteristics)
- **Waste Package Downhole Emplacement** – This includes activities and SSCs associated with emplacement of waste packages (i.e., directly above or within the borehole). Specific considerations include:
    - waste package integrity during operations
    - guidance casing and EZ liner maintaining an internally smooth pathway to facilitate package emplacement and to avoid getting packages stuck
    - emplacement options and rates
- **Borehole Sealing and Plugging** – This includes activities associated with placing seals and plugs in the seal zone and in the UBZ following waste emplacement and ensuring that the seals and plugs, acting in conjunction with the DRZ, meet design requirements.

- **Facility Closure** – This includes activities and SSCs associated with decommissioning of the surface facilities, site closure, performance confirmation monitoring, and active and passive institutional controls.

Additional details of the engineered features and pre-closure activities are presented in Sections 4.1 and 4.2.

3.2.2.2 Design Criteria and Requirements

The design criteria and requirements are intended to describe the characteristics of the pre-closure activities, SSCs, and engineered barriers that contribute to pre-closure safety and that work in conjunction with the natural barriers to contribute to long-term isolation of the deep geologic environment of the crystalline basement.

General design criteria for the SSCs of geologic repository were published in 10 CFR 60. These criteria include:

- 10 CFR 60.131 – General design criteria for the geologic repository operations area
- 10 CFR 60.132 – Additional design criteria for surface facilities in the geologic repository operations area
- 10 CFR 60.133 – Additional design criteria for the underground facility
- 10 CFR 60.134 – Design of seals for shafts and boreholes
- 10 CFR 60.135 – Criteria for the waste package and its components
- 10 CFR 60.136 – Preclosure controlled area

More specific details of these general design criteria for a mined geologic repository are presented in Appendix C.

Design considerations for the engineered features and components of a DBD facility were originally developed for DBD disposal of SNF (Arnold et al. 2011; Arnold et al. 2012, Section 4; Arnold et al. 2013, Section 3). Design considerations for DBD disposal of Cs and Sr (Cs/Sr) capsules, building upon the earlier SNF design considerations, are documented in Arnold et al. (2014, Sections 3 and 4). More specific design requirements and controlled assumptions for DBD disposal were initially developed in SNL (2015) and refined in SNL (2016b); details can be found in Appendix C. These design requirements and controlled assumptions are summarized below for engineered features and components (Table 3-1) and for operations (Table 3-2).

While these design requirements support DBD of Cs/Sr capsules, many of the requirements are transferrable to DBD of other waste forms.

Table 3-1. DBD Design Requirements for Engineered Features

Feature or Component	Design Requirement(s) and Controlled Assumptions	Value(s)
Borehole	**Borehole Depth –**	TBD
	Borehole Diameter – Borehole and casing diameters shall permit emplacement of WPs with sufficient radial clearance.	TBD
	Borehole Horizontal Deviation –	≤ 50 m
	Borehole Dogleg Severity –	TBD
	Borehole Service Lifetime – Borehole construction, completion, and associated surface facilities shall be designed with service lifetime sufficient to accommodate safe disposal operations and sealing.	TBD
Waste Forms (WFs)	**WFs for Disposal –** Specific waste form requirements	TBD
	Waste Acceptance Criteria - Requirements might include, for example, restrictions on the activity concentration or total activity of particular radionuclides (or types of radionuclide) in the waste, or requirements concerning the waste form or packaging of the waste. (IAEA 2007)	TBD
Waste Packages (WPs)	**WP Length** –	TBD
	WP Diameter and Radial Clearance –	TBD, to be informed by DBFT
	WP Weight –	TBD
	WP Exterior Surface – The exterior WP package surface, including connectors, shall be smooth and free of features that could hang up on casing joints, hangers, collars, etc., when moving upward or downward.	Smooth
	WP Buoyancy – WPs, including the waste load, shall have negative buoyancy in borehole fluid to prevent WPs from floating	> borehole fluid density
	WP Temperature – WPs shall perform at the maximum waste-heated package temperature assumed.	≤ 250°C
	WP Mechanical Integrity – WPs shall maintain mechanical integrity (structural, dimensional) during transport, handling, emplacement, plugging, and sealing. Mechanical load limits for waste package design are TBD.	Mechanical load limits for WPs are TBD
	WP Factor of Safety (FoS) – FoS for mechanical integrity calculations.	TBD, to be based partly on DBFT
	WP Containment – WPs shall prevent leakage of radioactive waste (solid, liquid or gaseous) throughout the operational phase including transport, handling, emplacement (and retrieval, if necessary), and borehole sealing. Also, no leakage of borehole fluid into WPs shall occur during these activities.	No leakage

Feature or Component	Design Requirement(s) and Controlled Assumptions	Value(s)
Emplacement Zone (EZ)	**EZ Temperature –** Temperature (and temperature rise due to heat-generating waste) in the EZ will depend on site-specific data, waste characteristics and packaging, etc.	≤ 250°C
	Thermal Expansion in the EZ – Casing, cement, and other features of EZ completion, shall accommodate thermal expansion of fluids and solids due to waste heating without breaching packages, plugs, casing, or seals.	
	Emplacement Fluid – Fluid composition for emplacement will be determined on consideration of properties, stability, and waste isolation.	TBD
	Emplacement Fluid Density – The minimum and maximum density of the borehole fluid at any location, when WPs are being emplaced. These parameters control buoyant weight of WPs, and borehole hydrostatic pressure.	≥ water ≤ TBD
	Emplacement Fluid Pressure – The minimum and maximum borehole fluid (water or mud) for WP design and performance.	≥ water (hydrostatic) ≤ TBD
Emplacement Zone Cement Plugs	**EZ Plug Interval** – Cement plugs shall be installed in the EZ to stabilize stacks of waste packages and limit axial compressive loading of packages.	≤ 40 WPs
	EZ Plug Removal – Cement plugs installed in the EZ shall be designed for possible removal to facilitate waste retrieval.	
Emplacement Zone Liner	**EZ Liner** – A perforated liner/casing of the same constant diameter as, and internally flush with, the guidance casing, shall run the length of the EZ for transit of WPs. The manner of perforating the EZ liner is TBD.	
Seal Zone (SZ)	**Seal Design** – Seals and sealing materials shall be designed to provide redundant performance.	
	Seal Durability – Seals shall resist mechanical loading and retain low-permeability properties at up to the maximum design temperature through the duration of the thermal period.	
	Seal-Borehole Contact – Seals shall form a low-permeability contact with the borehole wall host rock to prevent bypass flow at the interface.	
	Seal Permeability –	≤ 10^{-16} m^2
	Seal Temperature –	≤ 200°C

Table 3-2. DBD Design Requirements for Operations

Feature, Component, or Operation	Design Requirement(s) and Controlled Assumptions	Value(s)
Safety Assessment	**Operational Safety Basis** – Requirements for radiological exposure and dose, nuclear criticality, nuclear quality assurance, nuclear material safeguards, etc. are applicable.	TBD
	Nuclear Material Safeguards – Safeguards and security requirements for DBD of radioactive waste.	TBD
	Nuclear Criticality – Design, handling, and emplacement of waste packages must preclude any possibility of nuclear criticality. (SNL 2015)	
Borehole Drilling and Construction	**Drilling and Construction Methods** – Drilling and construction of boreholes shall be conducted using methods selected for successful completion, waste isolation performance, and achieving characterization objectives.	Specific performance criteria are TBD
	Permitting – National (i.e., NEPA), state and local drilling, land use, and environmental permits are required, as appropriate, from cognizant jurisdictions.	
Waste Package Surface Handling	**Shielding** – Shielding is required for DBD operations, but the level of shielding depends on waste form characteristics and packaging.	TBD
Waste Package Downhole Emplacement	**WP Emplacement** – WPs shall be emplaced at the intended positions in the EZ, and shall not become stuck anywhere else in the borehole.	
	Emplacement System Redundancy – Transfer and emplacement equipment shall have redundant means for holding WPs at the surface during staging so that single-point failures cannot result in a dropped WP.	
	WP Retrieval – Retrievability and reversibility (as applicable).	TBD
	Terminal Velocity – Limit on terminal velocity of a free-falling WP.	TBD
	Bottom-Hole Assembly Weight Limit – The weight of the bottom-hole assembly (waste package, tool string, etc.) shall not exceed the service limit of the emplacement equipment, including an appropriate FoS.	TBD
	Guidance Casing – A casing of constant diameter shall be run from the surface to total borehole depth (possibly in sections) for transit of WPs to the EZ. The guidance casing shall be internally flush with uniform diameter over the full borehole length.	TBD
Borehole Sealing and Plugging	**Seal Zone** – Permanent seal(s) shall be installed in a borehole interval directly above the EZ.	
	Seal Zone Casing – Casing shall be removed from SZ, exposing the rock where seals are to be set.	

Other design considerations may include prevention of impacts from external/disruptive events such as flooding, extreme weather, seismicity, and sabotage on the pre-closure activities.

3.3 Assessment Strategy

The assessment strategy includes the approach to evaluate pre-closure operations, analyze the post-closure evolution of the system, perform quantitative safety assessments (including uncertainties), and collect and evaluate complementary qualitative evidence and arguments. The assessment strategy is described in the following subsections: pre-closure safety analysis methodology (Section 3.3.1); post-closure performance assessment methodology (Section 3.3.2); and confidence enhancement methodology (Section 3.3.3). These three assessment methodologies are all based on achieving safety goals, functions, and criteria as established by the regulations. As noted in Section 2.1, the current regulatory framework for high-activity waste disposal was not intended for DBD. Instead, the regulatory assumptions outlined in Section 2.1 guide this preliminary iteration of the DBD safety case.

3.3.1 Pre-Closure Safety Analysis Methodology

As outlined in Section 2.1.1, a pre-closure safety analysis is conducted to estimate (i) the occupational dose from on-site radiation levels and radiological exposures, and (ii) the dose to the public from off-site releases of radioactive materials. The pre-closure safety analysis addresses the period before permanent closure, which includes decontamination and/or dismantlement of surface facilities.

Section 1.2.1.4 identifies the need for pre-closure analyses for transportation safety and for operational safety. The transportation safety analysis is not further addressed in this preliminary iteration of the DBD safety case (see Sections 2.1 and 2.1.3.9). A pre-closure operational safety analysis includes (Section 1.2.1.4):

- Description of the surface and subsurface facilities (i.e., the borehole) and their operation, and
- Comparison with safety standards that includes:
    - Initiating event and event probability identification and screening
    - Event sequence identification
    - Radiological dose and consequence analyses
    - Criticality analyses
    - SSCs and procedural safety controls intended to prevent or reduce the probability of an event sequence or mitigate the consequences of an event sequence, should it occur
    - Uncertainty analysis
    - Software verification and model validation

The implementation of these steps for a pre-closure safety analysis is shown in Figure 3-3. These steps are progressively updated and repeated during the various phases of repository lifecycle. The iterative nature of the pre-closure safety analysis methodology provides input and feedback to the implementation and prioritization of R&D activities.

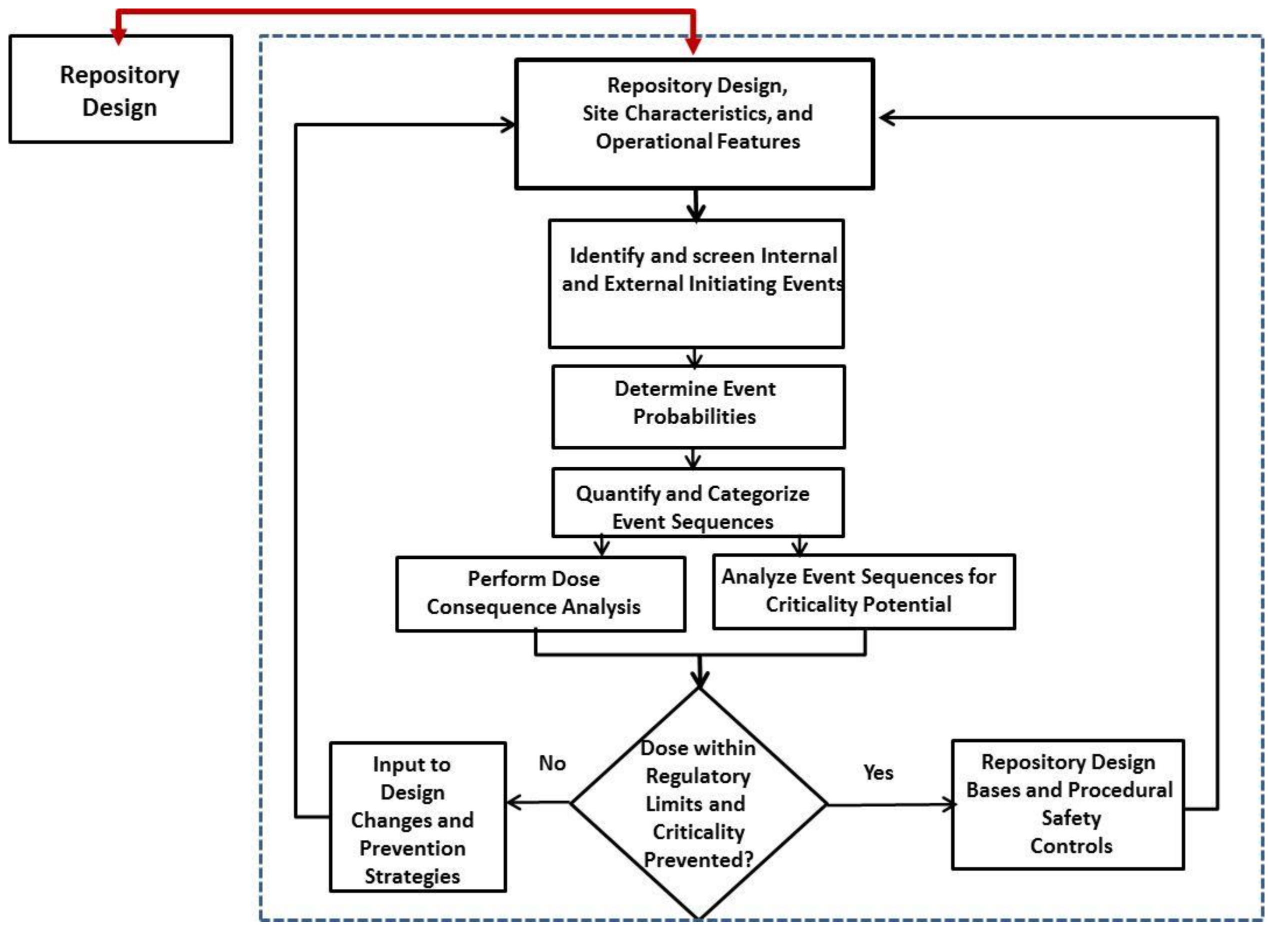


Figure 3-3. Steps in the Pre-Closure Safety Analysis Methodology

An example of a detailed pre-closure safety analysis, in support of the Yucca Mountain Repository license application, can be found in DOE (2008, Chapter 1).

3.3.2 Post-Closure Performance Assessment Methodology

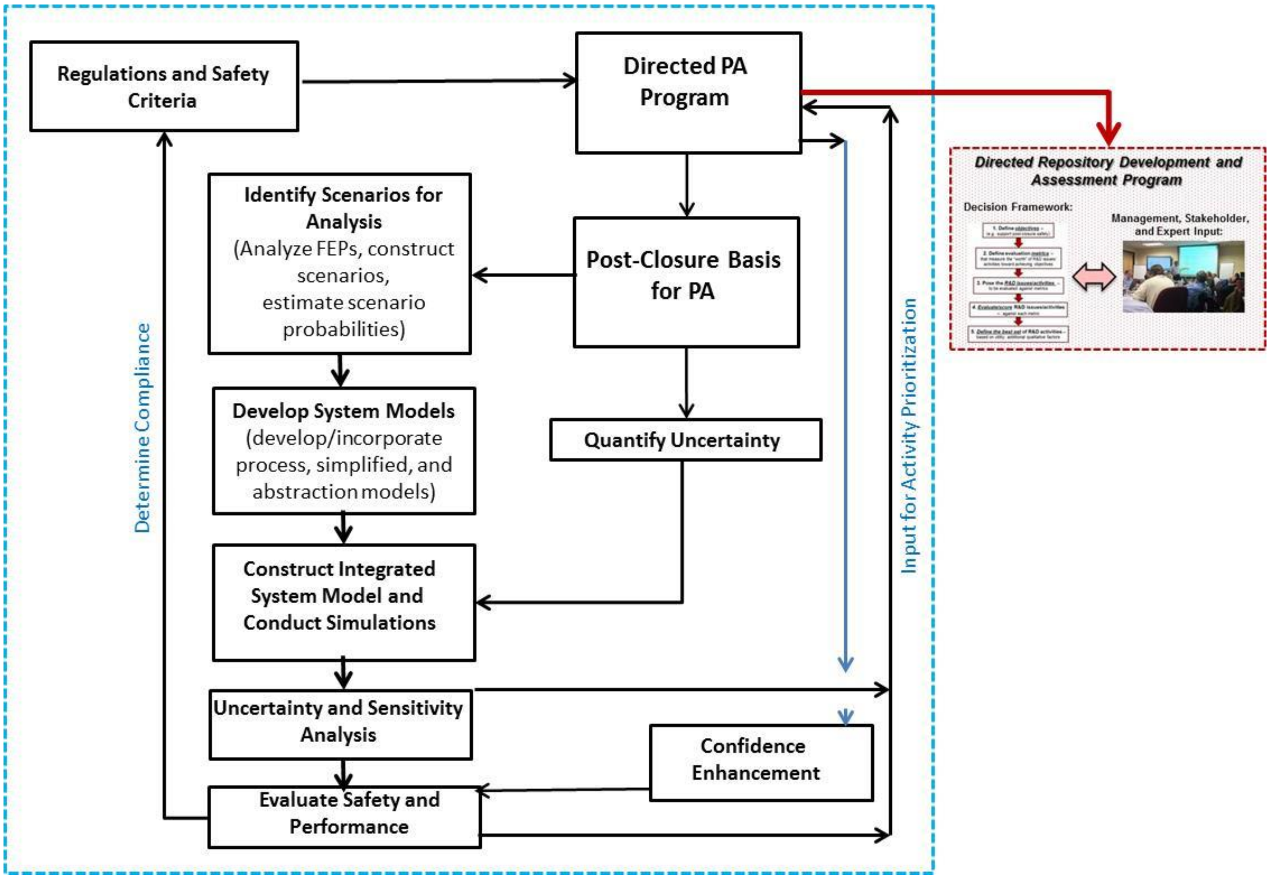
As outlined in Section 2.1.2, a post-closure PA is conducted to estimate (i) radiological exposures to members of the public, and (ii) radiological releases to the accessible environment. The post-closure PA addresses the period after permanent closure through the period of geologic stability (commonly 1,000,000 years).

A post-closure PA includes (Section 1.2.1.4):

- Description of the natural barriers (information related to the geology, hydrology, and geochemistry (including disruptive processes) and events of the site, and the surrounding region), and information on the design of the engineered barriers used to define parameters and conceptual models used in the assessment;
- Description of how the barriers/components are expected to provide safety functions
- Comparison with safety standards that includes:
    - FEP analysis
    - Scenario development
    - Model development (conceptual, mathematical, and computational models, and integrated PA model)
    - Software verification and model validation
    - Subsystem and barrier analyses
    - PA model analyses
    - Uncertainty and sensitivity analyses

At the heart of a quantitative post-closure is the PA model, the integrated mathematical and numerical implementation of the conceptual description of the disposal system components and their interactions (i.e., the FEPs and scenarios). To perform calculations with a PA model, a software code that implements the numerical model must be utilized.

A quantitative post-closure PA is performed as part of an overarching PA methodology. The PA methodology has been developed over a period of 40 years for probabilistic risk analysis of radioactive waste disposal methods, facilities, and systems and has been used to inform key decisions concerning radioactive waste management both in the U.S. and internationally (Meacham et al. 2011, Section 1.1). The steps of the PA methodology, shown in Figure 3-4, are progressively updated and repeated during the various phases of repository lifecycle. The iterative nature of the post-closure PA methodology provides input and feedback to the implementation and prioritization of R&D activities.



adapted from Meacham et al. (2011, Figure 2)

Figure 3-4. Steps in the Performance Assessment Methodology

3.3.3 Confidence Enhancement Methodology

As described in Section 1.2.1.4, confidence enhancement refers to the qualitative information that provides additional support for the quantitative pre-closure and post-closure safety assessments. It includes evidence, arguments, and scientific observations and analyses that were not directly included in the safety assessment models, but that provide additional insights into the robustness, behavior, and evolution of the repository system. The role of confidence enhancement in the post-closure PA methodology is shown in Figure 3-4. Examples of types of qualitative information that may provide confidence enhancement for the DBD concept are provided in Section 5.3.

4. ASSESSMENT BASIS FOR DEEP BOREHOLE DISPOSAL

The role of the assessment basis in a safety case is to present the quantitative information necessary to support site selection and to perform the pre-closure safety analyses and post-closure PAs. The components of the assessment basis for DBD are discussed in the following subsections.

The pre-closure technical basis (Section 4.1) documents the quantitative information (i.e., a description of the surface and subsurface facilities and their operation) to support the pre-closure safety analysis (Section 5.1).

The post-closure technical basis documents the quantitative information (i.e., a description of the natural and engineered barriers) that supports the post-closure PA (Section 5.2). The post-closure technical basis is divided into three components: waste and engineered barriers (Section 4.2); geosphere and natural barriers (Section 4.3); and biosphere and surface environment (Section 4.4). The post-closure technical basis also supports confidence enhancement (Section 5.3).

The site selection basis (Section 4.5) documents information used to address the siting strategy, guidelines, and/or criteria (described in Section 3.2.1). The site selection basis draws heavily on the geosphere and natural barriers post-closure basis.

Normally, a safety case, and associated safety assessment and assessment basis, address a specific site, a well-defined inventory, waste form, and waste package, a specific repository design, specific concept of operations, and an established regulatory environment (Vaughn et al. 2013). However, this level of specificity does not currently exist for the DBD concept or for this preliminary iteration of the DBD safety case. Instead, a DBD reference case for Cs and Sr disposal (hereafter referred to as the "reference case") is established as a surrogate for site-specific and design-specific information upon which a safety case can be developed. The DBD reference case includes a reference design, concept of operations, and information describing the engineered barriers, geosphere and natural barriers, and biosphere.

The DBD reference design (Sections 4.1 and 4.2) is based on the reference disposal concept for DBD of Cs/Sr capsules in crystalline basement documented in SNL (2016b, Section 3), which in turn is based on earlier work (Arnold et al. 2011; Arnold et al. 2014) with modifications. The DBD reference case barrier descriptions (Sections 4.2 through 4.4) are based on the reference disposal concept and on generic information and assumption about crystalline basement rock and overlying sediments. This assessment basis information will be revised as necessary by knowledge gained during the DBFT.

4.1 Pre-Closure Basis

The pre-closure basis includes a description of the surface and subsurface facilities (i.e., the borehole) and their operation for use in the quantitative pre-closure safety analysis (Section 5.1). The description below is based on the reference disposal concept documented in SNL (2016b, Section 3) with dimensions and depths adapted for the specific Cs/Sr capsule disposal configuration described in Section 4.2.4. Specific pre-closure basis information, which helps define the DBD reference case and reference design, includes (Section 1.2.1.3):

- Repository design and layout (surface facilities, borehole, and engineered barriers)
- Effects of drilling and construction methods (including quality control) on operations and post-closure
- Operational procedures (e.g., for surface waste handling, subsurface waste emplacement, and site closure)
- Potential impact of external/disruptive events such as flooding, extreme weather, seismicity, and sabotage on the pre-closure activities
- Potential impacts of any pre-closure activities on post-closure safety

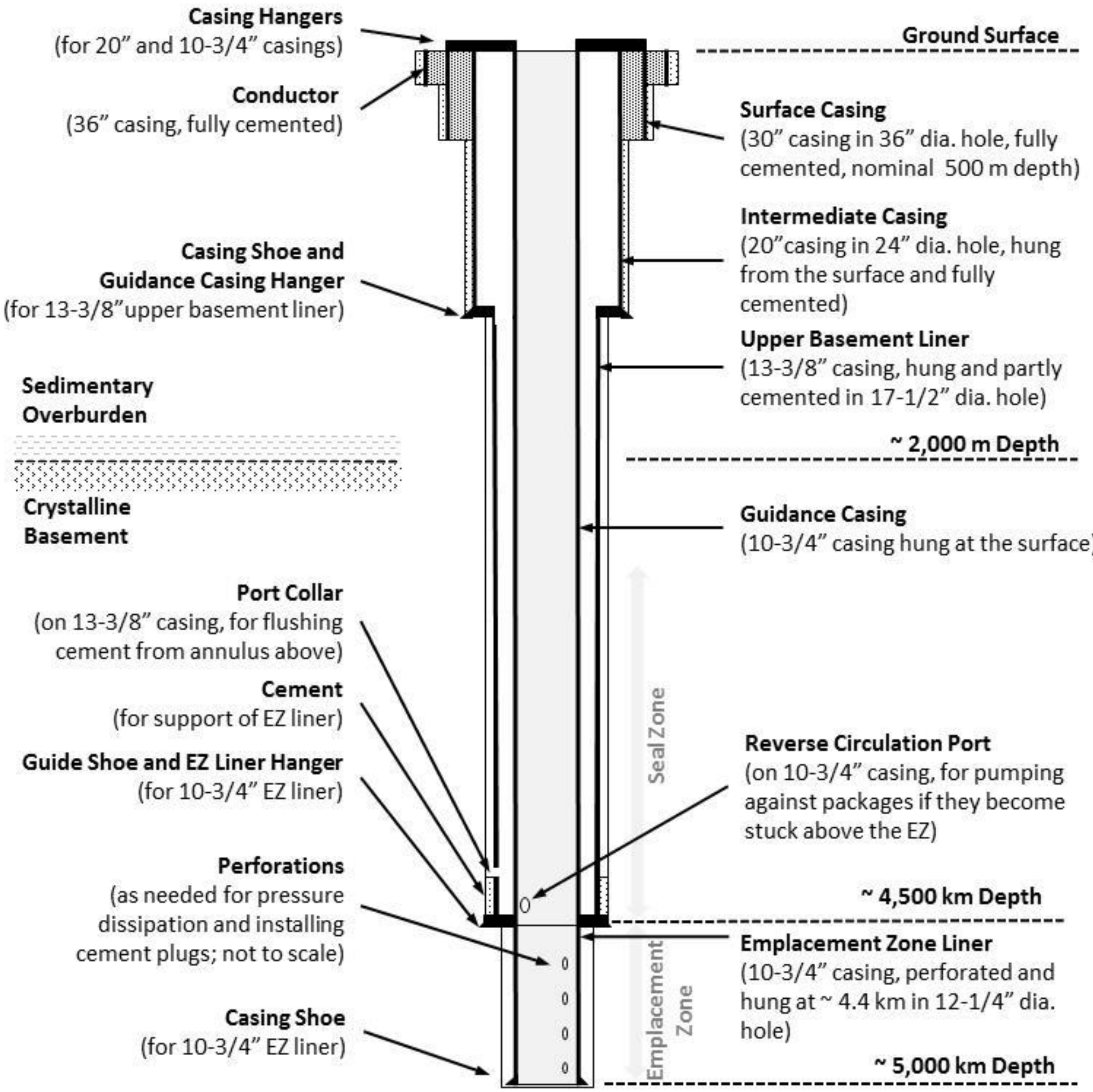
This information, quantitative with uncertainty where possible, is described in more detail in the following subsections.

4.1.1 DBD Site Design and Layout

The DBD site design and layout includes the surface facilities, the borehole, and the engineered barriers. The surface facilities are described as part of the surface facility operations in Section 4.1.3.1. The DBD reference design for the borehole and for the pre-closure aspects of engineered features and components are described in this subsection; design details of engineered features and components relevant to post-closure are deferred to Section 4.2.

The reference design for the disposal borehole is shown in Figure 4-1. It uses a telescoping set of liners and casing extending from the bottom of the borehole to the top of the borehole, consistent with requirements given in Table 3-1. Casing and liner specifications are given in Table 4-1. English units are used intentionally in this subsection because of their prevalence in the oil and gas industry, with metric equivalents provided for consistency with other sections of the report. Available casing and liner materials include steel of various grades, stainless steels, titanium, aluminum, and even non-metallic options (SNL 2016b, Section 2.7.2); steel is assumed for the casing and liner materials in the DBD reference design. Although not illustrated in Figure 4-1, the wellhead is below grade.

This reference borehole design, with an EZ (i.e., bottom-hole) diameter of 12.25 in (0.311 m), is for the disposal of “3-packs” of Cs and Sr capsules (see Section 4.2.4). The outside diameter for waste packages for this capsule configuration is 8.625 in (0.219 m) (SNL 2016b, Table 3-2). Heat output from the Cs and Sr capsules is presented in Section 4.2.2. The unshielded surface dose rate from a cesium capsule is over 600,000 rem/hr, while the unshielded surface dose rate from a strontium capsule is almost 30,000 rem/hour (Price et al. 2015), as of January 1, 2016.



(Source: adapted from SNL 2016b, Figure 3-1)

Figure 4-1. Disposal Borehole Schematic

Table 4-1. Disposal Borehole Casing and Liner Specifications

Interval	Depth (m)	Borehole Diam. (in) (m)	Casing/Liner Outer Diam. (in) (m)	Casing/Liner Thickness (in) (m)	Casing/Liner Inner Diam. (in) (m)
Surface Casing	0 to 500	36.0 0.914	30.0 0.762	0.75 0.019	28.5 0.724
Intermediate Casing	0 to ~1500	24.0 0.610	20.0 0.508	0.50 0.013	19.0 0.483
Upper Basement Liner	~1500 to 4466	17.5 0.445	13.375 0.340	0.375 0.010	12.625 0.321
Guidance Casing	0 to 4466	12.25 0.311	10.75 0.273	0.35 0.009	10.05 0.245
EZ Liner	4466 to 5000	12.25 0.311	10.75 0.273	0.35 0.009	10.05 0.245

(Source: Arnold et al. 2014, Table 3-6; SNL 2016b, Tables 2-2, 3.1, and 3-2)

Surface casing consists of 30-inch (0.76 m) casing fully cemented in a 36-inch (0.91 m) hole; it provides initial well control. If a blowout preventer (BOP) is required by the permitting authorities, the BOP stack would be installed on the surface casing. Intermediate casing consists of 20-inch (0.51 m) casing fully cemented in a 24-inch (0.61 m) hole within the surface casing, and extending from the surface to approximately 1,500 m depth. The depth of the intermediate casing depends on site characteristics; it may be necessary to run the intermediate casing down below the overburden/crystalline basement contact. The upper basement liner consists of 13.375-inch (0.34 m) casing hung in a 17.5-inch (0.44 m) hole from the bottom of the intermediate casing. Only the lowermost 100 m of the upper basement liner is cemented.

The guidance casing consists of about 4,500 m of 10.75-inch (0.27 m) casing hung from the intermediate casing at the surface. A reverse circulation port installed at the lower end of the guidance casing will allow fluid to be pumped down the intermediate casing and the upper basement liner, through the port, and back up inside the guidance casing toward the surface to assist in dislodging a package that becomes stuck above the EZ during the emplacement process. A casing shoe at the bottom of the guidance casing will make a slip-fit with the EZ liner to ensure an internally smooth path for package emplacement and to accommodate thermal expansion.

The EZ liner consists of slightly more than 500 m of 10.75-inch (0.27 m) casing hung from the bottom of the upper basement liner. The liner is partially cemented and has perforations spaced along its length. The perforations are used for cementing and for pressure relief from thermal expansion of fluid.

The guidance casing and the EZ liner serve several functions that are important to pre-closure safety, including (SNL 2016b, Section 3.1):

- Providing a continuous, clear, smooth path from the surface for package emplacement
- Preventing rock or cement debris from falling in the path
- Helping to control surge pressure when packages are lowered or retrieved
- Aligning packages as they are stacked in the EZ
- Facilitating the placement of cement plugs and bridge plugs in the EZ
- Limiting the terminal sinking velocity if a package is accidentally dropped
- Facilitating recovery of packages in case of an accident (e.g., protection from rock debris, recovery of stuck packages by pulling guidance casing)

Following package emplacement, the upper basement liner and the guidance casing will be removed to expose the borehole wall to sealing. The EZ liner, intermediate casing, and surface casing will all be left in place.

During operations the borehole will be filled with fluid. During drilling and completion, the borehole fluid serves several purposes: lubrication of drill string and wireline operations, flushing of cuttings during drilling, and flushing before and after cementing. During emplacement operations, the borehole fluid provides buoyant support to downhole tools and waste packages. Borehole fluid can be replaced as needed with a fluid that meets the requirements for the current operation (e.g., drilling, testing, waste emplacement) as outlined in Table 3-1 and Table 3-2.

4.1.2 Borehole Drilling and Construction

Borehole drilling and construction will utilize technologies that are currently available and that can drill to a depth of 5,000 m into crystalline basement at a reasonable cost (in accordance with the borehole specifications in Section 4.1.1). These technologies have not yet been specified and, to some extent, are beyond the scope of the DBD design concept. However, drilling and construction will have to be performed such that certain requirements are met and certain features are incorporated (e.g., see Table 3-1 and Table 3-2). For example, maximum deviation and dogleg severity requirements are intended to reduce the probability of a waste package getting stuck; the selected drilling technology must be able to meet those requirements.

4.1.3 DBD Site Operations

DBD site operations that may be important to pre-closure safety include: surface facility operations, waste package surface handling, waste package downhole emplacement, borehole sealing and plugging, and facility closure. These are discussed in the following subsections.

4.1.3.1 Surface Facility Operations

Operations at the DBD site are related to waste receipt, waste handling, package emplacement, and package recovery (if necessary). Surface facilities for these operations include (SNL 2016b, Section 3.3):

- a crane for lifting the transportation cask containing waste that has been transported to the site,
- a cylindrical transfer cask with an operable opening on each end,
- a transfer shield that can be used to move the waste package from the transportation cask to the transfer cask,
- a crane for moving the transfer cask containing waste from the transfer shield to the borehole,
- a wellhead carousel that is used to position the transfer cask above the borehole and shield workers as the waste package is lowered into the borehole, and
- a washdown station to clean the transfer cask after each operation.

Additional surface facilities may be required for:

- waste storage to allow for schedule disruptions, emplacement stoppages, etc.,
- waste re-packaging, if the waste in a transportation cask is not in a waste package suitable for disposal, and
- compliance with nuclear material safeguards and security requirements.

4.1.3.2 Waste Package Surface Handling

Waste will be unloaded from the transportation cask once it arrives at the DBD site. The DBD reference design assumes that the waste is transported to the disposal site in a waste package that is suitable for disposal in the borehole. A crane is used to move the transportation cask containing the waste package from the transportation conveyance (e.g., truck or railcar) to the transfer shield.

The transfer shield is used to move waste packages from the transportation cask to the transfer cask, consistent with shielding requirements (Table 3-2). The transfer from transportation cask to transfer cask is done with both casks resting on horizontal cradles that are axially aligned with each other. The end of the transportation cask with the shield plug and the open bottom of the transfer cask, which must have operable openings at both ends, are positioned against the transfer shield. The transfer shield is rectangular, consisting of a three-position moving slab between metal plates. The thickness of the slab is determined by shielding requirements and the thickness of plugs used in each cask. With the slab in the first position, the shield plug in the transportation cask is removed and pulled into a cavity in the slab. When the slab is in the second position, there is a clear path between the two casks, and a grapple assembly on an extension rod is inserted through the far end of the transfer cask and engaged to the upper end of the waste package. The package is then pulled into the transfer cask. When the slab is in the third position, the transfer cask plug, which had been pre-positioned in the shield slab, is inserted in the bottom of the transfer cask. SNL (2016b, Section 3.3.4) provides a more detailed description of the transfer shield and its operations.

Once the waste package is in the transfer cask and the transfer cask plug has been inserted and fastened, a side latch inside the transfer cask will secure the waste package to the transfer cask. A crane is used to rotate the transfer cask to a vertical orientation and place it on the wellhead carousel. The wellhead carousel is directly over the borehole and provides for precise alignment of the transfer cask over the borehole, placement of the transfer cask over a plug removal system, shielding to workers, and access to borehole equipment for maintenance. Once the transfer cask is secured to the wellhead carousel, a small plug in the top shield of the transfer cask will be removed and the waste package will be attached to an electric wireline. Once the waste package is secured, the lower transfer cask shield plug will be removed so that the waste package can be lowered into the borehole.

4.1.3.3 Waste Package Downhole Emplacement

Waste packages will be emplaced one at a time using an electric wireline and stacked one on top of the other. To avoid radioactive contamination of drilling fluid during the emplacement period, waste packages will be designed to provide containment throughout the operational phase (see Table 3-1). In addition, each waste package will have an impact limiter attached at the bottom, and a latch and a fishing neck attached at the top.

A headframe supports the electric wireline; the wireline being considered (Schlumberger Tuffline®) has a safe working loading of 26,000 lb or greater and does not require a capstan for loads up to 12,000 lb. An electromechanical wireline cable release mechanism used to release the waste package once it has been emplaced would be attached to the bottom of the tool string, which is also part of the wireline system. This release mechanism would be designed to be able to re-latch the waste package in case waste retrieval is necessary. The tool string would contain logging tools and monitoring devices (SNL 2016b, Section 3.4).

Prior to package emplacement, an acoustic caliper log, a radiation detector, and a gauge ring with a junk basket would be run into the hole and back out. The acoustic caliper provides information regarding the inner surface and geometry of the casing. The radiation detector detects whether any of the previously emplaced waste packages are leaking, and the gauge ring with a junk basket would decrease the likelihood of a waste package getting stuck because of debris in the borehole.

The waste package descent rate during wireline emplacement is about 0.5 ft/s for the first kilometer (slower to control load transients that could break the wireline), then 2 ft/s thereafter (SNL 2016b, Section 2.9.3). Once a waste package has reached its position in the EZ, it would be disconnected by activating the electromechanical release. The wireline and tool string would then be hoisted out of the borehole with an ascent rate of 4 ft/s. Once the tool string is back in the transfer cask, the wellhead valve would be closed, and the transfer cask and tool string would be moved to a wash-down area for cleaning, inspection, and preparation for the next use.

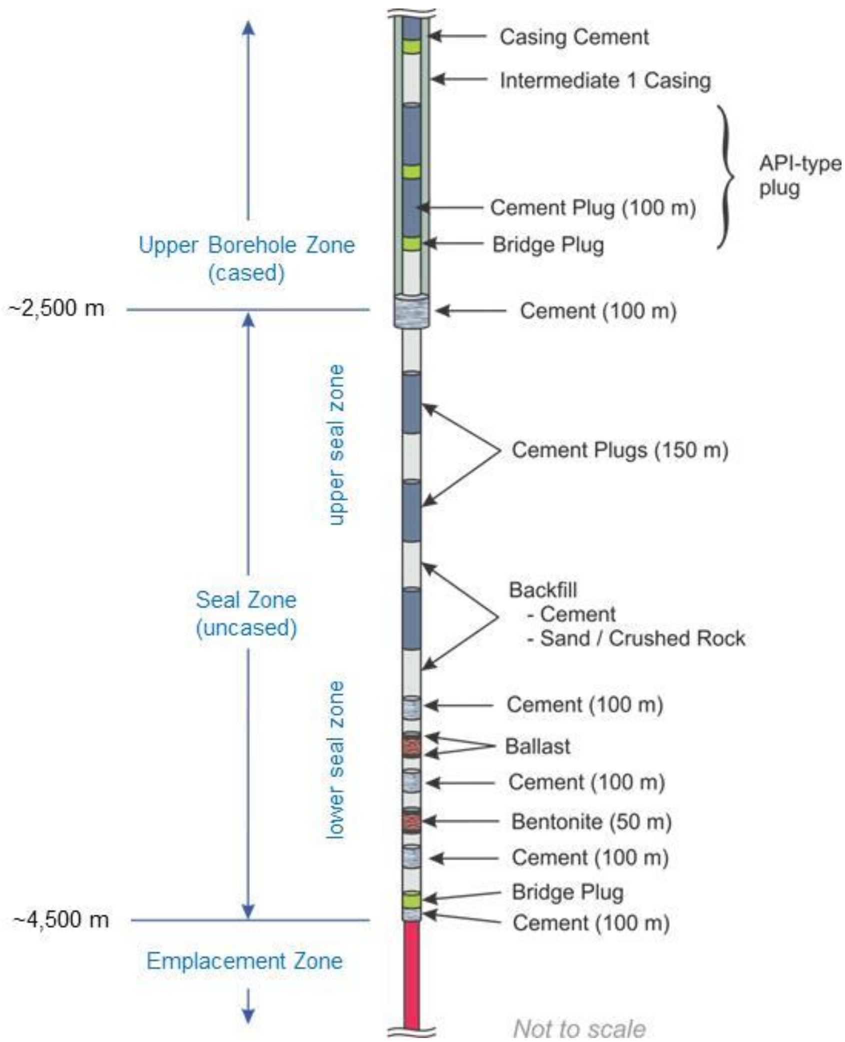
After every stack of 40 waste packages (or fewer, see Table 3-1), a bridge plug would be installed above the top waste package and a squeeze packer would be set 10 m above the bridge plug. Using a cementing tool run on coiled tubing, cement would be injected under pressure through the packer to create a 10-m cement plug. Perforations in the EZ liner in the 10-m interval would allow cement to flow into the annulus between the liner and the borehole wall, following the path of displaced fluid. The borehole would then be ready for emplacement of the next 40 waste packages.

At the time of borehole sealing, waste packages will be surrounded by emplacement fluid (e.g., brine), both in the annular space between the waste package and the EZ liner and between the EZ liner and the borehole wall. The cement in the cement plugs will be confined to the 10-meter interval between stacks of waste packages and will be in both the borehole and the annulus between the EZ liner and the borehole wall (SNL 2016b, Section 2.7.4).

The EZ emplacement fluid, cement plugs, and liner are described further in Section 4.2.5.

4.1.3.4 Sealing and Plugging

A general concept for sealing and plugging the borehole, in accordance with the design requirements in Section 3.2.2.2, is shown in Figure 4-2. It includes a seal zone entirely within the crystalline basement rock, where seals and plugs will be emplaced directly against borehole wall, and an upper borehole zone primarily within the sedimentary overburden, where plugs will be emplaced against the cemented casing.



(Source: Arnold et al. 2011, Figure 9)

(Source: SNL 2016b, Figure 3-2)

Figure 4-2. Borehole Sealing and Plugging Schematic

To accommodate seal emplacement in the seal zone, the uncemented interval of the upper basement liner (see Figure 4-1) will be cut off and removed, along with the guidance casing, and the unlined borehole will be filled with a sequence of sealing materials (bentonite seals, cement plugs, silica sand/crushed rock ballast). Seals and plugs in the seal zone would act directly against the rock (the DRZ) and be designed to limit upward radionuclide transport.

The UBZ would be predominantly filled, inside the casing, with cement and cement plugs, and might include an American Petroleum Institute (API)-type plug consisting of bridge plugs and cement plugs. The UBZ might also include other low-permeability materials.

Additional DBD sealing considerations, designs, and materials are discussed in Sections 4.2.6 and 4.2.7 and Appendix D.

4.1.3.5 Facility Closure

DBD site closure activities may include:

- decommissioning of the surface facilities, which may produce low-level waste,
- performance confirmation monitoring,
- active institutional controls (e.g., performance confirmation monitoring, post-closure maintenance), and
- passive institutional controls (e.g., land use restrictions, records maintenance).

4.1.4 Potential Impacts of External Events on Pre-Closure Safety

The description of the repository design and operations in the preceding subsections assumed normal operating conditions. However, off-normal and/or external events that occur during the pre-closure period have the potential to affect pre-closure safety. Such events are identified below; their effects on pre-closure safety are discussed in Section 5.1.

Perhaps the most significant off-normal events are those that occur during waste handling and emplacement operations:

- Dropping a waste package during handling at the ground surface
- Dropping a waste package while it is in the borehole
- Dropping foreign objects into the borehole
- A waste package getting stuck in the borehole
- Breach of a waste package in the borehole prior to closure with subsequent radioactive contamination of the borehole fluid
- Boiling of emplacement fluid for heat-generating waste packages that are stuck above a depth of about 2,200 meters (below ~ 2,200 m the formation pressure (and the pressure in a fluid filled borehole) exceeds the critical point of water so boiling cannot occur (SNL 2016b, Appendix B))

Equipment, procedures, and processes would be designed, developed, and implemented to prevent, correct, and/or mitigate the effects of these off-normal events. The DBD reference design includes some of these:

- The waste package is transferred from the transportation cask to the transfer cask in a horizontal position, reducing the probability of dropping a waste package during handling at the ground surface.
- A latch on the side of the transfer cask holds the waste package in place until it is ready to be lowered into the borehole. The waste package is also secured by the wireline or by the grapple; thus the waste package is secured by two separate systems, reducing the probability of dropping the waste package.
- The waste package includes an impact limiter that will reduce the consequences of dropping a package in the borehole.
- The waste package includes a fishing neck to enable retrieval of the package from the borehole, reducing the probability that a waste package will get stuck irretrievably in the borehole.
- An acoustic caliper log and a gauge ring with a junk basket would be run before emplacing each waste package, decreasing the probability of a waste package getting stuck.

Naturally occurring external events could also affect pre-closure safety, such as flooding and extreme weather or seismicity (e.g., ground motion or faulting). These events have minimal consequences if standard construction and operational practices are followed, but would be addressed as part of the siting, design, and licensing of a DBD site. Other off-normal events, such as sabotage and theft, must also be considered as part of the siting, design, and licensing of a DBD site. However, the DOE has experience in providing adequate security to nuclear sites, and this experience would extend to the DBD site as well.

4.1.5 Potential Impacts on Post-Closure Safety

Some pre-closure activities and components may have effects on post-closure safety. For example, corrosion of iron and other metals in casing and packaging materials could cause reduction of aqueous hydrogen ions, producing hydrogen gas, H_2. If this gas were to be contained to a sufficient degree by the host rock and engineered barriers, the gas pressure could increase significantly. This process can be addressed by selecting appropriate materials for the liner and waste packages, perforating the liner as needed, and careful selection of the EZ completion approach.

The manner in which the borehole is sealed and plugged can also affect post-closure safety. The seals and plugs must meet closure requirements associated with the borehole permit, and must also impede radionuclide transport. An R&D plan for sealing designs, methods, and materials is presented in Appendix D.

4.2 Post-Closure Basis: Waste and Engineered Barriers

The post-closure basis includes a description of the natural and engineered barriers for use in the quantitative post-closure PA (Section 5.2). The description below is based on the reference disposal concept documented in SNL (2016b, Section 3) with dimensions and depths adapted for the specific Cs/Sr capsule disposal configuration described in Section 4.2.4.

Specific post-closure basis information related to the wastes and engineered barriers, which helps define the DBD reference case and reference design, includes (Section 1.2.1.3):

- Characteristics of the borehole and engineered barriers (e.g., design, layout)
- Inventory characterization (characteristics and quantities of the potential radionuclide and chemotoxic inventory)
- Waste form characterization (features, processes, and evolution over time – e.g., degradation and radionuclide release processes)
- Waste package characterization (features, processes, and evolution over time – e.g., material degradation, coupled THCMBR processes)
- Emplacement Zone characterization (features, processes, and evolution over time – e.g., degradation and radionuclide transport processes)
- Seal Zone characterization (features, processes, and evolution over time – e.g., degradation and radionuclide transport processes)
- Upper Borehole Zone characterization (features, processes, and evolution over time – e.g., degradation and radionuclide transport processes)
- Potential impact of external events such as seismicity, igneous activity, and human intrusion on the performance of the engineered barriers

This information is described in more detail in subsequent subsections, including an assessment of uncertainties over time and how it will be used to define parameters and conceptual models used in the post-closure PA.

The post-closure basis information also informs the following analyses, which are described in more detail in Section 5.2:

- FEP analysis
- Scenario development
- Subsystem and barrier analyses

4.2.1 Engineered Barrier Characteristics

The features and components of the engineered barriers are outlined in Section 3.2.2.1. The design and layout of the borehole and casing and a description of the pre-closure operations were provided in Section 4.1. Sections 4.2.2 through 4.2.7 provide design details and material properties of the remaining engineered features and components, consistent with the design requirements in Section 3.2.2.2. Section 4.2.8 describes the impacts of external events and Section 4.2.9 describes barrier safety functions.

4.2.2 Inventory

Current DBD R&D focuses on the disposal of smaller DOE-managed waste forms (DOE 2014a), such as direct-disposed Cs and Sr capsules and direct-disposed calcine waste in purpose-built canisters (SNL 2016b). DOE-managed SNF including metallic, non-oxide, oxide, and coated-particle fuels (and excluding Naval SNF) is currently packaged or projected to be packaged in multicanister overpacks (MCOs) and standardized canisters 0.457 m (18 in) or 0.610 m (24 in) in diameter (SNL 2014b). Some of these SNF waste types are composed of small pieces or particles that could be packaged in purpose-built canisters for DBD. DOE-managed engineered waste forms, such as hot isostatically-pressed calcine, that have yet to be produced could also potentially be engineered for DBD (SNL 2014b).

The DBD reference case assumes direct disposal of Cs/Sr capsules. There are 1,335 Cs capsules and 601 Sr capsules stored on the Hanford Site (SNL 2014b). They contain Cs and Sr that was extracted from liquid wastes generated from the processing of defense fuel to decrease the thermal load of underground waste storage tanks. The capsules were fabricated at the Waste Emplacement and Storage Facility (WESF) at the Hanford Site between 1974 and 1985 (SNL 2014b, Section A-2.3.3). Cs capsules were filled with molten CsCl and Sr capsules with SrF_2 precipitate chiseled from drying pans (SNL 2014b, Section A-2.3.3). The resulting CsCl waste form is glass-like and the SrF_2 waste form is a granular material that has been mechanically compacted in the capsule. The Cs and Sr capsules account for approximately one third of the total radioactivity on the Hanford Site (SNL 2014b).

Cs and Sr capsules vary in radioactivity and heat output (Table 4-2 and Table 4-3). In 2007, the average radioactivity of a Cs capsule was 30.4 kCi and average thermal output was 143.6 W. Corresponding averages for the slightly hotter Sr capsules were 28.9 kCi and 193.3 W. Radioactivity and heat output of the Cs capsules is due to the decay of ^{137}Cs, its daughter ^{137m}Ba (which decays to the stable ^{137}Ba), and ^{135}Cs (which decays to the stable ^{135}Ba). Radioactivity and heat output of the Sr capsules is due to the decay of ^{90}Sr and its daughter ^{90}Y (which decays to the stable ^{90}Zr). Decay constants, half-lives, and decay heat for these radionuclides are listed in Table 4-4.

Assuming that ^{137}Cs is the sole source of the radioactivity in the Cs capsules in 2007 allows the minimum, maximum, and average quantity of ^{137}Cs in a Cs capsule (in 2007) to be calculated. Similar calculations can be made for the inventory of ^{90}Sr in 2007. ^{135}Cs inventory is calculated on the basis of ^{135}Cs/^{137}Cs mass ratios measured for seven capsules in 1984 (Table 4-5). Projecting these ratios forward in time from 1984 results in an average ^{135}Cs/^{137}Cs mass ratio of 0.7 in 2007. Radionuclide inventories in 2007 were decayed using the decay constants in Table 4-4 to project minimum, maximum, and average capsule inventories to 3,000 years (Figure 4-3). Heat outputs projected to 3,000 years (Figure 4-4) sum the decay heats of ^{135}Cs, ^{137}Cs, and ^{137m}Ba for Cs capsules and ^{90}Sr and ^{90}Y for Sr capsules.

Table 4-2. Radioactivity and Heat Output of Cesium Capsules

Capsules	Number		Wattage[a]	Activity (kCi)[a]	Original Activity (kCi)
All	1,335	Average	143.61	30.43	56.50
		Std Dev	14.10	2.99	6.89
		Maximum	195.37	41.39	75.85
		Minimum	16.29	3.45	4.24
Standard	1,312	Average	144.01	30.51	56.72
		Std Dev	12.86	2.72	6.29
		Maximum	195.37	41.39	75.85
		Minimum	93.86	19.89	36.86
Type W	23	Average	118.46	25.10	42.82
		Std Dev	38.87	8.24	17.88
		Maximum	158.64	33.61	62.50
		Minimum	16.29	3.45	4.24

[a] As of August 29, 2007

(Source: SNL 2014b, Table A-43)

Table 4-3. Radioactivity and Heat Output of Strontium Capsules

Capsules	Number		Wattage[a]	Activity (kCi)[a]	Original Activity (kCi)
All	600[b]	Average	193.26	28.89	369.75
		Std Dev	101.00	15.10	211.47
		Maximum	504.63	75.43	1045.00
		Minimum	22.12	3.31	38.00
Standard	411	Average	235.97	35.27	454.23
		Std Dev	86.42	12.92	189.20
		Maximum	504.63	75.43	1045.00
		Minimum	22.12	3.31	38.00
Waste	189	Average	100.38	15.00	186.04
		Std Dev	59.57	8.90	121.89
		Maximum	384.75	57.51	797.00
		Minimum	27.24	4.07	50.00
Tracer	1	Average	0	0	0

[a] As of August 29, 2007
[b] Does not include Tracer capsule

(Source: SNL 2014b, Table A-44)

Table 4-4. Decay Constants and Decay Heat of Radionuclides in Cesium and Strontium Capsules

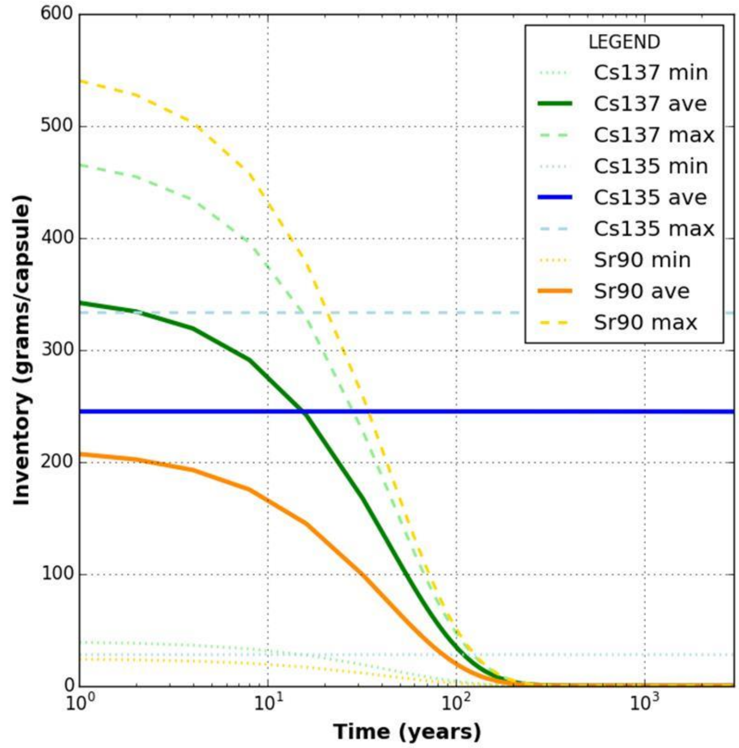
	Decay Constant (1/s)	Decay Constant (1/yr)	Half-life (yr)	Decay Heat (W/g)
^{90}Sr	7.54×10^{-10}	2.38×10^{-2}	29.12	1.58×10^{-1}
^{90}Y	3.01×10^{-6}	9.49×10^{1}	7.30×10^{-3}	3.02×10^{3}
^{135}Cs	9.55×10^{-15}	3.01×10^{-7}	2.30×10^{6}	3.84×10^{-7}
^{137}Cs	7.32×10^{-10}	2.31×10^{-2}	30.00	9.62×10^{-2}
^{137m}Ba	4.53×10^{-3}	1.43×10^{5}	4.85×10^{-6}	2.11×10^{6}

(Source: ORIGEN 2.2 Database (Croff 1983))

Table 4-5. $^{135}Cs/^{137}Cs$ Ratios in 1984

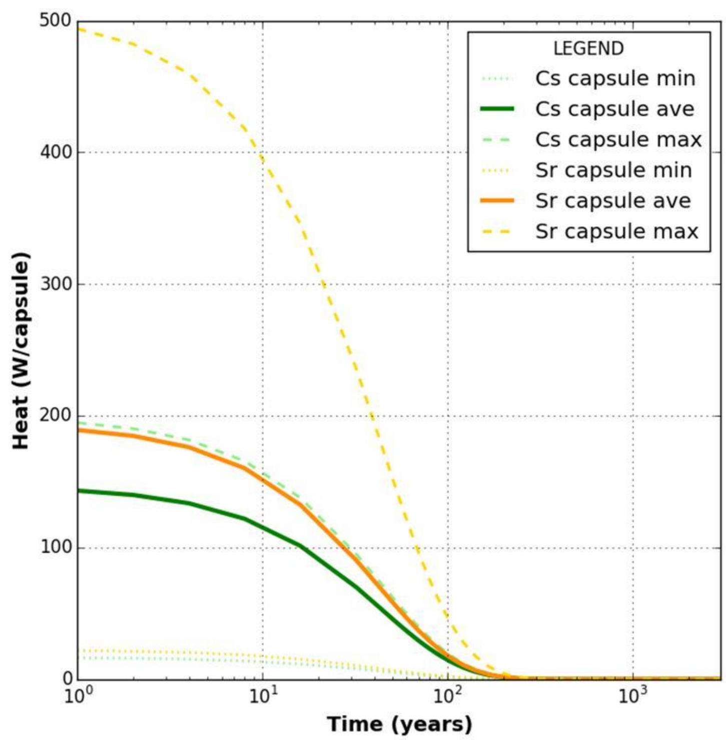
Capsule Identifier	Year of Measurement	$^{135}Cs/^{137}Cs$ Ci Ratio	$^{135}Cs/^{137}Cs$ Mass Ratio
Characterization of Two WESF Capsules, Table 11, Capsule C-74	1984	5.263×10^{-6}	3.954×10^{-1}
Characterization of Two WESF Capsules, Table 11, Capsule C-73	1984	5.263×10^{-6}	3.954×10^{-1}
Characterization of Two WESF Capsules, Table 11, Capsule C-206	1984	5.329×10^{-6}	4.003×10^{-1}
Characterization of Two WESF Capsules, Table 11, Capsule C-134	1984	5.344×10^{-6}	4.015×10^{-1}
Characterization of Two WESF Capsules, Table 11, Capsule C-17	1984	5.353×10^{-6}	4.021×10^{-1}
Characterization of Two WESF Capsules, Table 11, Capsule C-130	1984	5.377×10^{-6}	4.040×10^{-1}
Characterization of Two WESF Capsules, Table 11, Capsule C-366	1984	5.924×10^{-6}	4.450×10^{-1}

(Source: Sasmor et al. 1988)



(Time Zero = 2007)

Figure 4-3. Radionuclide Inventory Versus Time for Cesium and Strontium Capsules



(Time Zero = 2007)

Figure 4-4. Heat Output Versus Time for Cesium and Strontium Capsules

The DBD reference case assumes waste emplacement in 2050 for consistency with previous thermal-hydrologic calculations (SNL 2016b); there is no regulatory or legal basis for this choice and an actual date for DBD emplacement of waste has not yet been determined. In 2050, average ^{135}Cs and ^{137}Cs inventories per capsule will be 244.9 g and 130.0 g, respectively; average Cs capsule heat output will be 54.2 W. Average ^{90}Sr inventory per capsule will be 76.1 g and average Sr capsule heat output will be 69.6 W.

The PA model implementation of the reference case (Section 5.2.3) includes three radionuclides, ^{90}Sr, ^{137}Cs, and ^{135}Cs. Radionuclide inventories for ^{137m}Ba and ^{90}Y are not included in the PA model because of their very short half-lives; however, decay heat from ^{137m}Ba and ^{90}Y is included.

Chemotoxic inventory is not considered in the current DBD reference case, although Cs/Sr capsules are contaminated with sodium, potassium, magnesium, and Dangerous Waste (per Washington State Regulations WAC 173-303) chemical impurities including chromium, lead, cadmium, silver, and barium (SNL 2014b, Section A-2.3.3).

4.2.3 Waste Forms

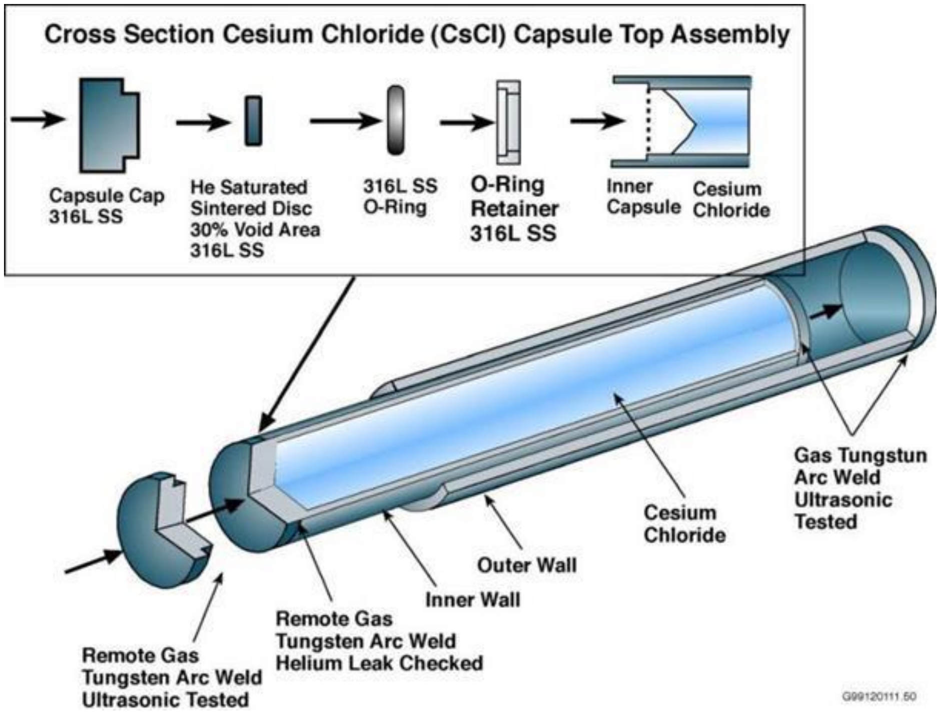
Cs and Sr capsules are double-walled capsules manufactured from either 316L stainless steel or corrosion-resistant Hastelloy C-276. Some variation in capsule design and dimensions exist, but dimensions generally fall between 0.502 and 0.554 m (19.75 to 21.825 in) in length and 0.067 and 0.083 m (2.625 to 3.25 in) in diameter (Table 4-6). Typical configurations for Cs and Sr capsules are shown in Figure 4-5.

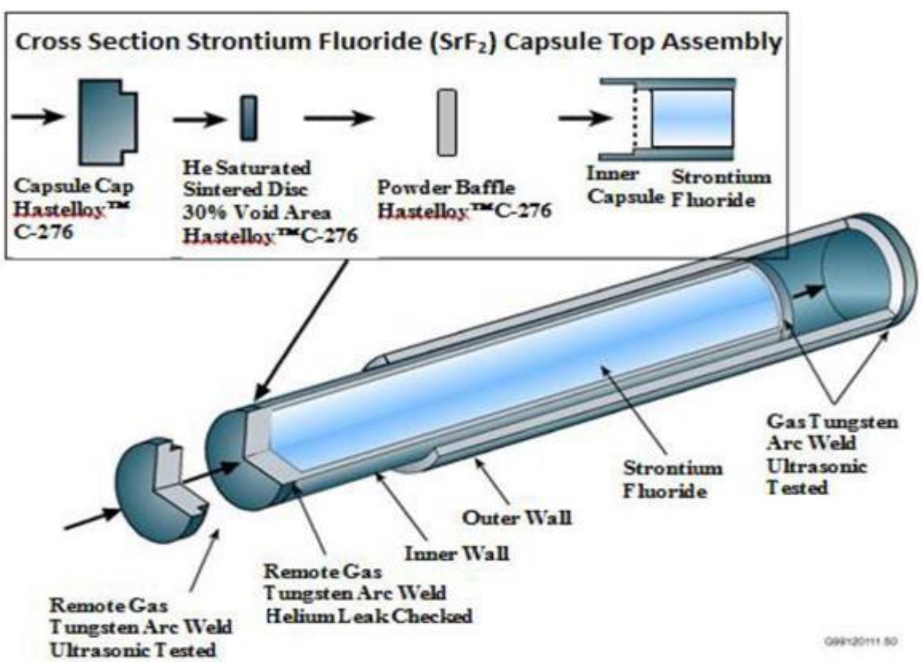
Table 4-6. Characteristics of Cesium and Strontium Capsules

Item	Containment Boundary	Material	Wall Thickness[a] (in)	Outside Diameter (in) (m)	Total Length (in) (m)	Cap Thickness (in)
CsCl Capsule	Inner	316L Stainless Steel	0.095 0.103 0.136	2.25 0.057	19.75 0.502	0.4
	Outer	316L Stainless Steel	0.109 0.119 0.136	2.625 0.067	20.775 0.528	0.4
CsCl Type W Overpack	Single	316L Stainless Steel	0.125	3.25 0.083	21.825 0.554	0.4
SrF_2 Capsule	Inner	Hastelloy C-276	0.12	2.25 0.057	19.75 0.502	0.4
	Outer	316L Stainless Steel or Hastelloy C-276	0.12	2.625 0.067	20.1 0.511	0.4

[a] The specified wall thickness of the CsCl capsules was increased twice during production. The capsules are referred to as Type 1, Type 2, and Type 3, with Type 3 being the most numerous (Heard et al. 2003)

(Source: SNL 2014b, Table A-41, after Plys and Miller 2003)





(Source: SNL 2016b, Figure 2-1, after Covey 2014)

Figure 4-5. Typical Cesium and Strontium Capsule Designs

Inner capsules were filled (with either molten CsCl or pieces of SrF_2), capped, welded, leak tested, and decontaminated, then placed in outer capsules, which were also welded closed. Twenty-three Cs capsules received an additional Type W overpack due to suspicion of poor integrity (Arnold et al. 2014, Section 3.2). The 189 Sr "waste" capsules (see Table 4-3), in addition to SrF_2, may contain a variety of materials caught in the process of chiseling SrF_2 from the drying pans, including carbon from carbonaceous materials; steel nuts, bolts, manipulator fingers, Hastelloy and Inconel chips, tungsten, and titanium; concrete, glass, and asbestos; and chemicals such as tri-sodium phosphate (SNL 2014b, Section A-2.3.3).

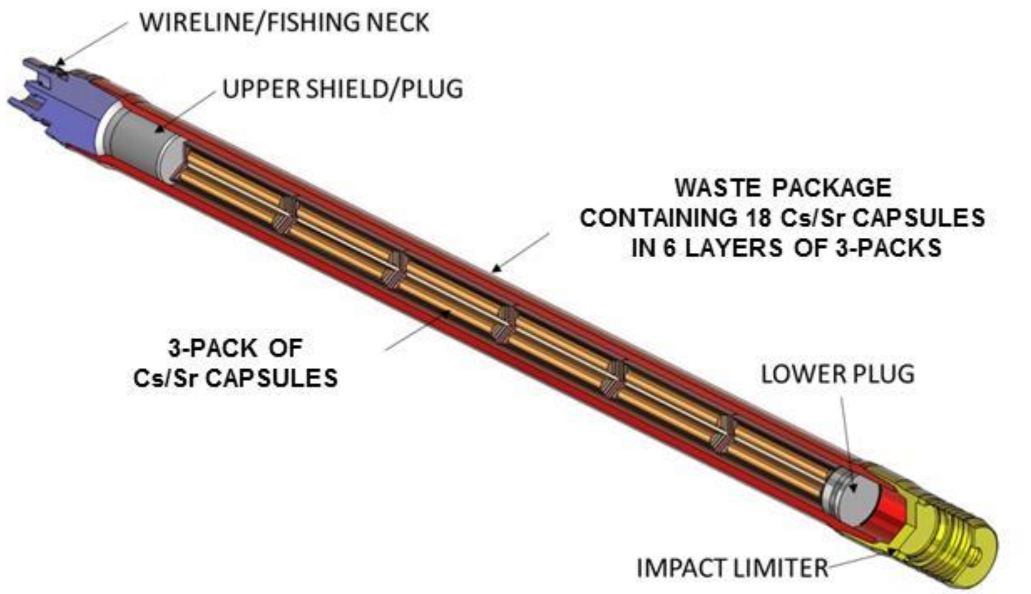
The solubility of CsCl in brines at standard temperature and pressure is approximately 11.3 mol/kg (Hu et al. 2007; Scharge et al. 2012). The solubility decreases with pressure and increases with temperature such that at 50 MPa and 40°C its solubility in water is 11.8 mol/kg (Matsuo et al. 2001). If SO_4 is present in deep borehole fluids, Cs_2SO_4 may impose a limit of approximately 10 mol/kg on dissolved Cs concentration (Scharge et al. 2012).

The solubility of SrF_2 is considerably lower than that of CsCl. A calculation of total dissolved Sr in equilibrium with SrF_2 in a 2 M NaCl brine at standard temperature and pressure gives a concentration of 2.4×10^{-3} mol/kg. The calculation was performed with PFLOTRAN (see Section 5.2.3.2) assuming log K_{SrF2} = -8.54, pH = 8.5, and using the Debye-Huckel formulation for activity coefficients. $SrCl_2$ and $Sr(OH)_2$ solid phases do not precipitate. If deep borehole fluids contain sufficient CO_3 or SO_4, Sr solubility may be controlled by equilibrium with $SrCO_3$ or $SrSO_4$.

Radionuclide solubilities for the DBD reference case are discussed further in Section 4.3.2.6.

4.2.4 Waste Packages

The DBD reference design assumes 18 Cs or Sr capsules per waste package, stacked in 6 layers of 3 capsules (3-packs) each (Figure 4-6). The waste package is likely to contain an internal canister (or canisters) and corresponding basket(s) to group and space the capsules. It will be plugged and sealed, and fitted with an impact limiter and a fishing neck. The cylindrical part of the waste package is to be constructed of oilfield casing, which is available in a variety of materials. Although final material selection will depend on site-specific properties such as formation temperature and fluid chemistry, the reference design assumes carbon steel casing (P110 grade) with an outside diameter of 0.219 m (8.625 in) and an inside diameter of 0.171 m (6.751 in), which has sufficient strength to withstand hydrostatic pressure at the base of the borehole (SNL 2016b, Section 3.2 and Table 3-2). The reference design waste package length is 4.76 m, which includes 3.76 m for the 6 layers of capsules, a 0.3-m long fishing neck, and a 0.7-m-long impact limiter. For the reference design, 108 such waste packages are necessary to dispose of all Cs/Sr capsules: 74 containing the 1,335 Cs capsules and 34 containing the 601 Sr capsules.



(Source: modified from SNL 2016b, Figure 3-3)

Figure 4-6. Schematic of a Waste Package for Cs/Sr Capsules

The corrosion behavior of P110 steel can be assumed to be similar to that of other carbon steels, which degrade via general corrosion. General corrosion rates for carbon steel have been measured in brines of various composition, in various environments (cementitious, etc.), and under aerobic and anaerobic conditions (see review of Kursten et al. 2004). General corrosion rates vary between <1 μm/yr to >1,000 μm/yr; they are higher in high Cl^- brines and at higher temperatures, lower in alkaline environments, and lower in anaerobic than aerobic environments (Kursten et al. 2004). Corrosion rates may be affected by microbial processes, radiation products, H_2 buildup, or formation of oxide coatings. At 1,000 μm/yr, a 5-cm thick waste package wall would corrode through in 50 years.

4.2.5 Emplacement Zone

DBD conceptual designs for disposal of SNF have specified an EZ 2,000 m in length and 0.432 m (17 in) in diameter (e.g., Arnold et al. 2011). For disposal of Cs/Sr capsules, the reference design EZ is 534 m in length with a diameter of 0.311 m (12.25 in). The base of the EZ lies 5,000 m below land surface. The EZ contains 108 waste packages (described in Section 4.2.4), two cement plugs supported by bridge plugs (described in Section 4.1.3.3), a perforated steel liner extending the length of the EZ (described in Section 4.1.1), emplacement fluid and traces of drilling fluid. These EZ components are illustrated in Figure 3-2 and further described in the following subsections. Borehole and casing dimensions, including the EZ liner, are listed in Table 4-1.

Radionuclide transport processes occurring in the EZ may include advection, mechanical dispersion, diffusion, and sorption.

4.2.5.1 EZ Buffer/Backfill Fluid

The EZ buffer/backfill region includes the void spaces between stacked waste packages and the annular spaces between the waste packages and the EZ liner and between the EZ liner and the borehole wall. For the DBD reference case, the EZ buffer/backfill region is assumed to be filled with fluid. As described in Section 4.1.1, the borehole will be flushed prior to waste package emplacement, and drilling fluid will be replaced with emplacement fluid. The reference case assumes that both fluids are brines of ionic composition similar to that of formation fluid at the depth of the EZ, which is expected to be a high density Na-Cl or Na-Ca-Cl brine (see Section 4.3.2.5). Emplacement fluid contains no organic additives; drilling fluid may contain organic viscosifiers or other additives, and traces of these may persist after flushing (SNL 2016b).

The chemistry of the fluid filling the EZ will change with time due to exchange with formation fluids and reactions with other materials in the EZ. Reactions affecting fluid chemistry may include: corrosion of the EZ liner, waste packages, and capsule shells; dissolution of CsCl and SrF_2 (salt) waste forms; reactions with cement plugs and crystalline host rock; radiolysis and other effects of ionizing radiation; and microbially-mediated reactions due to the introduction of foreign organic material and/or the presence of chemoautotrophic microbes (e.g., Lin et al. 2006). The density of the fluid in the EZ will change in response to chemical and thermal processes. Density may increase with dissolution of the salt waste forms; it will decrease as temperatures rise due to the thermal output of the waste packages.

4.2.5.2 EZ Cement Plugs

The DBD reference design includes 10-m-long cement plugs supported by bridge plugs installed above (counting from the bottom) the 40th and 80th waste packages. The cement plugs are emplaced to prevent waste packages at the base of the EZ from being crushed by the weight of overlying waste packages, but may also serve to partially isolate lengths of the borehole. Properties of cement vary with water to cement ratio and degree of hydration; intact cement has low porosity (0.15 (Jove Colon et al. 2014)) and very low permeability (on the order of 10^{-18} to 10^{-21} m^2 (Halamickova et al. 1995; Jove Colon et al. 2014)). The effective diffusion coefficient of Cl^- in cement is on the order of 10^{-11} m^2/s (Halamickova et al. 1995).

Cement in the EZ will experience chemical and mechanical processes that may damage its integrity with time. These processes include reactions with emplacement and formation fluids, and with adjacent materials including the steel EZ liner and the host rock. Thermal expansion (of cement, steel EZ liner, and pore fluids), H_2 buildup from corrosion reactions, and degradation of the steel liner may also cause permeable pathways to open through the cement plugs. However, even degraded cement will inhibit fluid fluxes relative to an open borehole.

4.2.5.3 EZ Liner

For the DBD reference design, the EZ liner is assumed to be perforated steel casing, of the same constant diameter as, and internally flush with, the guidance casing, to provide a smooth pathway for package emplacement and to avoid getting packages stuck. The EZ liner can be expected to corrode as a function of casing material, temperature, and fluid chemistry.

Following waste emplacement, the perforated steel EZ liner facilitates cementing and plugging of the EZ, accommodates pressure relief from thermal expansion of waste-heated fluid, and allows dissipation of H_2 gas resulting from corrosion (SNL 2016b, Section 3.1).

The method and geometry of the perforations has not been finalized (SNL 2016b, Section 2.7.2), but small perforations (on the order of 1 to 2 cm in diameter) distributed along the length of the EZ (with a spacing on the order of 50 m to limit the effect on package terminal sinking velocity) could be sufficient (SNL 2016b, Section 2.7.4).

4.2.6 Seal Zone

Borehole seals should have a low permeability, bind effectively to the surrounding DRZ, be relatively straightforward to emplace, and be resistant to chemical alteration which might affect permeability. Seals are primarily needed during the first few hundred years of maximum heat production in the borehole (Figure 4-4). After this period, borehole temperatures will return to ambient and there will be little driving force for upward movement of water. Further evaluation of sealing requirements and necessary sealing R&D is discussed in Appendix D.

The DBD reference design seal zone is a 2,000-m interval above the EZ and within crystalline basement, divided into lower and upper portions each 1,000 m in length. Casing and liners placed in the seal zone to facilitate borehole and waste emplacement operations will be cut and removed prior to borehole sealing so that the seal materials can lie in direct contact with the DRZ of the borehole wall (SNL 2016b). The lower portion of the seal zone is comprised of multiple seals of bentonite (or bentonite/sand mixture) bracketed by cement plugs and separated by zones of silica sand and/or crushed rock ballast, whose function is to minimize chemical interaction between adjacent seals. The upper portion of the seal zone is comprised of cement plugs alternating with ballast. A schematic representation of the seal zone is shown in Figure 4-2. Seal and plug dimensions for the reference design are given in Table 4-7. Material properties for sealing and plugging components are discussed in the following subsections.

Radionuclide transport processes occurring in the seal zone may include advection, mechanical dispersion, diffusion, and sorption.

Table 4-7. Seal and Plug Dimensions

Zone	Component	Thickness (m)	Depth to Top of Interval (m)
Seal Zone – Upper	Cement Plug	150	2466
	Ballast	100	2616
	Cement Plug	150	2716
	Ballast	100	2866
	Cement Plug	150	2966
	Ballast	100	3116
	Cement Plug	150	3216
	Ballast	100	3366
Seal Zone – Lower	Cement Plug	100	3466
	Ballast	50	3566
	Cement Plug	100	3616
	Bentonite Seal	50	3716
	Cement Plug	100	3766
	Ballast	50	3866
	Cement Plug	100	3916
	Bentonite Seal	50	4016
	Cement Plug	100	4066
	Ballast	50	4166
	Cement Plug	100	4216
	Bentonite Seal	50	4316
	Cement Plug	100	4366

4.2.6.1 Bentonite Seals

Bentonite is a naturally-occurring montmorillonite clay of low permeability and high sorption capacity. It would be emplaced in the seal zone as dry compressed pellets or plugs, which would swell to fill the borehole as they hydrated. A successfully emplaced bentonite seal would have sufficient swelling pressure to form a tight seal with the borehole wall and to penetrate cracks in the DRZ. It is likely to have a fluid-saturated porosity of approximately 0.4 and a permeability on the order of 10^{-21} m^2 (Jove Colon et al. 2014). Ranges for the linear distribution coefficient (K_d) describing sorption of Cs and Sr to bentonite are listed in Table 4-10. Section 4.3.2.7 provides a more complete discussion of sorption.

The permeability, porosity, and sorption capacity of a bentonite seal may alter over time due to chemical and mechanical processes. Bentonite seals would be emplaced sufficiently far from waste packages that they are unlikely to experience temperatures greater than ambient formation temperatures, and thus unlikely to experience temperature-induced changes in mineralogy (Jove Colon et al. 2014). Water/rock reactions involving bentonite, formation fluids, adjacent cement plugs, and the host rock are possible. Fluid advection during bentonite saturation may cause piping, a process whereby permeable channels open and grow in the direction of fluid flux (Suzuki et al. 2013).

4.2.6.2 Cement Plugs

As mentioned in Section 4.2.5.2, intact cement has very low permeability (on the order of 10^{-21} m^2 (Jove Colon et al. 2014)), but cement in the borehole environment is expected to degrade. Cement in the seal zone will experience fewer processes contributing to degradation than cement in the EZ. Cement in the seal zone will not have a corroding steel liner running through it, nor will it experience the mechanical effects of thermal expansion and corrosion-related H_2 buildup. It may experience chemical alteration through reaction with formation fluids and with adjacent bentonite and host rock.

4.2.6.3 Sand/Crushed Rock Ballast

The ballast separating bentonite seals in the lower portion of the seal zone and the backfill separating cement plugs in the upper portion of the seal zone may be composed of silica sand or crushed rock alone or mixed with bentonite or other low-permeability, high-sorption capacity material (SNL 2016b).

4.2.7 Upper Borehole Zone

Above the seal zone, the borehole will be plugged with cement and silica sand and/or crushed rock ballast. The upper 1,500 to 2,000 m of the borehole will retain casing that was cemented in place during the operational phase (see Section 4.1.1); in this interval, the plugs will be set against the casing. The UBZ might also include an API-type plug consisting of bridge plugs and cement plugs. Cement plugs in the UBZ inhibit fluid flow in the borehole, including downward fluxes of surface water, and contribute to the stability of engineered components of the seal zone.

As in the EZ, the UBZ casing can be expected to corrode as a function of casing material, temperature, and fluid chemistry; and the integrity of cement plugs may degrade due to corrosion of the casing contained within them, water/rock reactions, or mechanical stresses.

Radionuclide transport processes occurring in the UBZ may include advection, mechanical dispersion, diffusion, and sorption.

4.2.8 Potential Impacts of External Events on Engineered Barriers

Because of the great depths involved, the potential impact of external events, including climate change, seismic events, igneous events, and human intrusion, on DBD engineered barriers are expected to be minimal.

Climate change can impact the surface and subsurface environments through changes in a variety of factors such as precipitation, glaciation, erosion, and rock hydraulic properties. DBD will occur at sufficient depth that none of these surface processes will penetrate to the EZ. For instance, isotopic analysis of formation waters in the crystalline basement of the Canadian Shield indicate that glacial meltwaters associated with the last glacial maximum penetrated 200 to 400 m below the land surface (Gascoyne 2004), while the composition of formation waters from deep boreholes in crystalline rock suggests the presence of ancient seawater modified by in situ water/rock reaction without communication with near surface groundwater (Stober and Bucher 2004; Lippman et al. 2005).

Depending on magnitude, seismic events have the potential to damage engineered barriers. A suitably chosen DBD site would have a low probability of such an event occurring, because siting requirements would be expected to exclude seismically active regions for reasons of both borehole stability and post-closure safety (see Section 3.2.1.2). Post-closure safety of DBD relies primarily upon the isolation provided by the great depth of disposal. In the event of a significant seismic event, damage to engineered materials would have little effect on performance.

Direct release of radionuclides to the biosphere could occur if a magmatic conduit for a volcanic eruption intersected the waste in the EZ. The presence of Quaternary age igneous rocks at land surface or at depth within the borehole would indicate an elevated probability of future igneous activity. Such regions would be expected to be excluded by siting requirements (see Section 3.2.1.2).

The probability of human intrusion is associated with the occurrence of natural resources such as fresh water, fossil fuels, ore deposits, or geothermal resources. Fresh water and fossil fuels may exist in overlying sediments and the drilling and mining activities associated with these resources would be well above the depth of the EZ and can be minimized by choosing a site sufficiently distant from known resources. The presence of ore deposits would be difficult to ascertain prior to drilling the borehole. If an ore body is encountered during drilling, the economic potential for development should be assessed; at the depth of the EZ, economic potential is likely to be low. Geothermal development occurs in regions of high heat flow, which should be avoided in siting, both to prevent inadvertent human intrusion and to minimize driving forces for upward fluid flow. Regulatory considerations for human intrusion for DBD are discussed in Section 2.1.3.5.

The treatment of disruptive events in post-closure PA scenarios is described in Section 5.2.2.

4.2.9 Engineered Barrier Safety Functions

A description of how each engineered barrier feature or component is expected to provide safety (i.e., its safety function) is provided in Table 4-8.

Table 4-8. Engineered Barrier Safety Functions

Barrier Feature or Component	Safety Function
Waste Form	The soluble salt (CsCl and SrF_2) waste forms do not provide any safety function.
Waste Package	Waste packages provide containment of radioactive wastes during borehole operations. The post-closure containment lifetime after borehole sealing will be consistent with the licensed safety-strategy, but is TBD.
EZ Buffer/Backfill Fluid	Using a high density brine for the emplacement fluid will contribute to the isolation of the EZ from the accessible environment by inhibiting upward thermally-driven fluxes in the borehole.
EZ Cement Plugs	Cement plugs in the EZ help maintain waste package integrity, and therefore contribute to containment. The plugs also contribute to isolation of the EZ by inhibiting upward fluid fluxes in the borehole. It would be possible to engineer the cement to sorb radionuclides and thereby limit and delay releases, but this safety function is not part of the current reference design.
EZ Liner	The EZ liner does not serve a post-closure safety function.
SZ Bentonite Seals	Bentonite seals isolate the EZ from the accessible environment by forming a low permeability barrier to fluid flow and creating a low permeability contact with the DRZ. They also limit and delay radionuclide release due to their high sorption capacity.
SZ Cement Plugs	Cement plugs in the seal zone support the bentonite seals and protect them from erosion. They contribute to isolation of waste in the EZ through this supportive role and through their own resistance to fluid flow. Though radionuclide sorption to cement is not included in the current reference case, cement plugs could be engineered to sorb radionuclides and thus delay and limit radionuclide release.
SZ Ballast Plugs	The ballast plugs in the seal zone do not of themselves have a safety function.
UBZ	The plugs in the upper borehole isolate the EZ from the accessible environment.

4.3 Post-Closure Basis: Geosphere/Natural Barriers

The post-closure basis includes a description of the natural and engineered barriers for use in the quantitative post-closure PA (Section 5.2). The description below is based on the reference disposal concept documented in SNL (2016b, Section 3), adapted for the specific Cs/Sr capsule disposal configuration and depths described in Sections 4.2.4 through 4.2.7.

Specific post-closure basis information related to the geosphere and natural barriers, which helps define the DBD reference case, includes (Section 1.2.1.3):

- Characteristics of the natural barriers (e.g., location, geologic setting)
- DRZ characterization (features, processes, and evolution over time – e.g., fluid flow, geochemical, and radionuclide transport processes and interaction with engineered barriers)
- Host rock characterization (features, processes, and evolution over time – e.g., fluid flow, geochemical, and radionuclide transport processes)
- Overburden characterization (features, processes, and evolution over time – e.g., fluid flow, geochemical, and radionuclide transport processes)
- Potential impact of external events such as climate change, glaciation, seismicity, igneous activity, and human intrusion on the performance of the natural barriers
- Discussion of how the engineered and natural barriers will function synergistically (i.e., the multiple-barrier concept)

This information is described in more detail in subsequent subsections, including an assessment of uncertainties over time and how it will be used to define parameters and conceptual models used in the post-closure PA.

The post-closure basis information should also be quantitative enough to inform the following analyses, which are described in more detail in Section 5.2:

- FEP analysis
- Scenario development
- Subsystem and barrier analyses

4.3.1 Natural Barrier Characteristics

The natural barriers include the host rock and the overlying geologic units. The DBD siting guidelines outlined in Section 3.2.1.2 include technical considerations (i.e., preferred characteristics and properties) for the host rock and overlying geologic units at a DBD site. Locations within the continental U.S. that best satisfy the technical siting guidelines are often associated with deep sedimentary basins, where Precambrian crystalline basement is typically overlain by Paleozoic and Mesozoic marine sedimentary sequences (Arnold et al. 2014; Perry et al. 2014), measured heat flow varies (with some exceptions) from about 40 mW/m^2 to 70 mW/m^2 (Blackwell et al. 2011), and lateral fluid flow in deep stratigraphic units is driven by head gradients on the order of 0.001 m/m (e.g., Downey and Dinwiddey 1988).

The following subsections provide additional details and material properties of the natural barrier features and components, including a subsection describing barrier safety functions.

4.3.2 Crystalline Basement Host Rock

The reference case crystalline basement host rock is assumed to extend from a depth of 2,000 m to depth of 6,000 m below land surface (the bottom of the DBD PA model domain), underlying a 2,000 m thick sedimentary overburden (Section 4.3.4).

Radionuclide transport processes occurring in the host rock may include advection, mechanical dispersion, diffusion, and sorption. The depth of emplacement combined with the low permeability and porosity of the host rock assures that groundwater travel times through the host rock to the accessible environment will be lengthy, diffusive fluxes will be small, and surface processes such as glaciation are unlikely to be propagated through the host rock to the EZ. Rock and pore water properties for the crystalline basement are described in the following subsections.

4.3.2.1 Permeability

The bulk permeability of crystalline rock depends on fracture distribution and connectivity. It generally increases with scale of measurement and is subject to heterogeneity and anisotropy due to the influence of fractures, joints, and faults whose orientation, density, and transmissivity depend on geologic history, lithology, extent and nature of fluid/rock reaction, and past and current states of stress.

In a global sense, the permeability of the continental crust appears to decrease with depth at least to the brittle/ductile transition (at approximately 12 km depth), beyond which it may be relatively constant (Ingebritsen and Manning 2010). Several authors have developed permeability versus depth curves for the continental crust, but all such functions are subject to limitations. A few are discussed below.

Manning and Ingebritsen (1999) present permeability of the continental crust as a function of depth up to 30 km ($\log k = -14-3.2(\log z)$, where k is permeability in m^2 and z is depth in km). They used two methods to constrain permeability. At depths from up to 3 – 10 km, permeability was constrained by inverse modeling of geothermal heat flow anomalies in a variety of geologic settings including sedimentary basins, active volcanic regions, and thrust belts. For greater depths, permeability was constrained by estimation of the fluid flow rates required for devolatilization during prograde metamorphism, i.e. fluid flow rates in regions of active crustal compression and thickening. Manning and Ingebritsen (1999) made clear that the permeability of the continental crust in tectonically stable regions is likely to fall considerably below that predicted by this relationship, and may "diminish to vanishingly small values at [depth]."

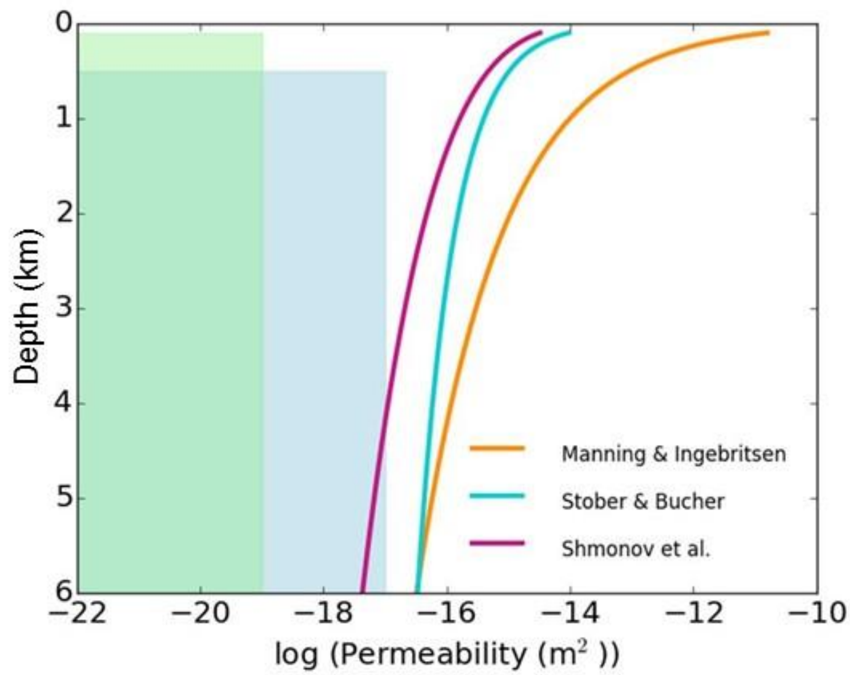
Stober and Bucher (2007a; 2007b) present a review of borehole permeability tests at several sites in crystalline rock at depths ranging from <500 m to about 4 km, and present a relationship for permeability as a function of depth ($\log k = -15.4-1.38(\log z)$, where the variables and units are the same as above) derived from measurements in multiple boreholes in the Black Forest region of Germany. Boreholes in this intensely fractured region adjacent to the Rhine Graben intersect both gneiss and granite; the permeability of the gneiss is overall lower than the permeability of the fractured granite and demonstrates a depth dependence, while that of the granite does not.

Permeability at the other sites reviewed (Urach 3, Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland (KTB), northern Switzerland, Soultz-sous-Forets, Cajon Pass, Aspo, Olkiluoto, Stripa, Carnmenellis, and Lac du Bonnet) ranges from 10^{-20} m^2 to 10^{-13} m^2, and as a whole depends less on depth than it does on lithology and geologic history (Stober and Bucher 2007a).

Follin et al. (2014) conducted packer tests at three depths in the sparsely fractured Forsmark metagranite. Calculated permeability varied with the length of the test interval, but overall decreased from approximately 10^{-16} m^2 above 200 m depth to 10^{-17} m^2 between 200 and 400 m depth to 10^{-18} m^2 below 400 m depth. The decrease in permeability corresponded to a decrease in the intensity of open and flowing fractures (Follin et al. 2014). Other sparsely fractured granites have similarly low permeability, including the Carnmenellis batholith, for which Pine and Ledingham (1984) calculated a permeability on the order of 10^{-17} m^2 between 1,500 and 2,000 m depth, and the Lac du Bonnet batholith, in which Stevenson et al. (1996) found permeabilities between 3×10^{-17} m^2 and 2.5×10^{-22} m^2 in domains of sparsely fractured rock. Not all granite bodies are sparsely fractured; fracture intensity and style can be related to emplacement history and rate of cooling with small plutons experiencing greater amounts of brittle deformation than large (Stone et al. 1989).

Shmonov et al. (2003) present a relationship for permeability versus depth calculated on the basis of laboratory permeability tests performed over a range of pressures and temperatures on gneiss and amphibolite samples from the super-deep Kola borehole. Results allowed them to develop a relationship between matrix permeability and depth up to 40 km ($\log k = -12.56 - 3.225 z^{0.223}$), variables and units same as above). Laboratory permeability tests performed on gneisses and amphibolites from the KTB borehole similarly indicate a decrease in matrix permeability with increasing effective stress, but in situ borehole tests demonstrate no dependence of matrix permeability on depth; instead mean values throughout the 9 km borehole are 7×10^{-20} m^2 with a log standard deviation of 1.2 (Huenges et al. 1997). In situ tests in the Lac du Bonnet URL and the Korean Underground Research Tunnel (KURT) give matrix permeability values between 10^{-22} m^2 and 10^{-20} m^2 for granitic rock (Martino and Chandler 2004; Cho et al. 2013); laboratory tests on samples of the Grimsel granodiorite give values on the order of 10^{-20} m^2 to 10^{-19} m^2 (Schild et al. 2001).

All three functions relating permeability to depth are plotted in Figure 4-7 along with zones indicating ranges of permeability for sparsely fractured granite (blue) and for crystalline matrix (green).



Orange line – based on large-scale heat flux and metamorphism constraints
Turquoise line – based on borehole flow tests in the Black Forest
Purple line – based on laboratory measurements of gneiss and amphibolite
Light blue rectangle – range derived from borehole measurements in sparsely fractured granites
Light green rectangle – range of matrix permeabilities for crystalline rocks

Figure 4-7. Permeability of Crystalline Rock from Various Sources

4.3.2.2 Porosity

The porosity accessible to flow and diffusion in deep crystalline rock is generally very small. From flow tests conducted at a depth of 4,000 m in the KTB borehole, Stober and Bucher (2007a) calculated a flow-accessible porosity of 0.68%. Laboratory measurements of porosity in core samples of crystalline rock often give values of approximately 1% (Schild et al. 2001), but these values may be exaggerated due to formation and growth of microcracks during unloading and sample preparation. Using samples of the Grimsel (meta)granodiorite, Schild et al. (2001) found that when rock samples were impregnated with resin prior to being sampled from depth, the measured porosity was between 0.55% and 0.59%, while non-impregnated samples measured between 1% and 1.17% porosity. Had microcracks not been enhanced during sampling, the impregnated samples would have had 0% porosity. Schild et al. (2001) took the difference between values measured on impregnated and non-impregnated samples to be the in-situ porosity, approximately 0.4%; even this value may be high as they were unable to avoid sampling within the DRZ.

4.3.2.3 Effective Diffusion Coefficient

Diffusion coefficients in free water (D_w) depend on temperature and pressure, on the salinity and viscosity of the fluid, on the size (including hydration layer) of the ion in solution, and on charge balance constraints, which will generally slow anion and speed cation diffusion (Li and Gregory 1974). A description of diffusion in a porous medium must also account for pore volume, saturation, and tortuous diffusion paths (Li and Gregory 1974; Boudreau 1996, Oelkers 1996). An effective diffusion coefficient (D_e) for diffusion in a porous medium can be calculated as a function of tortuosity (τ), porosity (ϕ), and saturation (s) according to:

$$D_e = \mathit{T} \phi s D_w$$

where $\mathit{T} = 1/(\tau^2)$, s (for the DBD reference case) is equal to 1 due to the assumption of fully saturated conditions, and $D_w = 1\text{x}10^{-9}$ m^2/s for all radionuclides (Li and Gregory 1974).

Tortuosity (τ), the ratio of diffusive path length to the length of a direct path, is always greater than unity. In unlithified sediments, it has been related to porosity by a number of authors (see review by Boudreau 1996). A commonly used relationship for natural sediments is derived from Archie's Law (McDuff and Ellis, 1979; Boudreau 1996):

$$\tau^2 = \phi^{1-n}$$

where n is an adjustable parameter with a value usually around 2 for a variety of rock types including unconsolidated sediment, consolidated sedimentary rock, and crystalline rock (Oelkers 1996). For natural materials of sedimentary origin and engineered materials of similar nature (e.g., bentonite, ballast), applying this relationship assuming $n = 2$, results in $\mathit{T} = \phi$. For other materials (e.g., waste package, DRZ), T is chosen to achieve a representative value of D_e.

Effective diffusion coefficients in crystalline rocks calculated from small scale experiments represent the ability of ions to diffuse through the unfractured rock matrix (e.g., Soler et al. 2015), while those calculated from large scale tracer tests in fractured rock represent strict matrix diffusion plus advective and dispersive processes that isolate fluids from the main flow path (e.g., Zhou et al. 2007). Soler et al. (2015) modeled in-situ diffusion of ^3H, $^{22}Na^+$, and $^{134}Cs^+$ and $^{137}Cs^+$ in granite at a maximum length scale of 20 cm; best-fit matrix diffusion coefficients ranged from $2\text{x}10^{-13}$ to $4\text{x}10^{-12}$ m^2/s. Zhou et al. (2007) reviewed matrix diffusion coefficients calculated from meter- to kilometer-scale tracer tests in fractured rock; in crystalline rocks they ranged from $3\text{x}10^{-12}$ to $3\text{x}10^{-8}$ m^2/s and were (with two exceptions) larger than matrix diffusion coefficients calculated for core-scale samples of the same rocks by a factor of 2 to 884. The largest of these values is larger than values for diffusion in free water, which though solute-specific and dependent on fluid properties, tend to be on the order of $1\text{x}10^{-9}$ m^2/s (Li and Gregory 1974).

4.3.2.4 Thermal Properties

The thermal properties of rock depend strongly on temperature; thermal conductivity decreases and heat capacity increases with increasing temperature (Vosteen and Schellschmidt 2003). Vosteen and Schellschmidt (2003) measured thermal properties of a variety of igneous and metamorphic rocks at temperatures from 0°C to 500°C, and compared their results to previous results in the literature. For felsic rocks at temperatures between 100°C and 200°C, as expected at the depth of the EZ, a thermal conductivity of 2.5 $Wm^{-1}K^{-1}$ and a heat capacity of 880 $Jkg^{-1}K^{-1}$ are appropriate.

The ambient temperature profile depending on the rock thermal properties (for both the crystalline basement and the overburden), the geothermal heat flux, and the average annual surface temperature. For the DBD reference case, the temperature profile is calculated assuming a geothermal heat flux of 60 mW/m^2 at 6,000 m depth and an average annual surface temperature of 10°C. The resulting thermal gradient is about 25°C/km, with ambient temperatures of about 125°C at the top of the EZ and 140°C at the bottom of the EZ.

For the heat-generating Cs and Sr capsules (Figure 4-4), the temperature in the EZ increases above ambient for a period of time (Figure 5-4); however, boiling of fluid in the EZ is precluded by the pressures at depth (SNL 2016b, Section 2.2).

4.3.2.5 Pore Fluid Chemistry

Pore fluid chemistry at depth is expected to (1) provide evidence that basement pore fluids are isolated from surface waters and (2) provide an environment in which radionuclide mobility is limited by solubility (see Section 4.3.2.6), sorption (see Section 4.3.2.7), density stratification, and lack of colloid formation.

Evidence for isolation

In cratonic shield environments including the Canadian Shield, the Fennoscandian Shield, and the Baltic Shield, formation waters tend to occur in distinct compositional zones correlated with depth (Gascoyne 2004; Kietavainen et al. 2013; NEDRA 1992). Fluid compositions depend on mineralogy and geologic history including episodes of marine transgression and glaciation, but in general, surficial fluids are dilute to brackish with major element compositions dominated by Na, Ca, and HCO_3; intermediate fluids evolve toward Na-Ca-SO_4-Cl compositions; and the deepest fluids are saline brines (TDS >50 g/L to upwards of 200 g/L) of Na-Cl or Ca-Na-Cl composition (Fritz and Frape 1982; NEDRA 1992; Gascoyne 2004; Kietavainen et al. 2013). The transition to saline fracture fluids occurs at depths from approximately 500 m (Gascoyne 2004) to 1500 m (NEDRA 1992; Kietavainen et al. 2013), and can be abrupt, indicating negligible vertical fluid flow (Kietavainen et al. 2014), even in regions that have experienced significant glacial recharge at shallower depths (Gascoyne 2004). The origin of saline fluids at depth may differ by locale. At the Lac du Bonnet batholith and other locations in the Canadian shield, paleoseawater is indicated (Fritz and Frape 1982; Gascoyne 2004; Bottomley et al. 1994). At Outokumpu Deep Drill Hole in the Fennoscandian Shield, the origin appears to be paleometeoric water that has experienced extensive water/rock reaction in a closed system (Kietavainen et al. 2014). In either case, the high salinity of deep fracture fluids indicates isolation over extended periods of time.

Saline fluids at depth have high concentrations of dissolved gases that reflect long exposure to the surrounding rocks in a closed system, including abiogenic H_2 and CH_4 resulting from extensive water/rock reactions, and stable isotopes of noble gases resulting from decay of U, Th, and K naturally occurring in crystalline rock (Holland et al. 2013; Lippmann-Pipke et al. 2011; Kietavainen et al. 2013). Absolute concentrations as well as ratios of radiogenic (^{4}He, ^{40}Ar), nucleogenic (^{21}Ne, ^{22}Ne), and fissionogenic (^{134}Xe, ^{136}Xe) stable isotopes of noble gases can be used to calculate fracture fluid residence times. Such analyses indicate residence times for deep fluids in the Outokumpu Deep Drill Hole (Fennoscandian Shield) of between 20 million and 50 million years (Kietavainen et al. 2014); residence times for deep (2.4 km) fluids in the Canadian Shield of greater than 1 billion years (Holland et al. 2013); and residence times for fluids from deep (up to 3.3 km) mines in the Witwatersrand Basin (South Africa) of between 1 million and 23 million years (Lippmann et al. 2003).

Additional lines of evidence that point to long fracture fluid residence times in deep cratonic rocks include $\delta D/\delta^{18}O$ and $^{87}Sr/^{86}Sr$ ratios indicative of extensive water rock reaction (Kietavainen et al. 2013) or pre-glacial recharge (Gascoyne 2004); and $\delta^{34}S$ and Br/Cl values indicative of seawater or evaporite origin in regions where the most recent marine transgression occurred millions of years ago (Fritz and Frape 1982; Bottomley et al. 1994; Gascoyne 2004).

Density Stratification

As shown by the occurrence of zones of distinct fluid composition within fractured cratonic rocks (NEDRA 1992; Gascoyne 2004; Kietavainen et al. 2013; Kietavainen et al. 2014), high density brines at depth tend not to advectively mix with overlying dilute fluids. Salinity stratification occurs even in the absence of a barrier to flow, due to the large fluid pressures required for dilute water to flush denser saline water and the resulting refraction or reflection of streamlines that occurs at the boundary between the fluids (Park et al. 2009).

Colloids

The high salinity of deep fluids is expected to limit colloidal transport of radionuclides, because in high ionic strength solutions colloids flocculate and settle out of suspension (Freeze et al. 2013a, Section 3.3.2.4).

4.3.2.6 Solubility

Deep fluids are chemically reducing, and will maintain multivalent radionuclides in their low-solubility reduced valence states. Table 4-9 gives estimates of radionuclide solubilities in brine at 200°C, a temperature similar to those expected at the depth of the EZ in the presence of heat-generating waste. Table 4-9 was initially generated in consideration of disposal of SNF, and assumes unlimited solubility of both Cs and Sr, which are not highly concentrated in SNF.

For CsCl waste forms, an assumption of unlimited solubility for Cs is still valid, given the relatively high solubility (≥ 10 mol/kg) of CsCl salt or a Cs_2SO_4 solubility-limiting phase under expected EZ conditions (see Section 4.2.3). For SrF_2 waste forms, an assumption of unlimited solubility for Sr is bounding within the EZ, given the lower solubility (2.4×10^{-3} mol/kg) of SrF_2 (see Section 4.2.3). Within the natural barriers outside the EZ, the solubility of Sr will depend on pore fluid composition and may be controlled by equilibrium with $SrCO_3$ or $SrSO_4$ mineral phases (Section 4.2.3).

Table 4-9. DBD Reference Case Radionuclide Solubilities

Element	Solubility Limit (mol/L)[a]	Solubility Limit (mol/L)[b]	Solubility-Limiting Phase[b]	Notes[b]
Am	6.50×10^{-9}	1.00×10^{-9}	Am_2O_3	$AmOH(CO_3)$ would control Am solubilities if carbonate present.
Ac	6.50×10^{-9}	1.00×10^{-9}	Ac_2O_3	Am solubility is used as proxy for chemically similar Ac.
C	Unlimited	Unlimited	None	
Cm	6.50×10^{-9}	1.00×10^{-9}	Cm_2O_3	Am solubility is used as proxy for chemically similar Cm.
Cl	4.2	No value reported	CsCl	
Cs	Unlimited	Unlimited	None	See discussion in Section 4.2.3.
I	Unlimited	Unlimited	None	
Nb	1.60×10^{-5}	No value reported		
Np	1.90×10^{-6}	1.10×10^{-18}	NpO_2	
Pa	1.90×10^{-6}	1.10×10^{-18}	PaO_2	Np solubility is used as proxy for chemically similar Pa.
Pd	4.00×10^{-4}	No value reported		
Pu	3.56×10^{-14}	9.10×10^{-12}	PuO_2	
Se	2.00×10^{-5}	No value reported		
Sb	6.30×10^{-5}	No value reported		
Sn	2.66×10^{-8}	No value reported		
Sr	Unlimited	Unlimited	$SrCO_3$, $SrSO_4$	See discussion in Section 4.2.3.
Tc	1.33×10^{-8}	No value reported		
Th	3.37×10^{-8}	6.00×10^{-15}	ThO_2	
U	9.40×10^{-13}	1.00×10^{-8}	UO_2	
Zr	1.00×10^{-10}	No value reported		

[a]Representative of a chemically reducing brine at 200 °C (Clayton et al. 2011, Table 3.4-4)

[b]Calculated for 200°C using the PHREEQC code version 2.12.03 and the thermo.com.V8.R6.230 database from Lawrence Livermore National Laboratory. The solution assumed 2 M NaCl, pH=8.5, Eh=-300mV (Brady et al. 2009, Table 4)

(Source: modified from Freeze et al. 2013a, Table 3-15)

4.3.2.7 Sorption

Many different models for the complex surface chemistry reactions included in sorption have been developed with varying levels of sophistication (e.g., Miller and Wang 2012). The simplest model assumes linear sorption, characterized by a distribution coefficient (K_d) for each element. Elemental K_ds depend heavily on porewater characteristics including temperature, pH, redox conditions, ionic strength, and concentrations of other solutes, as well as on mineralogy and the porosity available to an ion (Miller and Wang 2012), and therefore provide only a rough predictor of the potential for radionuclide or contaminant retardation.

For the DBD reference case, radionuclide sorption is assumed to occur in the bentonite seals, the crystalline basement (including the DRZ), and the overlying sediments. Ranges of K_d values for these materials, based on a literature review, are listed in Table 4-10. Values for crystalline basement are reduced by a factor of 10 relative to values in the original sources to account for the effect of high-salinity fluid (Clayton et al. 2011).

The DBD reference case conservatively assumes no sorption in the EZ materials or in the SZ cement plugs or ballast.

Table 4-10. DBD Reference Case Radionuclide K_d Values

Element	Crystalline Basement[a]	Bentonite Seal[b]	Sediments[c]
	K_d (mL/g)	K_d (mL/g)	K_d (mL/g)
Am, Ac[d], Cm[d]	5–500	300–29,400	100–100,000
C	0–0.6	5	0–2,000
Cl, Pb	0	0	0
Cs	5–40	120–1,000	10–10,000
I	0–1	0–13	0–100
Nb	1	10	10
Np, Pa[d]	1–500	30–1,000	10–1,000
Pd	1	5–12	4–100
Pu	1–500	150–16,800	300–100,000
Sr, Ra[d]	0.4–3	50–3,000	5–3,000
Sb	10	100	100
Se	0.2–0.5	4–20	1–8
Sn	2–10	17–50	50–700
Tc[e]	0–25	0–250	0–1,000
Th	3–500	63–23,500	800–60,000
U	0.4–500	90–1,000	20–1,700
Zr	3–500	100–5,000	100–8,300

[a] K_d values for deep basement granite at T=100°C under chemically reducing conditions, reduced by a factor of 10 to account for sorption in a highly saline emplacement zone. (Source: Clayton et al. 2011, Table 3.4-3, based on Brady et al. 2009, Table 5 and McKinley and Scholtis 1993)

[b] K_d values for bentonite seals at T=100°C under chemically reducing conditions. (Source: Clayton et al. 2011, Table 3.4-5, based on Brady et al. 2009, Table 5 and McKinley and Scholtis 1993)

[c] K_d values for sediments at T=25°C under less chemically reducing conditions than the seal and emplacement zones. (Source: Clayton et al. 2011, Table 3.4-6, based on Brady et al. 2009, Table 5 and McKinley and Scholtis 1993)

[d] K_d values for Ac and Cm are set equal to those of chemically similar Am. K_d's for Pa are set equal to those of chemically similar Np. K_d values for Ra were set equal to those of somewhat chemically similar Sr.

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

(Source: modified from Freeze et al. 2013a, Table 3-16)

4.3.3 Disturbed Rock Zone

The DRZ is defined as the portion of the host rock adjacent to the engineered barriers that experiences durable (but not necessarily permanent) changes due to the presence of the repository (Freeze et al. 2013a, Section 2.1.2.1). For DBD, the DRZ is the host rock radially adjacent to the borehole. Immediately adjacent to the borehole, these induced changes are more likely to be permanent (e.g., mechanical alteration due to drilling), whereas further radially from the borehole the induced changes are more likely to be time-dependent but not permanent (e.g., thermal effects due to radioactive decay of waste). The DRZ is sometimes referred to as the excavation disturbed zone (EDZ), but DRZ is preferred because it more accurately represents the fact that the disturbed zone includes effects from both drilling/excavation and waste emplacement.

The DRZ is expected to have elevated permeability with respect to the permeability of the host rock matrix due to the changes in stress induced by drilling. Fractures perpendicular to the direction of least principle stress will open in the direction of least principle stress, which, due to high lithostatic pressure at depth, will likely be horizontal (e.g., Brudy et al. 1997). Thus subvertical fractures open on opposite sides of the borehole. The direction of least principal stress may vary with depth, and the strain the rock experiences will additionally depend on structural features of the rock such as fabric/foliation and pre-existing fractures and joints. Therefore, the DRZ will experience spatially variable opening along the length of the borehole. The radial thickness of the DRZ that is expected to experience these mechanical changes is one to two times the radius of the borehole (Tsang et al. 2005), or in the case of the EZ and the seal zone, approximately 0.15 to 0.30 m (~ 6 to 12 in).

In-situ DRZ permeability has been measured in URLs in crystalline rock in Korea (Cho et al. 2013) and Canada (Martino and Chandler 2004). In both locations permeability was variable but generally decreased from disturbed to undisturbed values over a discrete distance from the tunnel wall. In the KURT, gas permeability was as high as 10^{-17} m^2 for distance of 2 m from the tunnel wall; beyond that distance it was approximately 10^{-20} m^2 (fluid permeabilities are approximately an order of magnitude less than gas permeabilities) (Cho et al. 2013). In the Lac du Bonnet URL, fluid permeability was between 10^{-16} and 10^{-19} m^2 for a distance of 0.3 to 0.5 m from the tunnel wall, beyond which it was between 10^{-22} and 10^{-20} m^2 (Martino and Chandler 2004).

The permeability and porosity of the DRZ may alter with time due to mechanical and chemical processes. Both cement and bentonite have the potential to penetrate exposed fractures in the DRZ, decreasing permeability and porosity. At the same time, thermal expansion of fluid in the DRZ may enhance fracture openings. Fresh mineral surfaces exposed by fracturing are likely to react with borehole and formation fluids. Dissolution reactions to the extent that they occur may increase fracture aperture, but hydration reactions will generally result in an increase in mineral volume (Yardley and Bodnar 2014; Stober and Bucher 2015) and thereby assist in sealing fractures.

Other rock and fluid properties in the DRZ (effective diffusion coefficient, thermal properties, fluid chemistry, solubility, sorption) are assumed to be similar to the intact crystalline basement host rock (Section 4.3.2).

As part of the host rock, the DRZ is categorized as part of the natural barriers. However, for DBD design, the primary consideration for the DRZ is how it functions in conjunction with the seal zone seals and plugs (i.e., seals should bind effectively to DRZ).

4.3.4 Overburden/Sediments

The sedimentary sequence overlying the crystalline basement is assumed to be similar to those existing in ancient marine sedimentary basins within the U.S. Such a sequence may contain limestones, dolomites, shales, sandstones, and evaporites overlain by more recent unconsolidated deposits (e.g., Downey and Dinwiddie 1988). Pore fluids will range from concentrated brines at depth and within evaporite units to fresh meteoric water near surface (e.g., Downey and Dinwiddie 1988). Low permeability units including shales, evaporites, and intact limestones or dolomites will provide a barrier to fluid flow, while higher permeability units including sandstones and fractured limestones or dolomites will function as aquifers. The rate at which radionuclides diffuse through sedimentary units will depend on pore fluid composition, porosity, and tortuosity. Effective diffusion coefficients in argillaceous sediments have been reviewed by Miller and Wang (2012), who compiled values between 10^{-11} and 10^{-13} m^2/s. Units containing clay minerals have the capacity to sorb radionuclides. Past deep borehole conceptual models have recommended ranges of sorption coefficients for the sediments overlying crystalline basement (see Table 4-10); Miller and Wang (2012) also provide sorption coefficients for argillaceous sediments.

4.3.5 Potential Impacts of External Events on Natural Barriers

For DBD, natural barriers, like the engineered barriers (see Section 4.2.8), are expected to have a low probability of being adversely impacted by external events. Climatic changes in precipitation, glaciation, or erosion are unlikely to significantly affect hydraulic properties or driving forces for flow at depth. Siting requirements (see Section 3.2.1.2) will exclude regions with high probability of seismic or igneous event. The probability of human intrusion is low both because of the very limited footprint of a DBD borehole and because of the great depth of disposal (Section 4.2.8). Regulatory considerations for human intrusion for DBD are discussed in Section 2.1.3.5.

The treatment of disruptive events in post-closure PA scenarios is described in Section 5.2.2.

4.3.6 Multiple Barriers

As described in Section 2.1.3.3, regulations typically require demonstration that multiple barriers, both engineered and natural, contribute to the safety functions of waste isolation and delaying/limiting radionuclide releases and transport.

While the safety of DBD concept relies primarily on the great depth of burial and the isolation provided by the natural barriers, there is also a reliance on the engineered barriers.

Natural features that contribute to isolation of waste and delay and/or limit radionuclide releases include:

- Depth of emplacement in the crystalline host rock
- Low permeability and porosity of crystalline host rock
- Low permeability of overlying sedimentary aquitards
- Sorption capacity of clay-bearing sedimentary units

Engineered features that contribute to isolation of waste and delay and/or limit radionuclide releases include:

- Waste Packages
  - Although preliminary DBD PA model results (Section 5.2.6) suggest that radionuclide transport beyond the EZ is minimal, the use of longer-lived, corrosion-resistant waste packages would further limit radionuclide transport
- Seal Zone
  - Low permeability and sorption capacity of the seal zone
  - Multiple bentonite seals and cement plugs provide redundancy in the seal zone
- Upper Borehole Zone
  - Cement plugs in the upper borehole zone inhibit fluid flow in the borehole, including downward fluxes of surface water, and contribute to the stability of engineered components of the seal zone

4.3.7 Natural Barrier Safety Functions

A description of how each natural barrier feature or component is expected to provide safety (i.e., its safety function) is provided in Table 4-11.

Table 4-11. Engineered Barrier Safety Functions

Barrier Feature or Component	Safety Function
Crystalline Basement Host Rock	Crystalline basement is expected to provide a stable environment for the EZ and to isolate waste from the accessible environment. The depth of emplacement combined with the low permeability and porosity of the host rock assures that groundwater travel times through the host rock to the accessible environment will be lengthy, diffusive fluxes will be small, and surface processes such as glaciation are unlikely to be propagated through the host rock to the EZ.
DRZ	Because of its elevated permeability, the DRZ is a potential pathway for radionuclide release. It does not serve a safety function.
Overburden/Sediments	Overlying sediments will contribute to isolation of the EZ as a function of their thickness and their resistance to fluid flow. They will assist in delaying and limiting radionuclide releases as a function of their capacity to sorb radionuclides.

4.4 Post-Closure Basis: Biosphere and Surface Environment

The post-closure basis includes a description of the natural and engineered barriers for use in the quantitative post-closure PA (Section 5.2). Specific post-closure basis information related to the biosphere and surface environment includes (Section 1.2.1.3):

- Surface environment characterization (location, features, and characteristics)
- Flora and fauna characterization
- Human behavior characterization (receptor location, receptor characteristics)

IAEA (2007) states: "In practice, the biosphere is not usually defined with great precision, but is generally taken to include the atmosphere and the Earth's surface, including the soil and surface water bodies, seas and oceans and their sediments. There is no generally accepted definition of the depth below the surface at which soil or sediment ceases to be part of the biosphere, but this might typically be taken to be the depth affected by basic human actions, in particular farming."

The biosphere is designed to capture phenomena (i.e., FEPs) that are relevant to the calculation of dose to the receptor, which may include radionuclide movement above the subsurface. The conceptualization of the biosphere is typically specified by regulation and can vary between different national radioactive waste disposal programs. The biosphere is commonly defined in relation to the accessible environment (see Section 2.1.3.2).

A commonly-used reference biosphere is based on the IAEA Example Reference Biosphere (ERB) 1B model (IAEA 2003, Sections A.3.2 and C.2.6.1). The ERB 1B dose model assumes that the receptor is an individual adult who obtains drinking water by pumping from a hypothetical well drilled into an aquifer in the far field of the natural system. The ERB 1B model is used to convert the dissolved radionuclide concentrations in groundwater at the hypothetical drinking well location to an estimate of annual dose to a receptor (dose from each radionuclide and total dose) based on the well dilution/pumping rate (typically assumed to be 10,000 m^3/yr), individual water consumption rate of the receptor (typically assumed to be 1.2 m^3/yr), and radionuclide-specific dose conversion factors (Freeze et al. 2013a, Section 4.2.3.3).

For this preliminary iteration of the DBD safety case, the biosphere is not yet conceptualized and is not part of the post-closure PA model. Future iterations of the DBD safety case will develop a reference case biosphere more fully. Determination of biosphere model parameter values will depend on the characteristics of the biosphere (e.g., climate) and the habits of the population (receptor) in that biosphere.

4.5 Site Selection Basis

As noted in Section 1.2.1.3, the site selection basis should address:

- Consent-based siting considerations
- Evaluation of siting guidelines and criteria
- Selection of disposal concept
- FEP considerations
- Transportation considerations

In the early stages of a repository program, preliminary site characterization information supports the site selection process, and may require information from multiple sites. Preliminary site investigations, including drilling and/or mined excavation, will produce a variety of site characterization data, including geologic, hydrologic, geochemical, geophysical, and thermo-mechanical data at the candidate site(s), similar to the geosphere/natural barrier assessment basis information identified in Section 4.3. In addition to this technical data, other data related to guidelines for health and safety, environmental, socio-political, and economic considerations should be gathered during the siting process (MacKinnon et al. 2012, Section 4.1).

5. SAFETY ASSESSMENTS FOR DEEP BOREHOLE DISPOSAL

Safety assessments for the DBD reference case (outlined in Section 4) are described in the following subsections: pre-closure safety analysis (Section 5.1); post-closure performance assessment (Section 5.2); and confidence enhancement (Section 5.3).

5.1 Pre-Closure Operational Safety Analysis

The pre-closure operational safety analysis provides a quantitative estimate of (i) the occupational dose from on-site radiation levels and radiological exposures, and (ii) the dose to the public from off-site releases of radioactive materials. The implementation of the pre-closure operational safety analysis methodology (Section 3.3.1) includes:

- Description of the surface facilities and borehole and their operation, and
- Comparison with safety standards that includes:
  - Initiating event and event probability identification and screening
  - Event sequence identification
  - Radiological dose and consequence analyses
  - Criticality analyses
  - SSCs and procedural safety controls intended to prevent or reduce the probability of an event sequence or mitigate the consequences of an event sequence, should it occur
  - Uncertainty and sensitivity analysis
  - Software verification and model validation

The facilities, operations, and SSCs are described in Section 4.1. However, a full quantitative pre-closure safety analysis has not yet been prepared or conducted. The only quantitative analysis that has been performed to date was an analysis to support the selection of an engineering concept for the emplacement of waste packages for DBD (SNL 2016b, Appendix A). The analysis used probabilistic risk assessment and multi-attribute utility analysis to compare emplacement of waste packages in a borehole by two different methods (wireline and drill string); the wireline emplacement method was chosen as a result of the study.

The study examined only the differences between the two emplacement methods; thus, many of the facilities, operations, and SSCs that would be included in a full pre-closure safety analysis were not included in this study. For example, event sequences and consequences associated with the receipt of transportation casks, transfer of waste packages from transportation casks to transfer casks, and movement of transfer casks to the borehole were not included in the study. In addition, the performance objectives that were used to evaluate the two emplacement methods included cost, time required for emplacement, and whether or not detectable levels of radiation would be found in case of an accident. Dose to members of the public and to workers, the customary pre-closure performance objectives, were not the objectives for the study. Future iterations of the DBD safety case will develop the pre-closure safety analyses more fully.

The wireline emplacement mode analysis is summarized in the following subsections.

5.1.1 Event Sequences and Probabilities for Wireline Emplacement

The wireline emplacement mode analysis considers accident hazards and accident event sequences associated with wireline emplacement, based on standard borehole and nuclear materials handling operations. Four top level off-normal events were identified that have the potential to lead to adverse consequences (SNL 2016b, Appendix A):

- Dropping the waste package from the surface
- Dropping the waste package during the trip in
- Waste package getting stuck in the borehole
- Dropping the wireline holding the tool string onto the waste package on the trip out

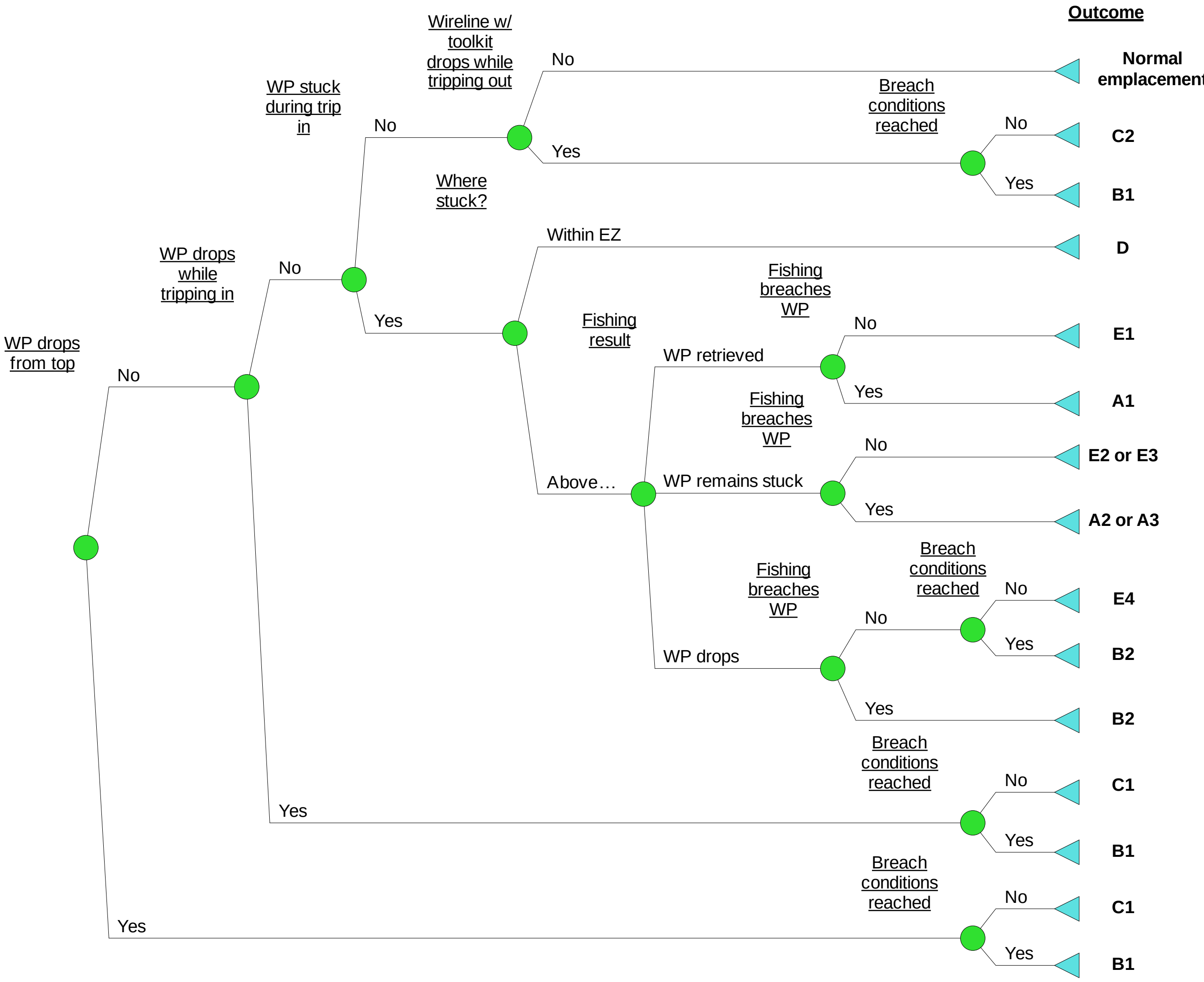
Table 5-1 lists the probabilities of occurrence for each off-normal top event; these were calculated using fault trees that considered various actions (e.g., human error, component failure), informed by expert panel discussion (SNL 2016b, Appendix A and Appendix B).

Table 5-1. Top-Level Event Probabilities for Wireline Emplacement

Fault Tree Top Event	Failure Probability (per package)	Primary Responsible Events
Drop waste package from surface	2.60×10^{-7}	Overtension due to winding the wrong way against the stops.
Drop waste package during trip in	5.09×10^{-5}	Wireline break due to dynamic overtension if the WP momentarily hangs up.
Waste package gets stuck	2.81×10^{-6}	Contributing causes: casing collapse after caliper log has been run and before or during lowering of a WP; concrete debris not picked up by junk basket.
Drop wireline during trip out	9.04×10^{-7}	Contributing causes: cask door or well head control feature shears wireline; wireline damage failure.

(Source: SNL 2016b, Table B-1)

There is uncertainty regarding the events that could occur after one of these top-level failures occurs. Figure 5-1 shows an event tree that summarizes the assumed sequence of events that would follow occurrence of any one of the off-normal top events. The four top-level off-normal events are shown along the top of the figure, moving from left to right. At each node (green dots in the figure), the upper branch represents the favorable outcome (i.e., no off-normal event) while the lower branch represents the occurrence of the off-normal event.



(Source: SNL 2016b, Figure A-2)

Figure 5-1. Wireline Emplacement Event Tree

As shown in the event tree, some of these top events (e.g., WP drops) could directly cause a breach of a waste package (Outcome B1), or not (Outcomes C1 and C2). Other top events (e.g., WP stuck) could indirectly result in a breach of a waste package if the primary mitigation technique (fishing) is not successful (Outcomes A1, A2, A3, and B2). Calculation of these outcome probabilities required additional event probabilities (SNL 2016b, Appendix A), summarized in Table 5-2. For the purposes of the hazard analysis, outcomes that resulted in a waste package breach were assumed to result in a radionuclide release, although the duration and magnitude of the release was not estimated.

Table 5-2. Event Probabilities for Wireline Emplacement Event Tree

Event	Probability	Basis
Waste package stuck above EZ	0.90	Conditional probability, given that a WP gets stuck. Based on relative lengths of crystalline rock above and within the EZ. (adapted from SNL 2016b, Table A-6).
Fishing successful	0.90	Expert panel discussion. WP retrieved to surface.
Fishing breaches waste package	0.03	Expert panel discussion. Assumes 30 fishing attempts per WP.

(Source: SNL 2016b, Table A-6)

5.1.2 Consequence Analysis for Wireline Emplacement

The event tree analysis described in SNL 2016b (Appendix A and Appendix B) was modified to represent the emplacement of 108 waste packages, one at a time, in a 534-m EZ, consistent with the Cs and Sr capsule DBD reference case. The results of this modified analysis are summarized in Table 5-3.

Table 5-3. Results for Wireline Emplacement Mode Analysis

Probability of incident-free emplacement of 108 WPs	**99.41%**
Aggregated probability of radiation release	**8.21×10^{-6}**
Outcome Probabilities	
Probability of a failure that leads to radiation release (Outcomes A1 – A3, B1 and B2)	**8.21×10^{-6}**
Outcome A1: Stuck above EZ/breached/fished/no more disposal	7.39×10^{-6}
Outcome A2: Stuck above EZ/breached/fishing failed/leave in place	2.87×10^{-7}
Outcome A3: Stuck above EZ/breached/fished with casing/no more disposal	2.87×10^{-7}
Outcome B1: Drop causes breach in EZ/complete hole/no more disposal	0.00×10^{-0}
Outcome B2: Fishing causes breach in EZ/complete hole/no more disposal	2.46×10^{-7}
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D and E1 – E4)	**2.95×10^{-4}**
Outcome D: Stuck in EZ/complete borehole/no more disposal	2.98×10^{-5}
Outcome E1: Stuck above EZ/no breach/fished/no more disposal	2.39×10^{-4}
Outcome E2: Stuck above EZ/no breach/fishing failed/leave in place	9.29×10^{-6}
Outcome E3: Stuck above EZ/no breach/fished with casing/no more disposal	9.29×10^{-6}
Outcome E4: Drop to EZ during fishing/no breach/complete/no more disposal	7.97×10^{-6}
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 and C2)	**5.6210^{-3}**
Outcome C1: Drop into EZ/no breach/continue disposal	5.53×10^{-3}
Outcome C2: Drop wireline into EZ/no breach/continue disposal	9.76×10^{-5}

(Source: modified from SNL 2016b, Table A-8)

The results show that the probability of incident-free wireline emplacement of 108 waste packages would be 99.41%. The potential for incidents (i.e., occurrences of off-normal events) arises, in part, because the waste packages are lowered one at a time; thus, 108 trips are needed to emplace all of the waste packages. The highest probabilities of incidents arise from (i) off-normal event Outcome C1 (0.55%), in which a waste package is dropped in the borehole, but is not breached, and (ii) off-normal event Outcome E1 (0.02%), in which a waste package becomes stuck above the EZ, but is successfully fished without a breach. The waste package drop event incidents were most commonly caused by wireline failure, but were not considered to result in waste package breaches, due in part to the incorporation of impact limiters on the bottom of the waste packages. The probability of an incident leading to a waste package breach and subsequent radiation release was much lower. The overall probability of a radiation release was 8.21×10^{-6} (0.0008%), due primarily to fishing damage during attempts to retrieve waste packages stuck above the EZ (Outcome A1).

As a result of this analysis, a number of factors were identified as being significant to the events evaluated in the study, which are, in turn, related to pre-closure safety. These are (SNL 2016b, Section 3.7):

- How the EZ is completed and the liner perforation scheme (e.g., how large, distance between perforations)
- Selection of emplacement fluid consistent with EZ completion and terminal sinking velocity in the event of a dropped package
- The need to design waste packages for the range of temperatures that could be encountered with heat-generating waste
- The downhole release mechanism used to release waste packages emplaced on the wireline
- Impact limiters that achieve needed performance without contributing to getting packages stuck while being emplaced or after impact (if retrieval is necessary)

While the wireline emplacement analysis did not examine dose to workers or members of the public, it did identify some initiating events and their probabilities, which will be required in a full pre-closure safety analysis for a DBD facility. In addition, the SSCs identified in Section 4.1.3 (transfer shield, transfer cask, crane, wellhead carousel, wireline) will be designed to improve pre-closure safety and reduce event probabilities and calculated doses to workers and members of the public. For example, the transportation cask, transfer cask, transfer shield, and wellhead carousel will be constructed of the appropriate materials and be of the appropriate thickness to provide adequate shielding. As another example, in the current DBD reference design, the wellhead is below grade, in a shielded pit, to reduce the dose to workers. In addition, several safety features will be incorporated to minimize the probability of dropping a waste package, either on the ground or in the borehole. These include: the waste package will be transferred from the transportation cask to the transfer cask in a horizontal position, the crane and wireline will be designed with an appropriate FoS, and the waste package will be secured to the transfer cask with a side latch as well as being attached to the crane or wireline to provide redundancy.

5.1.3 Criticality Analysis

A criticality analysis is not needed for Cs and Sr capsules because they do not contain fissile material. For disposal of waste that does contain fissile material, a criticality analysis would be conducted as required.

5.2 Post-Closure Performance Assessment

The post-closure PA provides a quantitative estimate of (i) radiological exposures to members of the public, and (ii) radiological releases to the accessible environment. The implementation of the post-closure PA methodology (Section 3.3.2) includes:

- Description of the natural barriers (information related to the geology, hydrology, and geochemistry (including disruptive processes) and events of the site, and the surrounding region), and information on the design of the engineered barriers used to define parameters and conceptual models used in the assessment,
- Description of how the barriers/components are expected to provide safety functions, and
- Comparison with safety standards that includes:
    - FEP analysis
    - Scenario development
    - Model development (conceptual, mathematical, and computational models, and integrated PA model)
    - Software verification and model validation
    - Subsystem and barrier analyses
    - PA model analyses
    - Uncertainty and sensitivity analyses

Some simple post-closure PAs for DBD of SNF have been documented (Brady et al. 2009; Arnold et al. 2013; Freeze et al. 2013a). However, this safety case is the first to include documentation of a post-closure PA for DBD of Cs/Sr capsules.

Sections 4.2 through 4.4 provide information describing the natural and engineered barriers, along with a discussion of how the barriers/components are expected to provide safety functions. The quantitative comparison with safety standards in presented in the following subsections.

Sections 5.2.1 and 5.2.2 describe FEP analysis and scenario development for DBD, respectively. Section 5.2.3 describes the development of a DBD PA model that describes selected FEPs and scenarios, supported by software verification and model validation (Section 5.2.4) and subsystem and barrier analyses (Section 5.2.5). The DBD PA model results are presented in Section 5.2.6 for deterministic analyses and Section 5.2.7 for uncertainty and sensitivity analyses.

5.2.1 FEP Analysis

The role of FEP analysis within a post-closure PA methodology is described in detail in Freeze et al. (2013a, Sections 4.2.1 and 4.2.2).

Formal FEP analysis includes (Freeze et al. 2014, Section 1):

- FEP identification – the development and classification of a comprehensive list of FEPs that cover the entire range of phenomena that are potentially relevant to the long-term performance of a repository system, and
- FEP screening – the specification of a subset of important FEPs that individually, or in combination with other FEPs, contribute to long-term performance of a repository system.

The identification of a set of FEPs for a range of generic disposal systems being investigated by the DOE-NE UFD Campaign is documented in Freeze et al. (2010) and Freeze et al. (2011). The UFD FEP list derives from prior FEP analyses, such as those summarized in the NEA International FEP Database (NEA 1999b, NEA 2006) and other earlier FEP lists, e.g. SNL (2008).

These generic UFD FEPs were modified to produce a set of DBD FEPs. The modifications included: (1) re-organizing the UFD FEPs in accordance with a new organizational structure, the FEP classification matrix (Freeze et al. 2014, Sections 2 and 3), and (2) creating a set of DBD-specific FEPs from the generic matrix-based FEPs. The resulting DBD FEPs are listed in Appendix E.

In addition to the identification of DBD FEPs, a preliminary screening of the DBD FEPs is also documented in Appendix E. FEP screening may involve quantitative analyses and/or reasoned arguments. The important FEPs (i.e., those with significant impact on long-term repository performance) must be included in (screened in) the post-closure PA model. The exclusion of a FEP from the PA model (e.g., by low probability, by low consequence, or by inconsistency with regulation) must be supported by a defensible rationale or justification. The preliminary screening decisions in Appendix E, provided for each Associated Process of each FEP, are based on the non-site-specific DBD reference case documented in Section 4, and on the PA model implementation described in Section 5.2.3. The FEP screening decisions will be iteratively updated as design and site-specific information becomes more refined. For this preliminary, generic DBD reference case, five categories of screening decisions are used:

- **Included** – A FEP that is likely to be screened in to the PA model, based on the reference design, engineered and/or natural barriers.
- **Included (Deferred)** – A FEP that is likely to be screened in to the PA model, but the implementation is deferred to a future iteration of the PA model.
- **Excluded (Low Consequence)** – A FEP that is likely to be screened out of the PA model because it is not expected to have a significant impact on post-closure repository performance, based on the reference design/design factors, site selection criteria, and/or engineered and/or natural barriers.
- **Excluded (Low Probability) –** A FEP that is likely to be screened out of the PA model because it is expected to have a low probability of occurrence based on the reference design/design factors, site selection criteria, and/or engineered and/or natural barriers.
- **Excluded (by regulation) –** A FEP that is likely to be screened out of the PA model because it is inconsistent with conditions expected to be specified in the regulations.

FEPs and scenarios are components of the safety case that provide a logical method for organizing both existing knowledge and the needed R&D according to their potential effect on repository performance, one of the key metrics for prioritizing research (Freeze et al. 2014, Section 1). The FEP structure supports logic, consistency, clarity, traceable documentation of decisions, and comprehensiveness (NEA 2013), and affords a systematic hierarchy for organizing work across multiple disciplines.

5.2.2 Scenario Development

The role of scenario development within a post-closure PA methodology is described in detail in Freeze et al. (2013a, Sections 4.2.1 and 4.2.3).

A scenario is "a well defined, connected sequence of features, events, and processes that can be thought of as an outline of a possible future condition of the repository system. Scenarios can be undisturbed, in which case the performance would be the expected, or nominal, behavior for the system. Scenarios can also be disturbed, if altered by disruptive events." (NRC 2003, Section 3)

Scenario development includes (Freeze et al. 2013a, Section 4.2.3):

- Scenario construction – formation of scenarios from the retained (included) FEPs, as appropriate, and
- Scenario screening – screening of scenarios using the same criteria applied to FEP screening to identify any scenarios that can be excluded from the PA model.

For any repository system, a large number of possible futures (scenarios) exist, due to uncertainties such as those caused by the randomness or unpredictability of certain events, the natural variability of geological media and the biosphere, the lack of complete characterization for geological processes over large spatial scales and long times, and the limited possibility of accurately forecasting human habits. Scenario screening limits the modeling of the broad possible evolutions of the system to a handful of likely scenarios (e.g. undisturbed performance, climate evolution impacts, human intrusion consequences, early feature/component failures) (NEA 2013, Section 5).

An informal scenario construction and screening was performed in Freeze et al. (2013a, Sections 4.2.3.3 and 4.2.3.3.4) for a PA model of a generic DBD system. Scenario construction considered the following simplified scenarios:

1. **Undisturbed Scenarios**
    a. **Transport in the Borehole** – Fluid flow (liquid or gas phase) up the borehole transports radionuclides to a shallow aquifer (or to the surface) from which they are pumped to the biosphere. This scenario requires sufficiently high permeability within the borehole (i.e., in the seals and plugs) and a sustained upward gradient in hydrologic potential for it to occur. Vertical permeability within the borehole in the EZ may be relatively high. Rapid degradation of the waste packages stacked within the borehole is assumed. Vertical permeability within the borehole seal zone above the level of waste emplacement will be engineered to be very low, significantly reducing fluid flow and creating diffusion-dominated transport conditions in this portion of the borehole. Some upward gradient in hydrologic potential (i.e., advection) within the borehole could result from (a) ambient

hydrologic conditions, (b) thermal pressurization of fluid within the EZ from waste heat, (c) buoyancy of heated fluid within the EZ, or (d) thermo-chemical reactions that release water and/or gases within the EZ. The duration of the thermal pulse is small compared to the regulatory period and occurs during the time when the upper sealing system is likely to be the most robust.

b. **Transport in the DRZ around the Borehole –** Fluid flow (liquid or gas phase) up the annulus of disturbed rock surrounding the borehole transports radionuclides to a shallow aquifer (or to the surface) from which they are pumped to the biosphere. This scenario requires sufficiently high and vertically-connected permeability in the DRZ surrounding the borehole and a sustained upward gradient in hydrologic potential for it to occur. Vertical permeability within the DRZ may be higher than that of the surrounding intact rock or intact sealing system components. An upward gradient in hydrologic potential within the DRZ could result from (a) ambient hydrologic conditions, (b) thermal pressurization of fluids within the EZ or DRZ from waste heat, (c) buoyancy of heated fluids within the EZ or DRZ, or (d) thermo-chemical reactions that release water and/or gases within the EZ or DRZ.

c. **Transport in Surrounding Rock Away from the Borehole –** Fluid flow (liquid or gas phase) up through the crystalline basement and sedimentary cover transports radionuclides to a shallow aquifer from which they are pumped to the biosphere. This scenario requires sufficiently high permeability within fracture zones and/or faults in the crystalline basement and sedimentary cover and a sustained upward gradient in hydrologic potential for it to occur. Given the low vertical permeability of the crystalline basement rocks and the stratified sedimentary cover, a through-going feature such as an interconnected group of fracture zones or faults would be required to conduct significant quantities of fluid to a shallow aquifer.

2. Defective Engineered Barrier Scenarios

a. Defective Waste Package
b. Defective EZ Buffer/Backfill
c. Defective Sealing System

Enhanced failure and/or degradation of these engineered features/components may be included in the undisturbed scenario, thus eliminating the need for consideration of explicit defective engineered barrier scenarios. These scenarios have the same three transport pathways as the undisturbed scenario but the consequences conditional on failed engineered barriers are likely to be larger because of their condition. For example, defective borehole seals could result in increased vertical flow through the borehole and DRZ during the thermal pulse period as well as increased lateral connectivity between the borehole and surrounding intact host rock.

3. Disturbed Scenarios

a. Human Intrusion
b. Seismic Activity
c. Igneous Event
d. Climate Change / Glaciation

These disturbed scenarios are caused by external events. During site selection, some of these disturbed scenarios may be excluded (see Section 3.2.1.2). For example, avoiding seismically-active or volcanically-active locations can reduce the probability of occurrence of these scenarios to below regulatory thresholds.

These simplified scenarios do not necessarily represent all aspects of undisturbed (expected or nominal) and/or disturbed conditions for DBD, but they do provide a basis for preliminary post-closure DBD system evaluations and sensitivity analyses. They also provide a convenient starting point for future FEP analysis, scenario development, and PA modeling as site- and/or design-specific information becomes available.

The focus of this preliminary iteration of the DBD safety case is on feasibility of the DBD concept. Disturbed scenarios, including human intrusion, are highly dependent on site-specific information and regulatory considerations. Therefore, evaluations of all but the undisturbed scenarios are deferred to future iterations of the DBD safety case. Similarly, consideration of the possible post-closure effects of a waste package stuck above the EZ is also deferred to a future iteration.

For the DBD PA model analyses in Section 5.2.6, the undisturbed scenarios identified above are combined into a single undisturbed scenario. Some aspects of the defective engineered barrier scenarios are incorporated into the undisturbed scenario through sensitivity analysis parameter variations (Section 5.2.7).

The undisturbed scenario includes the following:

- Radionuclide inventory that consists entirely of Cs and Sr capsules aged to the year 2050.
- Defective waste packages that are assumed to fail instantaneously after borehole closure (i.e., at the beginning of the post-closure period).
- Defective sealing system effects are partially accounted for in the characterization of the DRZ and in seal and DRZ parameter variations in sensitivity analyses.
- Undisturbed conditions with the potential for advective and diffusive aqueous-phase transport. Consideration of gas-phase and/or colloidal transport is deferred to a future iteration of the DBD safety case.
- Consideration of undisturbed transport up the borehole, up the DRZ around the borehole, and into the surrounding rock away from the borehole. The transport pathway includes a 534-m emplacement zone and a 2,000-m seal zone under chemically reducing conditions.

The possibility of a continuous, high-permeability transport pathway into the surrounding rock away from the borehole is screened out (deferred) due to the low permeability of basement crystalline rock relative to the borehole/DRZ pathways and the low probability of a continuous 4,000-to-5,000-m fracture or fault from the deep basement to a hypothetical overlying aquifer.

Details of the implementation of the undisturbed scenario in the DBD PA model are described in Sections 5.2.3 and 5.2.6, based on the parameter values in Section 4.

5.2.3 Model Development

5.2.3.1 Conceptual Model

The conceptual framework for this preliminary generic post-closure DBD PA model focuses on the components of the engineered barrier (Section 4.2) and the natural barrier (Section 4.3) in the undisturbed scenario (Section 5.2.2). Key characteristics of and processes occurring (i.e., FEPs) in each of the components of the engineered and natural barriers are summarized in Table 5-4.

For a complete description of the bases for these representations see Sections 4.2 and 4.3; for a detailed description of the numerical representation of these components see Sections 5.2.3.5 through 5.2.3.7. Because the PA model does not consider the biosphere (Section 4.4), the performance metric is radionuclide concentration rather than dose. Conceptual models of the biosphere and of disturbed scenarios are likely to be site-specific. As the site-selection process proceeds, the impact of disturbed scenarios and the behavior of the biosphere will be considered.

Table 5-4. Conceptual Representation of the Engineered and Natural Barriers in the DBD PA Model

Feature / Component	Key Characteristics	Key FEPs Included in DBD PA Model
	Radionuclides	
Inventory	^{135}Cs, ^{137}Cs, ^{90}Sr	Radionuclide decay, heat generation[1]
	Engineered Barriers	
Waste Form	$CsCl$, SrF_2	Radionuclide decay, waste form dissolution
Waste Package	Carbon steel	Waste package breach
EZ Buffer/Backfill Fluid	High density brine	Radionuclide advection, diffusion, decay
EZ Liner	Steel	Not represented in PA
EZ Cement Plugs	Low permeability	Radionuclide advection, diffusion, decay
SZ Bentonite Seals	Low permeability, High sorption capacity	Radionuclide advection, diffusion, sorption, decay
SZ Cement Plugs	Low permeability	Radionuclide advection, diffusion, decay
SZ Ballast	Crushed rock/sand	Radionuclide advection, diffusion, decay
UBZ Cement Plugs	Low permeability	Not represented in PA
UBZ Ballast	Crushed rock/sand	Not represented in PA
UBZ Cement Plug	Low permeability	Not represented in PA
UBZ Liner	Steel	Not represented in PA
	Natural Barriers	
Crystalline Basement	Sparsely fractured, Low permeability	Radionuclide advection, diffusion, sorption, decay
DRZ	Enhanced permeability	Radionuclide advection, diffusion, sorption, decay
Sediments	Thick, layered sequence	Not represented in PA

[1] Includes decay heat from ^{137m}Ba and ^{90}Y (see Section 4.2.2).

5.2.3.2 Numerical Implementation

DBD PA, comprising a single deterministic simulation and a suite of probabilistic simulations for uncertainty and sensitivity analysis, was implemented within the Generic Disposal System Analysis framework (Mariner et al. 2015).

PFLOTRAN, a massively parallel multiphase flow and reactive transport code (Hammond et al. 2011; Hammond et al. 2014; Lichtner and Hammond 2012), was used to simulate flow and transport in the deep borehole disposal system. PFLOTRAN solves the non-linear partial differential equations describing non-isothermal multi-phase flow, reactive transport, and geomechanics in porous media. Parallelization is achieved through domain decomposition using the Portable Extensible Toolkit for Scientific Computation (PETSc) (Balay et al. 2013). PETSc provides a flexible interface to data structures and solvers that facilitate the use of parallel computing. PFLOTRAN is written in Fortran 2003/2008 and leverages state-of-the-art Fortran programming (i.e. Fortran classes, pointers to procedures, etc.) to support its object-oriented design.

The suite of probabilistic simulations was run using the DAKOTA toolkit, an analysis package for uncertainty quantification, sensitivity analysis, optimization, and calibration in a parallel computing environment (Adams et al. 2013a; 2013b). Given parameter ranges and distributions, DAKOTA performs Latin Hypercube Sampling, inserts sampled values into the PFLOTRAN input deck, and calls PFLOTRAN. It also provides tools for quantifying uncertainty and parameter sensitivity after the suite of simulations is complete.

5.2.3.3 Model Domain and Discretization

The PA model domain (Figure 5-2) is two-dimensional (2-D) axisymmetric with a radius of approximately 1,000 m (923.627 m), and a height of 2,534.08 m. The base of the 534.08-m long EZ lies at 5,000 m below the land surface; the model domain extends 1,000 m below and 1,000 m above the EZ. The EZ contains 108 4.76-m long waste packages (which consist of a 3.76 m length of waste – 6 layers of Cs/Sr capsule 3-packs, and a 1.0 m length of associated hardware – a fishing neck and an impact limiter) and 2 10-m long cement plugs, which sit above the 40th and 80th waste packages. To minimize peak temperature in the EZ, the 74 Cs waste packages (identified as wp0 through wp73) are emplaced in the lower portion of the EZ, overlain by the 34 Sr waste packages (identified as wp74 through wp107), which are hotter. The EZ liner is not modeled. Instead, the entire annular space between the waste packages and the borehole wall (DRZ) is modeled as a brine-filled EZ annulus.

The PA model includes only the lower portion of the seal zone (see Figure 4-2), a 1,000-m interval consisting of alternating lengths of cement, bentonite, and ballast (Table 4-7), extending from the top of the uppermost waste package in the EZ to the top of the model domain. Two 100-m-long cement plugs sit at the top and bottom of the lower seal zone; five additional cement plugs (each 100-m long) separate alternating 50-m lengths of bentonite seal and ballast material (Table 4-7). A narrow DRZ (0.15 m in width) envelopes the entire length of the borehole. PA model dimensions are summarized in Table 5-5.

Discretization within the EZ corresponds to waste package and borehole dimensions. In the radial direction beyond the DRZ, cell width gradually increases to 5 m. Above and below the EZ, cell height is 5 m.

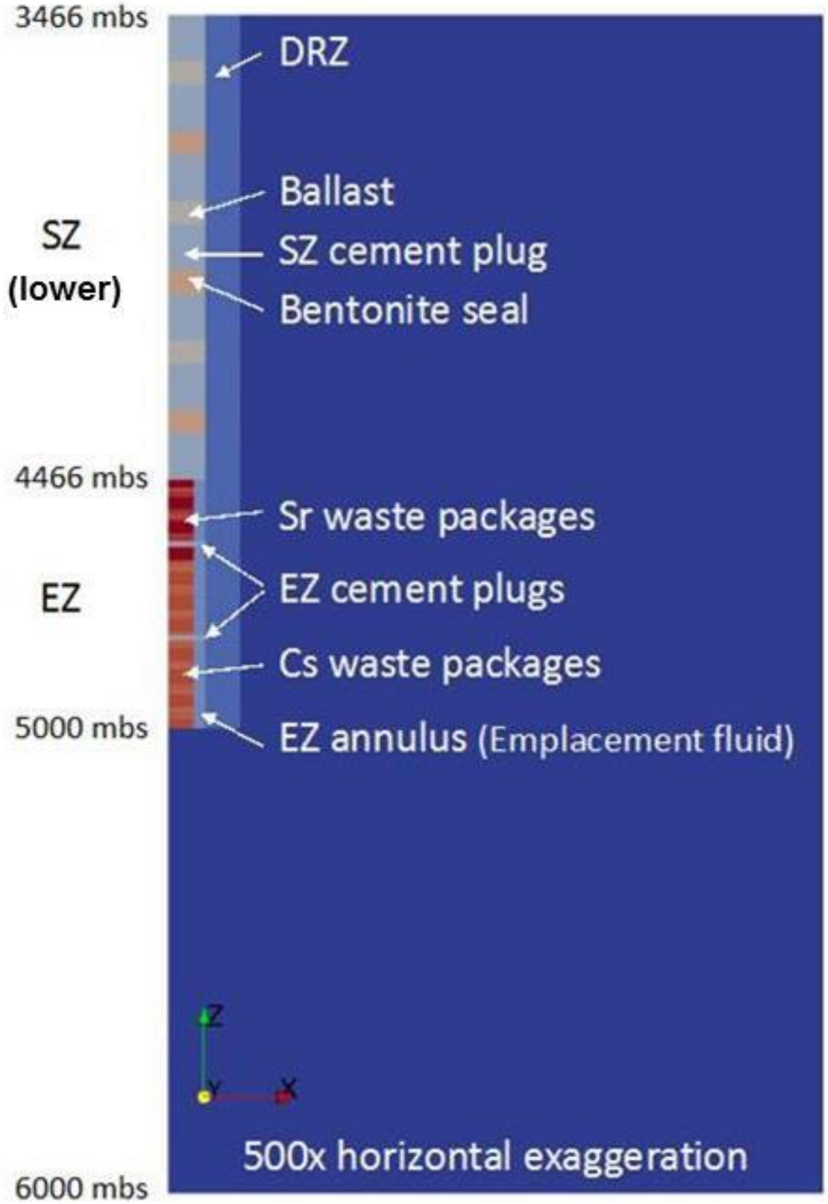


Figure 5-2. A Portion of the DBD PA Model Domain at 500x Horizontal Exaggeration

Table 5-5. DBD PA Model Dimensions

Feature	Component	No. of Units	Diameter (m)	Length (m)	Depth (mbs)[2]
Model Domain – Top					3,465.92
Crystalline Basement – Top			923.627	2,534.08	3,465.92
DRZ – Top			0.62	1,534.08	3,465.92
Seal Zone (Lower) – Top			0.32	1,000.00	3,465.92
Seal Zone (Lower)	SZ Ballast	3	0.32	50.00	
Seal Zone (Lower)	SZ Bentonite Seals	3	0.32	50.00	
Seal Zone (Lower)	SZ Cement Plugs	7	0.32	100.00	
Seal Zone – Bottom			0.32		4,465.92
Emplacement Zone – Top			0.32	534.08	4,465.92
Emplacement Zone	Waste Packages	108	0.22	3.76	
Emplacement Zone	WP Hardware[1]	108	0.22	1.00	
Emplacement Zone	EZ Cement Plugs	2	0.32	10.00	
Emplacement Zone	EZ Annulus (Emplacement Fluid)		0.32	534.08	
Emplacement Zone – Bottom			0.32		5,000.00
DRZ – Bottom			0.62		5,000.00
Crystalline Basement – Bottom			923.627		6,000.00
Model Domain – Bottom					6,000.00

[1] A 1-m tall cell separates each waste package from the next and is assigned properties representing the fishing neck of the waste package below and the impact limiter of the waste package above. Where fishing neck and impact limiter are not adjacent (at top and bottom of EZ; adjacent to cement plugs), the impact limiter is 0.7-m long and the fishing neck 0.3-m long.

[2] Meters below surface

5.2.3.4 Initial and Boundary Conditions

The initial and boundary conditions for the PA model are based on: (1) a 4,000-m thickness of crystalline basement and a 2,000-m thickness of overlying sedimentary units; (2) a geothermal heat flux of 60 mW/m^2 and an average annual surface temperature of 10°C; and (3) no regional head gradient. Note that the actual PA model domain only includes the lowermost 2,534 m (from a depth of 3,466 m to a depth of 6,000 m) of the crystalline basement.

Initial conditions specified are pressure, temperature, and radionuclide concentrations. Initial pressures and temperatures applied throughout the PA model domain (2-D axisymmetric) were calculated in a one-dimensional (1-D) model domain extending from the land surface to 6,000 m depth. Within the 1-D domain, a liquid flux of 0 m/s and an energy flux of 60 mW/m^2 were maintained at the base, and a constant temperature (10°C) and pressure (approximately atmospheric) were held at the top. The 1-D model was run to 10^6 years in order to develop a geothermal temperature gradient and a hydrostatic pressure gradient. Initial concentrations of all radionuclides (^{90}Sr, ^{137}Cs, and ^{135}Cs) in all cells of the PA model domain are 10^{-20} mol/L.

Boundary conditions must be set for the top, bottom, and radial boundaries of the PA model domain. At the top and radial boundaries, initial pressures and temperatures are held constant. At the bottom boundary, zero fluid flux and an energy flux of 60 mW/m^2 are maintained. Radionuclide concentrations are held such that any fluid entering the model domain contains 10^{-20} mol/L of each radionuclide, while fluid exiting the model domain is allowed to carry with it ambient concentrations. Diffusive flux across boundaries is disallowed by specifying a zero concentration gradient.

5.2.3.5 Waste Package Heat Source Term

Each waste package is modeled as a transient heat source. The energy (watts per waste package) entering the PA model domain is updated periodically according to values in a lookup table. The initial value assumes disposal in 2050, at which time the heat output of each of the 74 Cs waste packages is 978 W, and that of each of the 34 Sr waste packages is 1,229 W (based on watts per capsule presented in Figure 4-4). Between times specified in the lookup table, the energy source term is linearly interpolated.

5.2.3.6 Waste Package Breach and Radionuclide Source Term

In the current DBD PA model, waste package corrosion and subsequent waste package breach are not represented mechanistically. Instead, waste package breach time is an input parameter. For the deterministic PA simulation, a waste package breach time of one year after closure is assumed. For the probabilistic PA simulations, waste package breach time is sampled between 1 year and 100 years. In the future, it is planned to model waste package corrosion mechanistically.

At the time of waste package breach, the entire (decayed) inventory of ^{137}Cs, ^{135}Cs, and/or ^{90}Sr in a waste package is assumed to be present in solution within the waste package cell, based on the reference case assumption of unlimited solubility of Cs and Sr in the EZ (Section 4.3.2.6). This assumption is conservative because it does not account for the time it takes to breach the double-walled Cs and Sr capsules contained within the waste packages, and because it disregards the relatively low solubility of the SrF_2 waste form.

Instantaneous dissolution of the entire 18-capsule inventory of ^{135}Cs and ^{137}Cs (in 2050) in a waste package into the void space of the waste package results in a dissolved Cs concentration (source term) of approximately 0.83 mol/L, well below the solubility limit of ≥ 10 mol/kg (Section 4.2.3). Instantaneous dissolution of the entire 18-capsule inventory of ^{90}Sr (in 2050) in a waste package results in a dissolved Sr concentration of approximately 0.25 mol/L, approximately 100 times the solubility limit of 2.4×10^{-3} mol/kg in Section 4.2.3.

Unlimited solubility for Cs and Sr is also assumed through the PA model domain beyond the EZ.

5.2.3.7 Material Properties

Material parameters for use in the deterministic PA simulation and parameter ranges for use in the probabilistic PA simulations were chosen on the basis of the information presented in Sections 4.2 and 4.3. Deterministic parameter values (Table 5-6) are either a representative value or the mean of the range sampled for probabilistic simulations. Sampled ranges (Table 5-7) are either from the literature or an attempt to capture the effects of material degradation. Parameter choices requiring further explanation are discussed in the remainder of this section.

Table 5-6. Numerical Representation of Materials in the Deterministic PA Simulation

Material	k (m^2)	ϕ (--)	τ[1] (--)	D_e[1] (m^2/s)	Thermal Cond. (W/m°K)	Heat Capacity (J/kg°K)	Density (kg/m^3)	Sr K_d (L/kg)	Cs K_d (L/kg)
Emplacement Zone									
Waste Package	$1x10^{-16}$	0.43	1.0	$4.30x10^{-10}$	17	500	7850	0	0
Fishing Neck, Impact Limiter	$1x10^{-16}$	0.43	1.0	$4.30x10^{-10}$	17	500	7850	0	0
EZ Annulus (Buffer/Backfill Fluid)	$1x10^{-12}$	0.99	1.0	$9.90x10^{-10}$	0.58	4192	1100	0	0
Cement Plug	$1x10^{-18}$	0.175	0.175	$2.89x10^{-11}$	1.7	900	2700	0	0
Seal Zone									
Cement Plug	$1x10^{-18}$	0.175	0.175	$2.89x10^{-11}$	1.7	900	2700	0	0
Bentonite Seal	$1x10^{-18}$	0.45	0.45	$2.03x10^{-10}$	1.3	800	2700	1525	560
Ballast	$1x10^{-14}$	0.20	0.20	$4.00x10^{-11}$	2.0	800	2700	0	0
Host Rock									
Crystalline Rock	$1x10^{-18}$	0.005	0.20	$1.00x10^{-12}$	2.5	880	2700	1.7	22.5
DRZ	$1x10^{-16}$	0.005	0.20	$1.00x10^{-12}$	2.5	880	2700	1.7	22.5

[1] The calculation of effective diffusion coefficient (D_e), tortuosity, and τ is described in Section 4.3.2.3.

Table 5-7. Sampled Parameters and Ranges for Probabilistic PA Simulations

Parameter	Range	Units	Distribution
Bentonite k	$10^{-20} – 10^{-16}$	m^2	log uniform
Cement k	$10^{-20} – 10^{-16}$	m^2	log uniform
DRZ k	$10^{-18} – 10^{-15}$	m^2	log uniform
WP τ	0.01 – 1.0	--	log uniform
Bentonite ϕ	0.40 – 0.50	--	uniform
Cement ϕ	0.15 – 0.20	--	uniform
DRZ ϕ	0.005 – 0.01	--	uniform
WP Breach Time	1 – 100	yr	uniform
Cs K_d bentonite	120 – 1000	L/kg	uniform
Sr K_d bentonite	50 – 3000	L/kg	uniform
Cs K_d crystalline	5 – 40	L/kg	uniform
Sr K_d crystalline	0.4 – 3	L/kg	uniform
Cs K_d DRZ	5 – 40	L/kg	uniform
Sr K_d DRZ	0.4 – 3	L/kg	uniform

Waste Package: Each waste package is represented by a single grid cell, which is assigned material properties representative of the waste package and all its contents. All such values are estimates. The permeability of 10^{-16} m^2 represents a degraded waste package. Porosity was estimated by summing void volumes within the waste package after waste form dissolution. Thermal properties of stainless steel were used; these are considered representative of the waste package materials (carbon steel exterior containing stainless steel capsules) during the thermal pulse due to decay heat. The thermal conductivity of stainless steel (17 $Wm^{-1}K^{-1}$) falls between that of carbon steel (43 $Wm^{-1}K^{-1}$) and its corrosion products (e.g., Fe_3O_4, 5 $Wm^{-1}K^{-1}$) (Shelton 1934; Takeda et al. 2009). Fishing necks and impact limiters were given the same material properties as the waste package proper.

EZ Annulus (Buffer/Backfill Fluid): The EZ annulus region, containing dense brine, was assigned a porosity of 0.99 and a permeability of 10^{-12} m^2. (Permeability higher than 10^{-12} m^2 required time steps that were too small to effectively complete the simulations).

EZ and SZ Cement Plug: Cement plugs in good condition could have permeability as low as 10^{-20} or 10^{-21} m^2 (Sections 4.2.5.2 and 4.2.6.2). Because cement in the EZ and SZ may be subject to thermal, chemical, and/or mechanical degradation, sampled permeability ranges extend to 10^{-16} m^2 in order to capture the potential effects of degradation on permeability.

SZ Bentonite Seal: Like a cement plug, a bentonite seal in good condition could have permeability as low as 10^{-20} or 10^{-21} m^2 (Section 4.2.6.1). However, the permeability and sorption capacity of a bentonite seal may alter over time due to chemical and mechanical processes. The sampled range of permeability and K_d values attempts to capture the potential effects of degradation on bentonite properties.

SZ Ballast: The ballast in the lower portion of the seal zone is conservatively represented as a high permeability material with no sorption capacity.

Crystalline Basement Host Rock: In sparsely fractured crystalline rock with matrix permeability on the order of 10^{-19} m^2 or less, advection through the undisturbed host rock will not be a mechanism of radionuclide transport to the accessible environment, unless fracture connectivity exists between the EZ and the accessible environment. In the current DBD PA model, explicit fracture pathways are not represented, instead sparsely fractured crystalline rock is represented with a homogeneous permeability of 10^{-18} m^2. In the future it is planned to model fractures discretely, including the scenario where a discrete fracture (or fractures) intersect the borehole.

DRZ: The DRZ is represented as a volume of uniform thickness and uniform properties surrounding the borehole. For the deterministic PA simulation, DRZ permeability is assumed to be 10^{-16} m^2, on the order of the highest values measured in URLs. For probabilistic PA simulations, DRZ permeability is a sampled parameter.

Fluid Properties: In the current PA model, fluid density is calculated as a function of temperature but not of salinity. In the future it is planned to also include the effect of salinity on fluid density.

5.2.4 Software Verification and Model Validation

Software verification ensures that the software code(s) used to perform calculations are returning the expected results given the assumed inputs. Model validation ensures that the conceptual model and its numerical implementation, including structural assumptions regarding how the system operates and data assumptions such as parameter distributions, result in a reasonably accurate representation of the system being modeled.

Portions of the PFLOTRAN code have been verified by comparison to a suite of test problems developed for the WIPP and by comparison to the reactive transport code TOUGH2 (Sevougian et al. 2014). Additional verification by comparison to analytical solutions for heat and mass conservation equations is planned for next fiscal year. Because the PFLOTRAN code is under continual development, verification is an ongoing process. Regression tests are automatically performed every time the code is updated to ensure that no inadvertent changes to the covered behavior have occurred. As new functionality is added to the code, new regression tests are added to the automated suite of tests.

Model validation includes activities such as examination of the conceptual model by people knowledgeable of the system, expert assessment of reasonable behavior of the model, validation of individual process models and couplings included in the larger PA model, validation of the data values and distributions used as input to the model, and comparison of model predictions to real world results (Sargent 2013). Because many of these validation activities are site-specific, model validation will be an ongoing process performed in conjunction with site selection and site characterization.

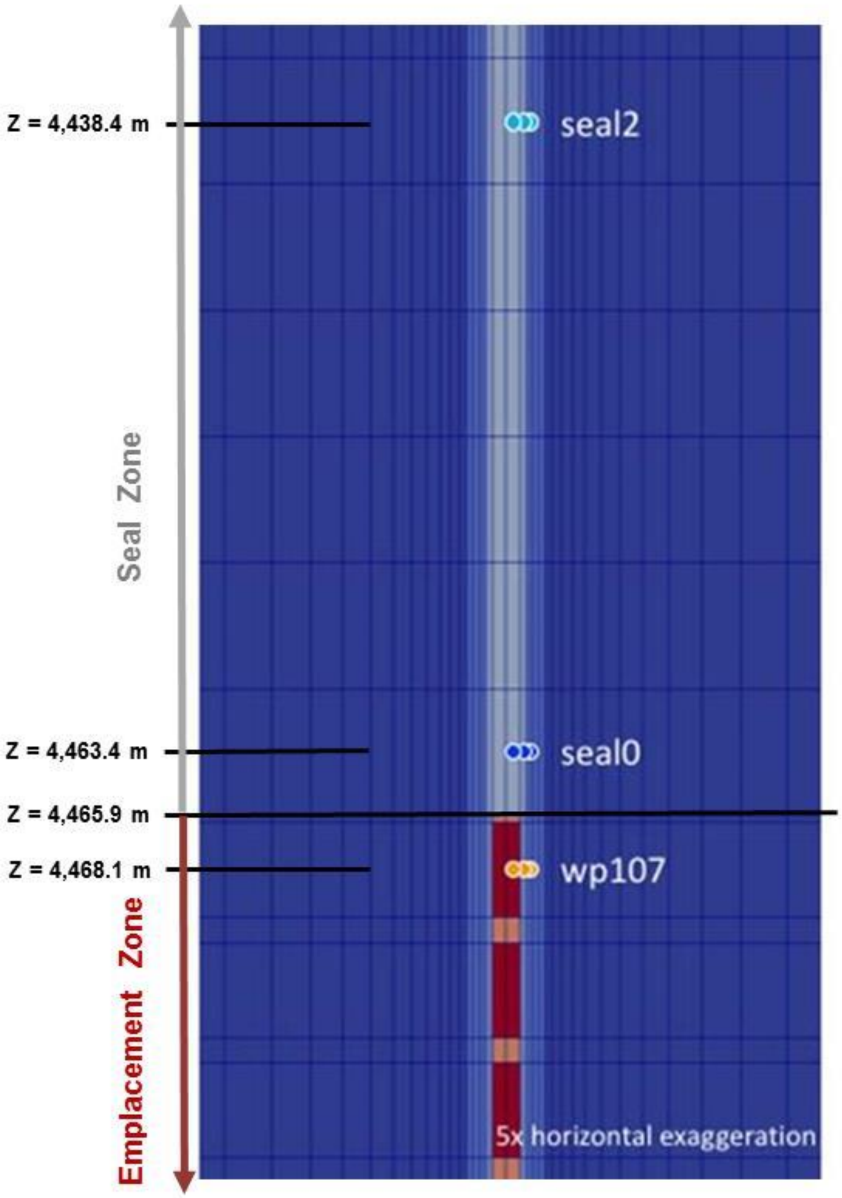
5.2.5 Subsystem and Barrier Analyses

Subsystem and barrier analyses support the safety case. However, they are deferred to a future iteration of the DBD safety case.

5.2.6 PA Model Analyses

Predicted temperatures, fluid fluxes (specific discharge), and radionuclide concentrations for 10,000,000 years were captured at several elevations within the model domain. Results are presented for the elevations of the lowest and highest Sr waste packages (wp74 and wp107, respectively) and for two locations within the 100-m cement plug at the base of the seal zone (2.5 m (seal0) and 27.5 m (seal2) above the top of the EZ) (Figure 5-3). At each of these elevations, 3 locations were observed, at the center of the waste package cell (r = 0.055 m), at the center of the borehole annulus cell (r = 0.135 m), and at the center of the first cell of the DRZ (r = 0.185 m). In the EZ, the borehole annulus cell contains the EZ annulus fluid (brine). In the seal zone, both the waste package cell and the borehole annulus cell contain seal material (cement plug).

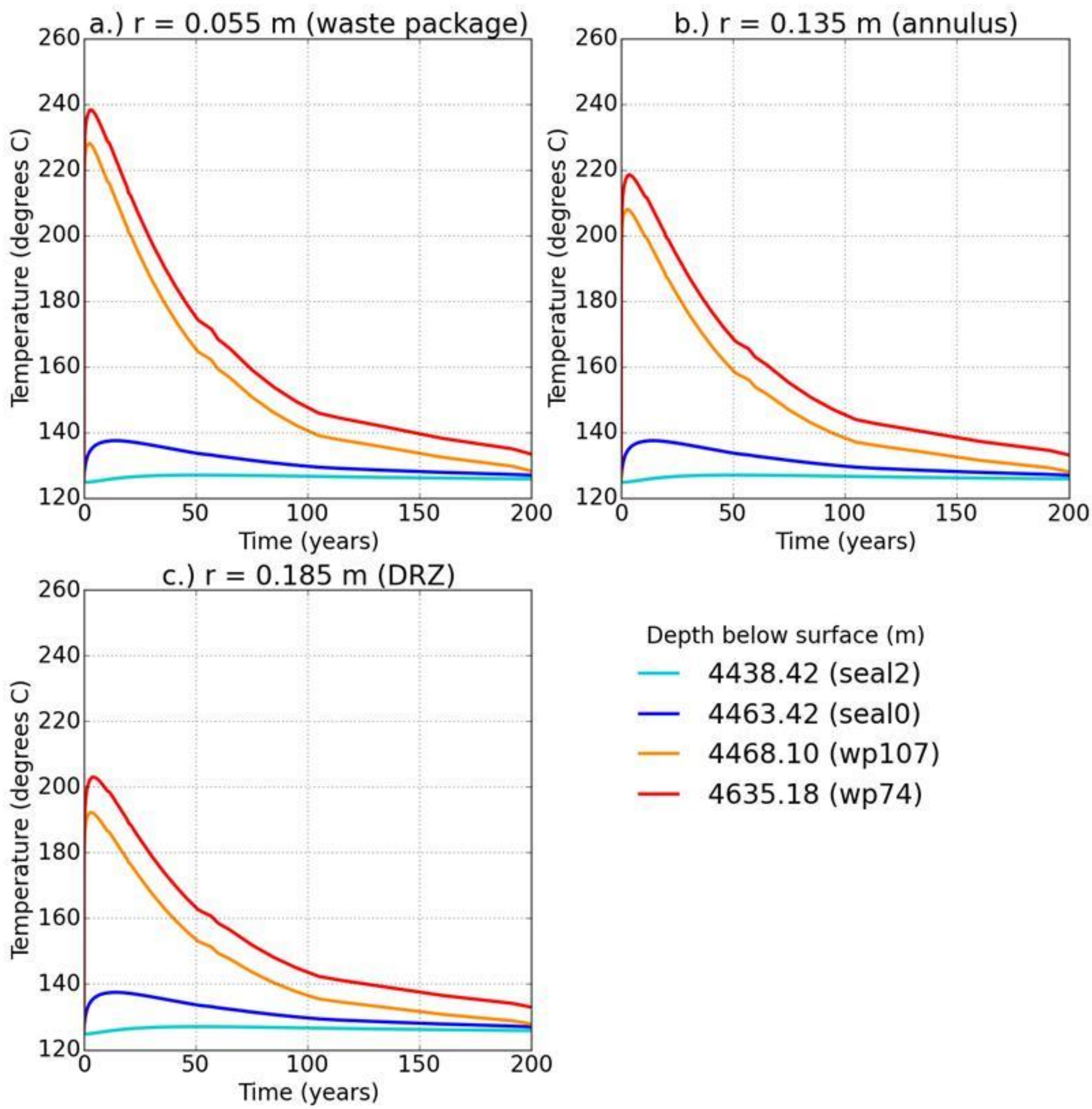
Temperatures driven by the heat of radioactive decay peak at approximately 3 years (Figure 5-4). The increase in temperature creates a thermally-driven upward fluid flux (Figure 5-5) that includes effects from fluid thermal expansion (early fluxes of very short duration that do not show in the Figure) and buoyant convection (later fluxes due to buoyancy of the hot fluid, which generally peak at the same time as temperatures, and are relevant to possible radionuclide release) (SNL 2016b, Section 5.3.2). The buoyancy-driven flux is largest in the fluid-filled EZ annulus of the borehole (Figure 5-5b); among the observation points shown, vertical specific discharge peaks at approximately 6 m/yr at the depth of wp74. Deeper in the EZ (but not shown in Figure 5-5b), vertical specific discharge peaks at approximately 10 m/yr between 3 and 10 years. Buoyancy-driven vertical specific discharge at the depth of the seal2 observation point does not exceed 10^{-4} m/yr within the cement plug (Figure 5-5a) or 0.006 m/yr within the seal zone DRZ (Figure 5-5c).



SZ Cement Plug, 27.5 m above the top of the EZ (seal2: light blue)
SZ Cement Plug, 2.5 m above the top of the EZ (seal0: dark blue)
Uppermost Sr waste package (wp107: orange)
Lowermost Sr waste package (wp74: not shown)

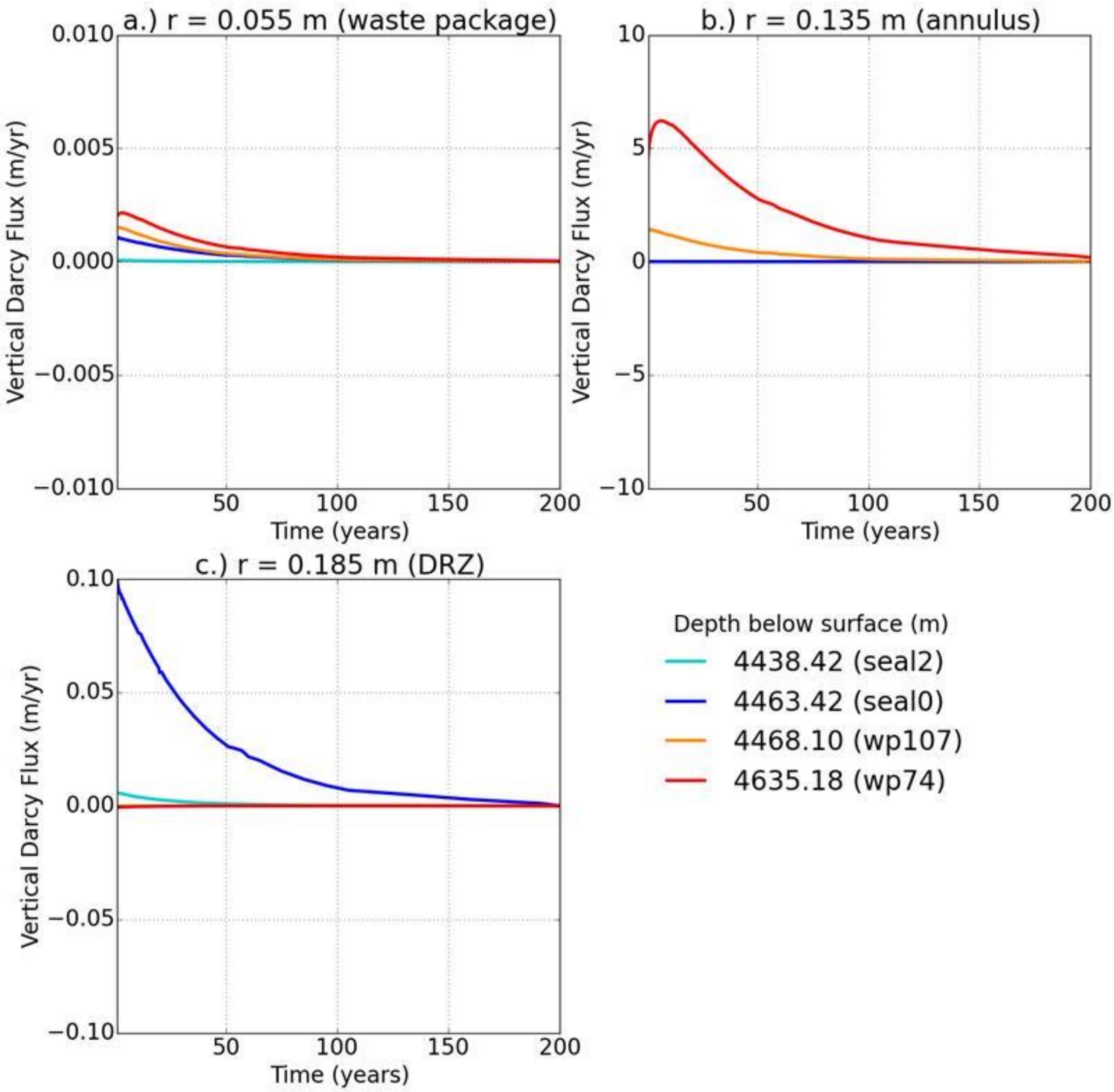
3 Radial Locations: WP (r=0.055 m), Borehole Annulus (r=0.135 m), DRZ (r=0.185 m)
[The domain is reflected at the axial (center of borehole) boundary to show a complete borehole]

Figure 5-3. Locations of Observation Points in the PA Model



3 Radial Locations: a) WP (r=0.055 m), b) Borehole Annulus (r=0.135 m), c) DRZ (r=0.185 m)
At each radius, temperature at four elevations is plotted: seal2, seal0, Sr wp107, and Sr wp74

Figure 5-4. Temperature Versus Time at Observation Points in the EZ and SZ



3 Radial Locations: a) WP (r=0.055 m), b) Borehole Annulus (r=0.135 m), c) DRZ (r=0.185 m)
At each radius, specific discharge at four elevations is plotted: seal2, seal0, Sr wp107, and Sr wp74
(Note the difference in y-axis scale)

Figure 5-5. Specific Discharge Versus Time at Observation Points in the EZ and SZ

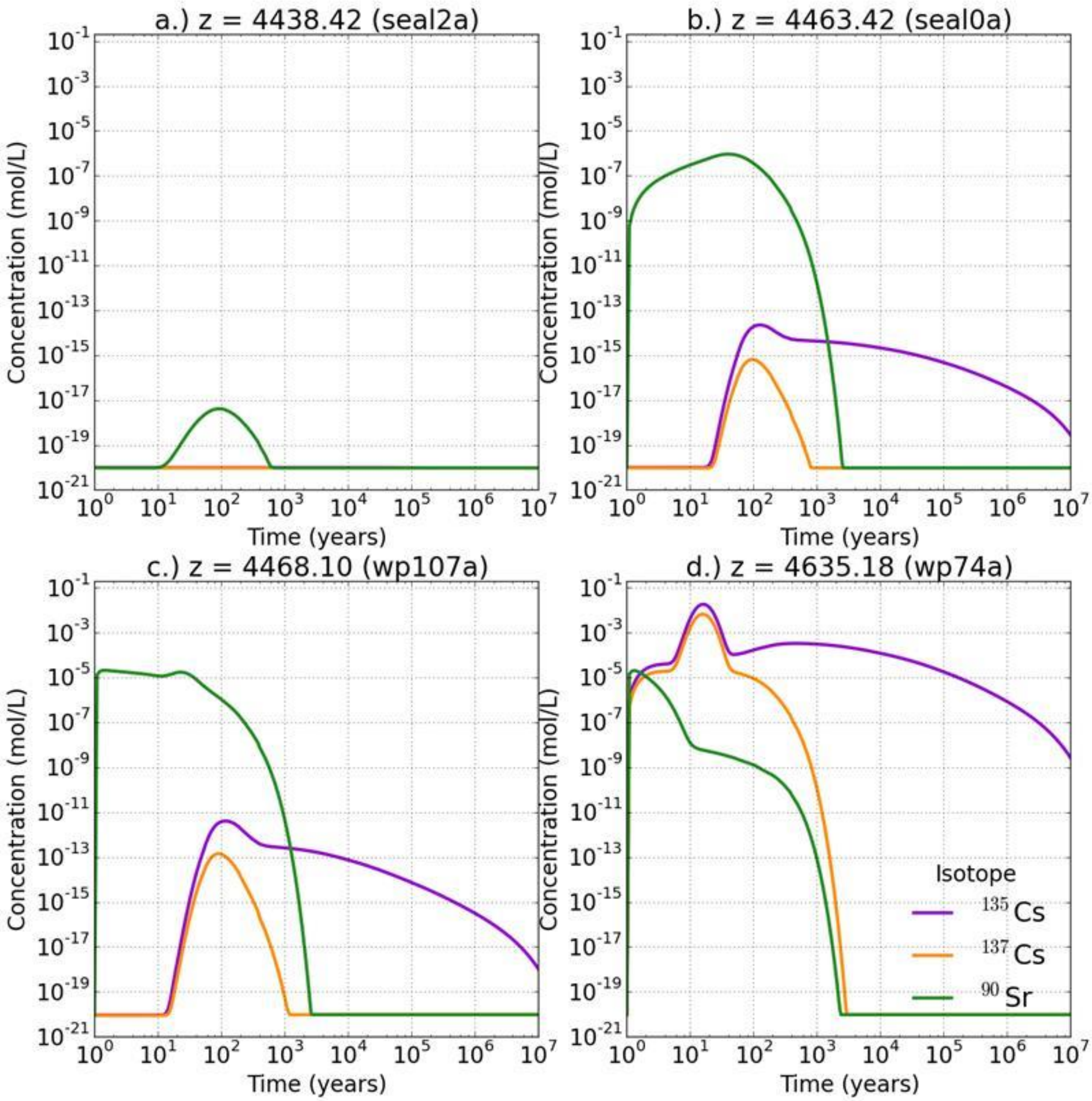
An upper bound on the distance traveled by fluids in the seal zone due to buoyancy-driven fluxes can be estimated from the relationship between linear pore velocity (*v*) and specific discharge (*q*):

$$v = q/\phi$$

where ϕ is porosity. Given a cement porosity of 0.175 and assuming a specific discharge of 10^{-4} m/yr for a period of 100 years, the distance traveled by fluids within the seal zone cement plug is not more than 0.06 m above seal2 depth. A similar calculation for the DRZ (ϕ = 0.005 and q = 0.006 m/yr) gives an upper bound on travel distance of 120 m.

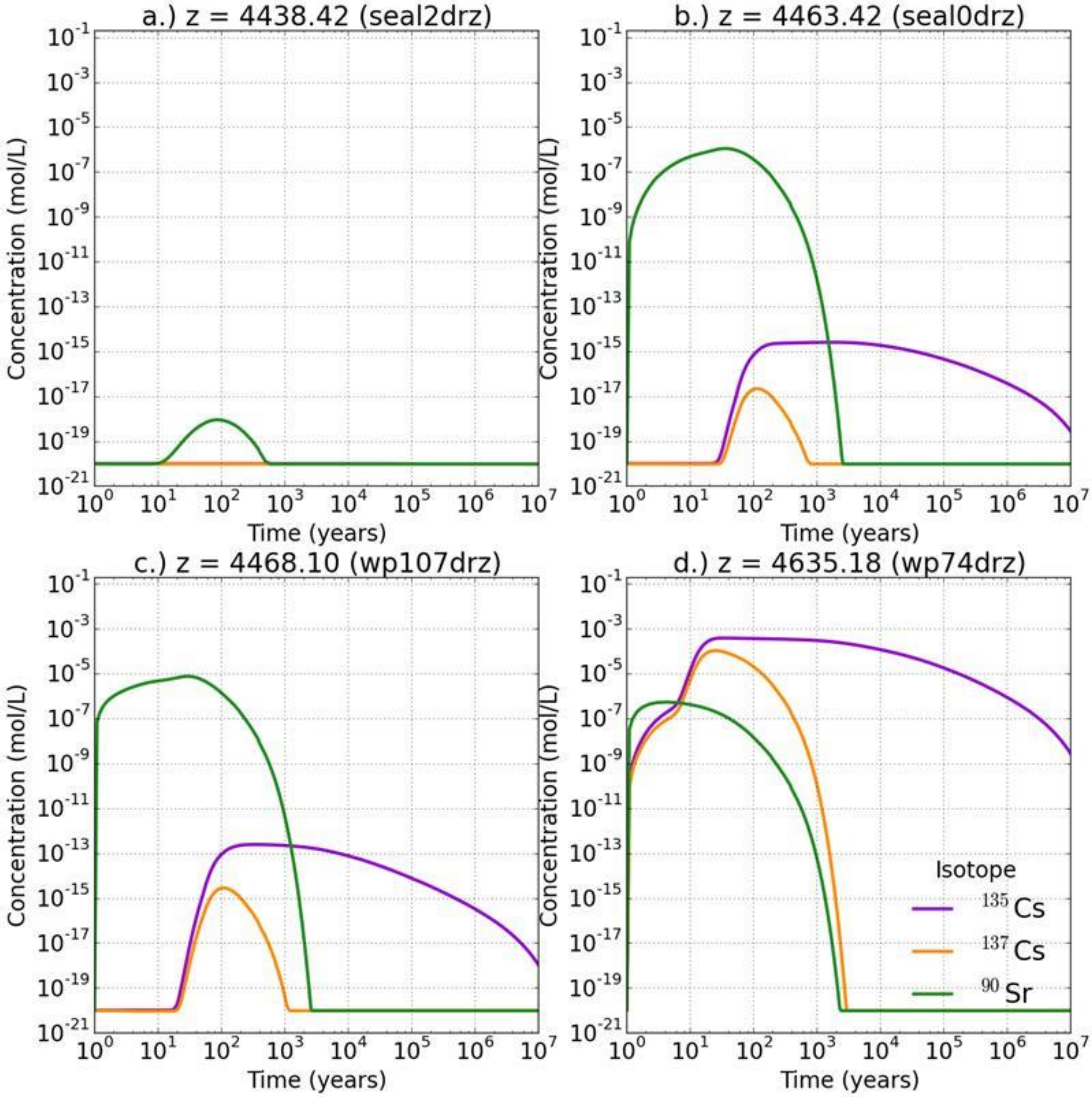
The lack of significant buoyancy-driven fluid flux in the seal zone is apparent in the predicted radionuclide concentrations within the seal zone. A very small concentration (< 10^{-17} mol/L) of ^{90}Sr travels approximately 25 m into the cement plug at the base of the seal zone (Figure 5-6); the peak concentration of ^{90}Sr in the DRZ at the same elevation is even lower (Figure 5-7). The Cs waste packages are emplaced below the Sr waste packages. Due to the longer travel distance, neither the short-lived ^{137}Cs nor the long-lived ^{135}Cs travel as far as 25 m into the seal zone through either the cement plug or the DRZ.

Figure 5-8 shows the ^{135}Cs concentrations throughout the model domain at 10,000,000 years. Most of the ^{135}Cs remains in the lower part of the EZ, where the 74 waste packages containing the Cs capsules were originally emplaced. The effects of the two 10-m long EZ cement plugs (centered at depths of ~4,805 mbs and ~4,604 mbs) on ^{135}Cs movement are also evident. Radionuclides diffuse laterally through the crystalline host rock away from the EZ. However, after 10,000,000 years, the ^{135}Cs concentration contour of 10^{-15} mol/L has only reached a radius of approximately 20 m beyond the EZ.



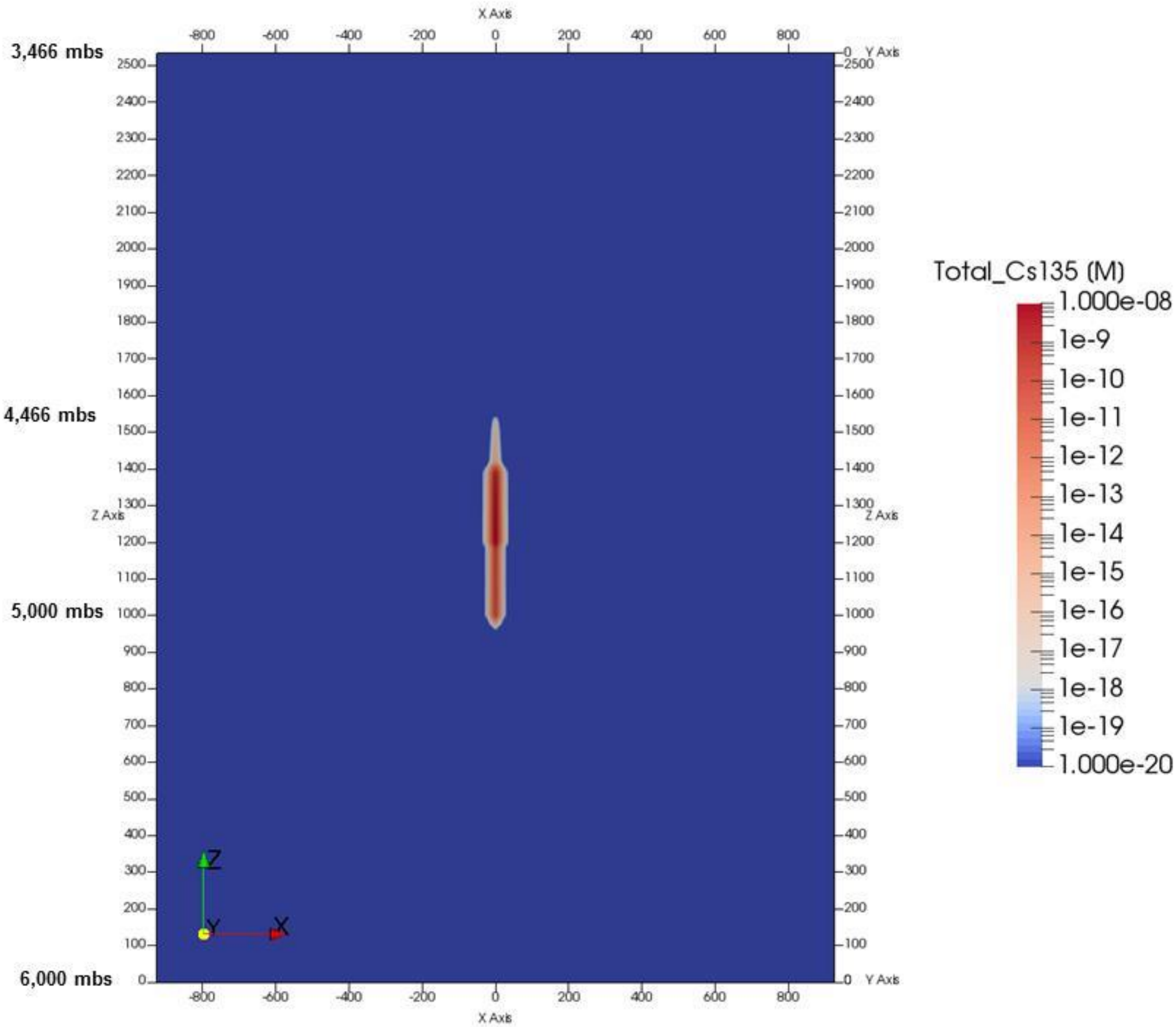
Concentrations at 4 Elevations: a) seal2, b) seal0, c) Sr wp107, and d) Sr wp74

Figure 5-6. Radionuclide Concentrations in the Borehole Annulus (r=0.135 m) in the EZ and SZ



Concentrations at 4 Elevations: a) seal2, b) seal0, c) Sr wp107, and d) Sr wp74

Figure 5-7. Radionuclide Concentrations in the DRZ (r=0.185 m) Adjacent to the EZ and SZ



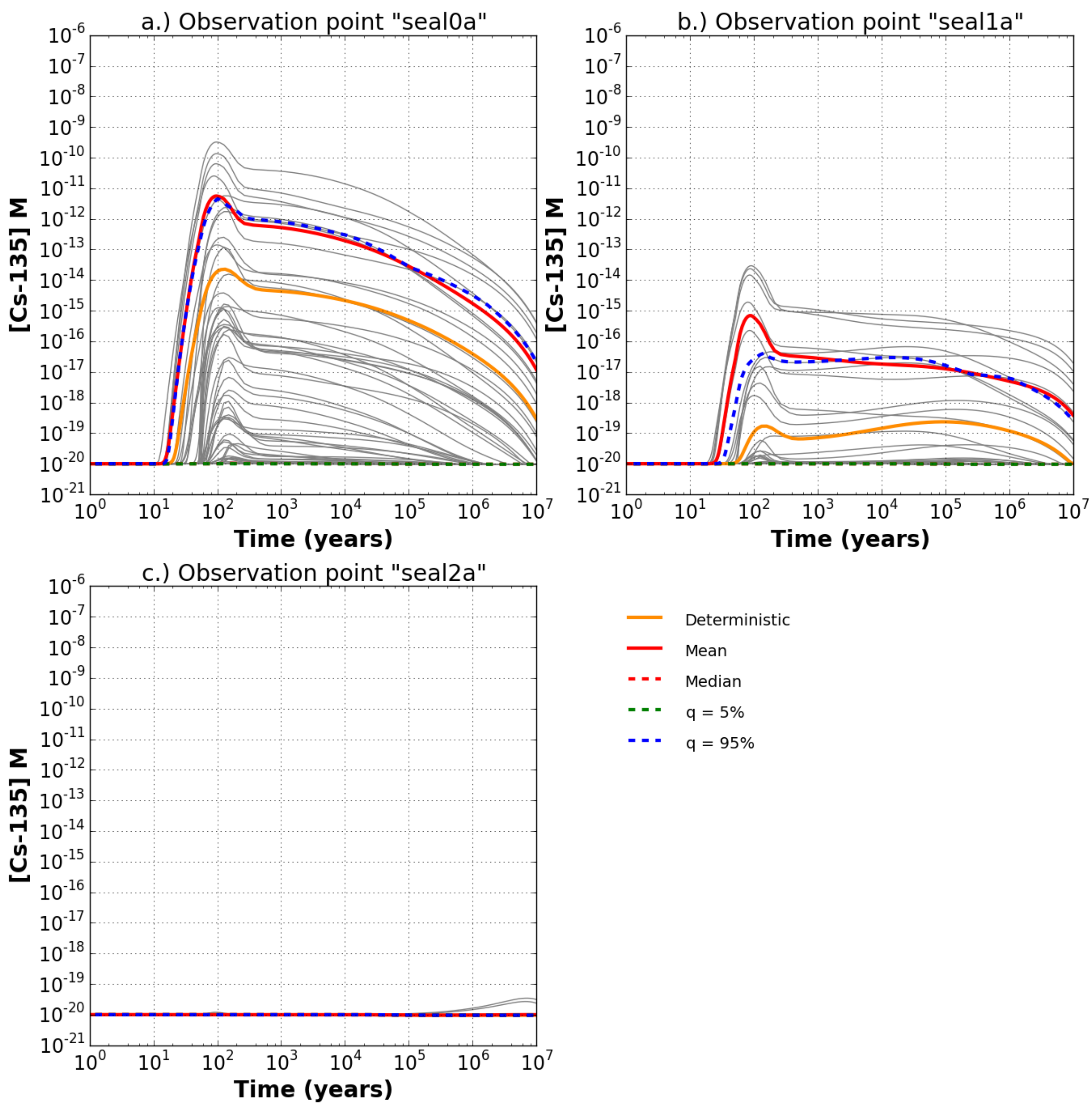
The top of the domain (z = 2,534 m) is 3,466 m below land surface.
The base of the domain (z = 0 m) is 6,000 m below land surface.
The model domain is reflected at x = 0 m.

Figure 5-8. ^{135}Cs Concentration at 10,000,000 Years

5.2.7 Uncertainty and Sensitivity Analyses

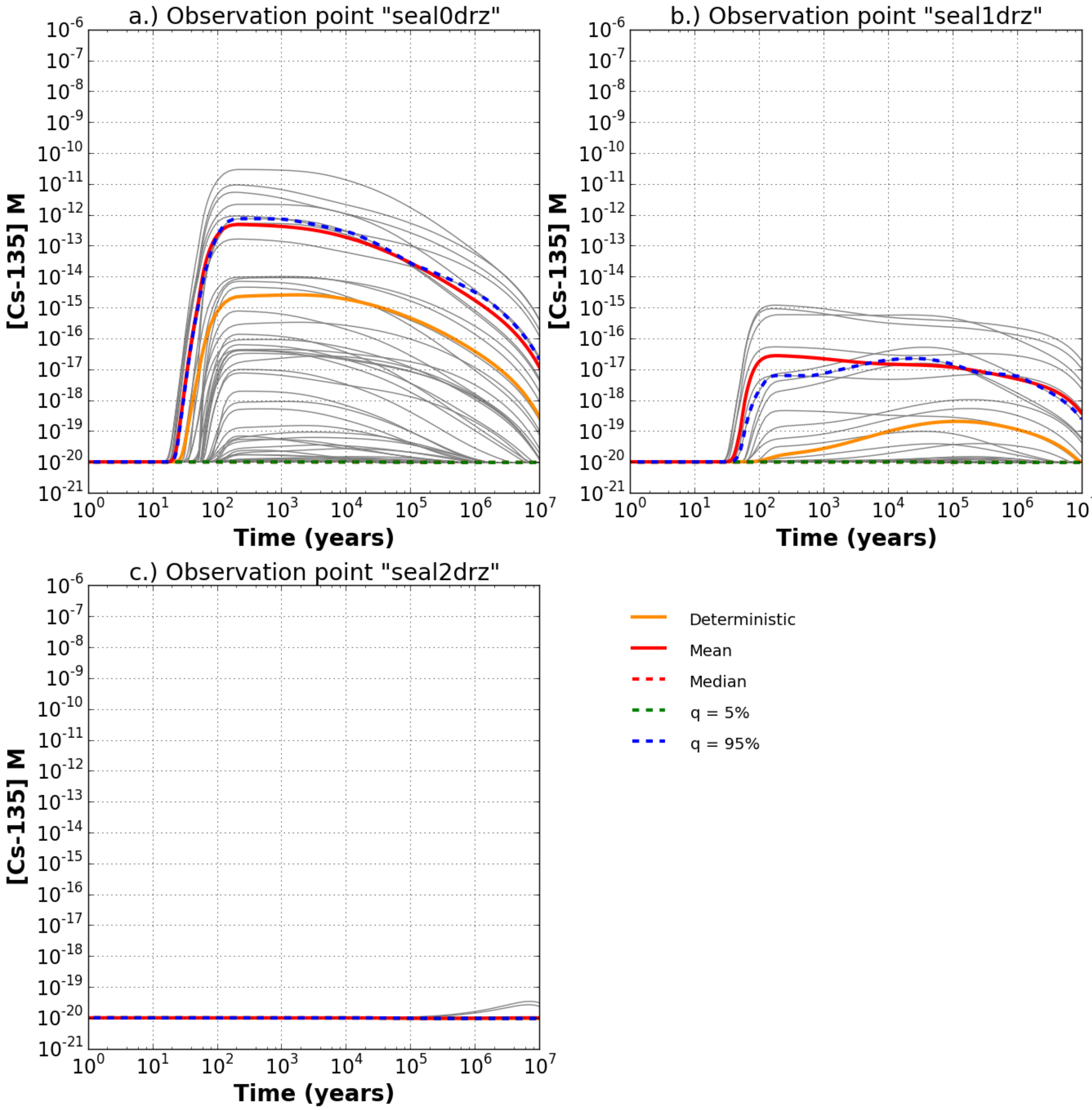
A suite of 100 probabilistic simulations were run to analyze uncertainty and sensitivity due to the parameters listed in Table 5-7. The concentrations of ^{135}Cs at three locations within the 100-m cement plug at the base of the seal zone (2.5 m (seal0), 12.5 m (seal1), and 27.5 m (seal2) above the top of the EZ) and at three corresponding elevations in the DRZ (seal1DRZ, seal2DRZ, and seal3DRZ) were used as performance metrics.

Horsetail plots show the uncertainty in predicted ^{135}Cs concentrations due to uncertainty in the sampled input parameters; concentration versus time is plotted for seal zone observation points in the cement plug (Figure 5-9) and in the DRZ (Figure 5-10). Concentrations do not exceed 10^{-9} mol/L at any location at any time. None of the realizations resulted in a ^{135}Cs concentration in excess of 10^{-19} mol/L in either the cement plug or the DRZ at an elevation of 27.5 m above the EZ.



100 Realizations at 3 Elevations: a) seal0, b) seal1, c) seal2

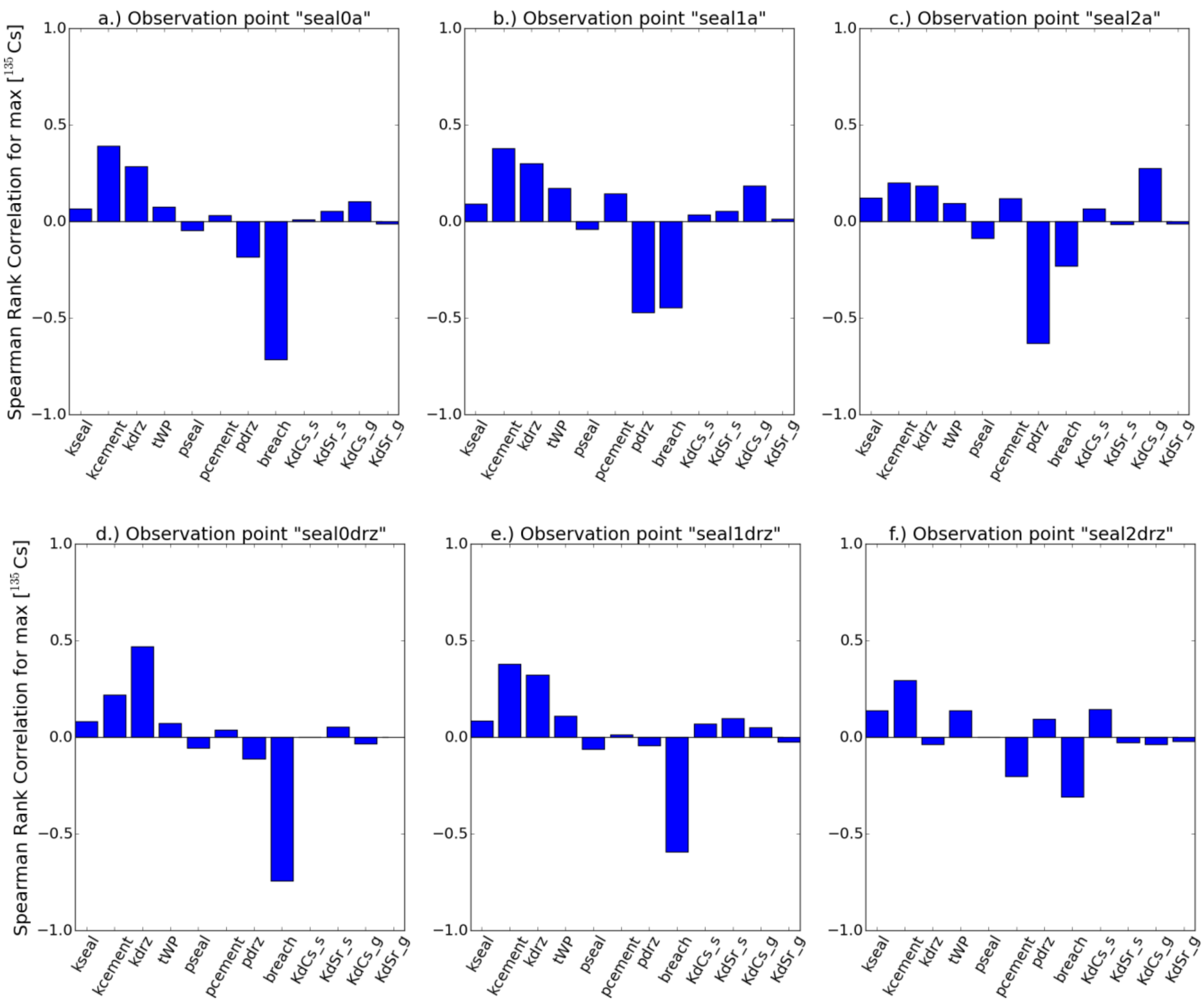
Figure 5-9. ^{135}Cs Concentrations in the Borehole Annulus (r=0.135 m) in the SZ



100 Realizations at 3 Elevations: a) seal0, b) seal1, c) seal2

Figure 5-10. ^{135}Cs Concentrations in the DRZ (r=0.185 m) Adjacent to the SZ

Sensitivity to sampled parameters was analyzed through the use of Spearman rank correlation coefficients relating the maximum concentration of ^{135}Cs at each of the six observation points to the sampled parameters (Figure 5-11). Directly (2.5 m) above the EZ, maximum ^{135}Cs concentration in the cement plug (Figure 5-11a) and in the DRZ (Figure 5-11d) is most sensitive to waste package breach time. Delayed waste package breach results in lower predicted concentrations because the radionuclide releases from the waste packages occur after the early peak buoyancy-driven fluxes. The permeability of the cement plugs and of the DRZ plays a secondary role; the larger the permeability of these materials, the greater the maximum ^{135}Cs concentration at all locations.



kseal: bentonite seal permeability; kcement: cement plug permeability; kdrz: DRZ permeability;
tWP: waste package tortuosity;
pseal: bentonite seal porosity; pcement: cement plug porosity; pdrz: DRZ porosity;
breach: waste package breach time;
KdCs_s: Cs Kd in bentonite seal; KdSr_s: Sr Kd in bentonite seal;
KdCs_g: Cs Kd in DRZ and host rock; KdSr_g: Sr Kd in DRZ and host rock

Figure 5-11. Spearman Rank Correlation Coefficients Relating Maximum ^{135}Cs Concentrations in the SZ Cement Plug (a. – c.) and SZ DRZ (d. – f.) to Sampled Parameters

5.3 Confidence Enhancement

In a safety case, the results of safety assessments – i.e. the calculated numerical results – are supplemented by a broader range of evidence that gives context to the conclusions or provides complementary safety arguments, either quantitative or qualitative (NEA 2012, Section 3.1). The types of qualitative information that may provide confidence enhancement include (Section 1.2.1.4):

- Independent evidence for the intrinsic robustness of the system, including passive safety features and consistency of site-specific features and processes with observations in nature
- Comparison with natural and/or anthropogenic analogues of a repository system (e.g., natural uranium deposits) or one or more of its components
- Scientific observation and analysis including: natural isotope profiles in some host rocks; groundwater ages and paleohydrogeological information in general; thermodynamic (e.g., waste package metal stability in deep groundwater) and/or kinetic (e.g., iron corrosion rate) arguments; and mass-balance arguments (e.g., showing that there is only a limited amount of reactant so that the extent of a detrimental reaction must be limited)
- Site monitoring and performance confirmation (for example, see 10 CFR 63.111(d) or 10 CFR 60.140)
- Large-scale demonstrations (e.g., field-scale tests, URLs)
- Long-term extrapolation of short-term experiments and observations
- Detailed process modeling studies
- Peer review and international collaboration

The DBFT (Section 1.1.3) will enhance the DBD knowledge base for operations (e.g., drilling, surface handling and downhole emplacement of packages), pre-closure safety (engineering analyses and testing), and post-closure safety (subsurface characterization and seals research).

Several references cited in the assessment basis (Section 4) provide confidence enhancement for DBD. In addition, SNL (2016b, Section 2.1) identifies the following DBD characteristics and conditions favorable to long-term isolation of radioactive waste from the accessible environment:

- Crystalline basement rocks are relatively common at depths of 2 to 5 km in stable continental regions, suggesting that numerous geologically appropriate sites may exist. The bulk permeability of deep crystalline rocks is generally low and decreases with depth, as shown by studies of permeability as a function of depth in the upper crust (Manning and Ingebritsen 1999).
- DBD safety relies on emplacing wastes in competent crystalline rock well below the extent of naturally circulating groundwater. Movement in groundwater is practically the only significant pathway for migration of radionuclides from a deep borehole to the accessible environment. If the groundwater has not moved for millions of years, then transport is limited to the mechanism of aqueous diffusion, a slow process. Diffusion-limited transport is the principle of isolation for mined repositories proposed at depths of 500 m in clay or shale, and salt. However, in DBD, waste would be situated at 3 to 5 km depth in low-

permeability granite or schist, so the radionuclide migration path distance would be an order of magnitude greater than for mined repositories.

- Recent studies have shown groundwater deeper than 2 km in the Precambrian basement to have been isolated from the atmosphere for greater than one billion years (e.g., Holland et al. 2013; Gascoyne 2004). The origin and residence time of deep groundwater can be estimated using natural cosmogenic tracers with long half-lives (e.g., Ar-isotopes and ^{81}Kr). Other tracers originate in the solid earth: accumulation of radiogenic He, and U-series equilibria, are indicators of long groundwater residence time.
- The chemical composition of deep groundwater can also be indicative of isolation from shallower water. Deep groundwaters are typically concentrated chloride brines with densities that range from 2.5% greater than pure water (seawater) to more than 30% greater than pure water (Park et al. 2009; Phillips et al. 1981). High salinity at depth indicates old groundwater and precludes use of deep groundwater as a future drinking water source. Types of brine in the basement range from sodium chloride to calcium and magnesium chloride brines at higher density. Low permeability and high salinity in the deep crystalline basement at many continental locations suggest very limited interaction with shallower sources of useable groundwater (Park et al. 2009).
- Density stratification of brine tends to limit the effects from future perturbations to hydrologic conditions such as climate change, or from early thermal convection borehole heating by the waste. The density gradient (fresh near the surface, concentrated at depth) is stabilizing and inhibits vertical flow or mixing. The existence of downward salinity gradients and concentrated brine in the deep crystalline basement has been extensively studied (e.g., Lemieux and Sudicky 2010, Person et al. 2007, and Grasby et al. 2000). Ancient brines have been found in crystalline basement rock over a large area of the northern plains of North America, an area subjected to glaciation during the Pleistocene epoch (e.g., as reported by Gascoyne 2004). The simple existence of concentrated chloride brines in the crystalline basement is a general indicator of great age, especially when no evaporites are present in the geologic setting. Absence of overpressured conditions at depth (so that in situ pressure cannot drive flow at the surface) is also expected at favorable locations for deep borehole disposal.
- Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the sorption of many radionuclides, leading to limited mobility in groundwater.

Also, there are hundreds of EPA-licensed deep-injection wells (see Section 2.1.3.7) for wastewater and liquid hazardous waste in the U.S. (EPA 2001). Approximately 500 to 600 wells have been put into service with depths from 3,000 to 12,000 ft. Injection intervals are typically separated from underground sources of groundwater by multiple low-permeability confining units. Injection wells have double casings, double-cemented, to isolate the waste path from overlying units. Final sealing and plugging of these wells follows established procedures for oil-and-gas wells (SNL 2016b, Section 1.2).

Confidence enhancement information will be more formally compiled in a future iteration of the DBD safety case.

6. SYNTHESIS AND CONCLUSIONS

6.1 Pre-Closure Safety

Pre-closure safety should consider all of the important components and activities, including: borehole construction, waste receipt and surface handling, emplacement operations, and waste package integrity during surface and downhole emplacement operations prior to borehole sealing.

Pre-closure risks during normal DBD operations include radiological accidents and exposure of workers. Pre-closure risks for off-normal DBD conditions include radiological exposure and contamination caused by operational failures (e.g., package breach following an accident such as dropping a package, damage incurred during package recovery after one or more packages becomes stuck above the EZ) or by external events (such as flooding, extreme weather, seismicity, or sabotage).

Pre-closure safety analysis for DBD to date is limited to a preliminary wireline emplacement hazard analysis (Section 5.1).

However, the DBFT will provide additional information to support the pre-closure safety case by means of engineering analyses and testing of important components of the disposal system including packages, handling and emplacement equipment, and impact limiters (SNL 2016b, Section 2.1).

6.2 Post-Closure Safety

Several factors suggest that the DBD concept is a viable approach for very long-term isolation of radioactive wastes from the accessible environment (see Section 5.3).

Post-closure risks for DBD are associated with potential releases of radionuclides from the engineered barriers and transport through the natural barriers to the biosphere. Post-closure DBD PA model results (Section 5.2) show minimal radionuclide transport away from the EZ under undisturbed conditions for 10,000,000 years, at which time long-lived ^{135}Cs has almost completely decayed away.

The post-closure safety of the DBD concept is a function of the multiple barriers (natural and engineered features) that isolate waste from the accessible environment and/or delay and limit radionuclide releases to the accessible environment. Specific features and characteristics of the DBD concept that contribute to post-closure safety include:

- **Depth of emplacement –** Preliminary DBD PA model results (Section 5.2.6) indicate that radionuclides from the Cs/Sr capsules emplaced between 4,500 to 5,000 m depth travel only about 25 m up the seal zone and 20 m out in the host rock in 10,000,000 years. The great depth of emplacement provides for long groundwater travel times from the EZ to the accessible environment.
- **Low permeability of crystalline host rock –** The low permeability of the crystalline host rock contributes to isolation of waste by limiting fluid fluxes and advection transport between the deep disposal horizon and the accessible environment. The crystalline basement is likely to be impermeable enough that fluid residence times may be on the order

of millions of years (Section 4.3.2.5).

- **Low porosity of crystalline host rock** – The low porosity of the crystalline host rock limits the amount of fluid available to move radionuclides away from the EZ and limits the rate of diffusive transport through the host rock. Effective diffusion coefficients in crystalline rock are orders of magnitude less than diffusion coefficients in free water (Section 4.3.2.3).
- **Low permeability of seal zone –** The low permeability of seal zone materials (bentonite and cement) inhibits vertical fluid flux and radionuclide transport up the borehole (see Section 4.2.6).
- **Sorption capacity of the seal zone –** The high sorption capacity of the bentonite component of the seals delays and limits radionuclide releases (Section 4.2.6). If desired, the cement component of the seals (and/or the EZ) could be engineered to effectively sorb radionuclides as well.
- **Upper borehole zone** – The cement plugs in the UBZ inhibit fluid flow in the borehole, including downward fluxes of surface water, and contribute to the stability of engineered components of the seal zone and the isolation of the EZ (Section 4.2.7).
- **Multiple seals** – Multiple sealing intervals and materials provide redundancy.
- **Sorption capacity of clay-bearing sedimentary units** – Preliminary DBD PA model results (Section 5.2.6) indicate that radionuclide transport to the overlying sediments is unlikely. However, should such transport occur, under undisturbed or disturbed scenarios, clay-bearing sedimentary units will sorb radionuclides, delaying and limiting releases to the accessible environment (Section 4.3.4).
- **Low permeability of overlying sedimentary aquitards –** Low-permeability sediments overlying the crystalline basement will provide an additional barrier to fluid flow and contribute to isolation of the waste (Section 4.3.4).

6.3 Confidence Enhancement

Confidence in the DBD concept, supporting the quantitative assessments, derives from (Section 5.3):

- great depth of disposal,
- low permeability of the crystalline host rock and sealing materials,
- high-likelihood of slow diffusion-dominated radionuclide transport,
- isolation and long residence time of deep groundwater,
- density stratification of brine at depth, and
- performance of EPA-licensed UIC wells.

The DBFT will enhance the DBD knowledge base for operations (e.g., drilling, surface handling and downhole emplacement of packages), pre-closure safety (engineering analyses and testing), and post-closure safety (subsurface characterization and seals research).

6.4 Open Issues

Preliminary information and evidence suggests that DBD is a viable concept for smaller DOE-managed waste forms. However, there are a number of issues requiring further evaluation and/or research (Brady et al. 2015; SNL 2016b, Section 2.2; NWTRB 2016). These include:

- **Borehole Feasibility** – Drilling a straight, large-diameter borehole to 5,000 m in crystalline basement rock may test the limits of currently available commercial technology. Drilling technology for a 5,000 m deep borehole with a 0.43 m (17 in) bottom-hole diameter is planned for the DBFT (SNL 2016b).
- **Operational Feasibility** – The safe performance of shielded waste receipt, waste package surface handling, and downhole waste package emplacement and retrieval operations needs to be demonstrated. These operations will be tested during the DBFT (SNL 2016b).
- **Thermal Expansion of Casing and Waste Packages During Emplacement** – In the vicinity of heat-generating waste, the guidance casing and waste packages are likely to expand. Thermal expansion of the casing that occurs after the casing is cemented will produce axial thermal stress, and possibly some buckling where the casing is not constrained by cement. A stack of waste packages could adjust to thermal loads by further compressing the impact limiters attached to each package. (SNL 2016b, Section 2.2)
- **Operational Failures** – Pre-closure and post-closure consequences of operational failures (e.g., package breach following an accident such as dropping a package, damage incurred during package recovery after one or more packages becomes stuck above the EZ) need to be examined.
- **Robustness of Waste Forms and Waste Packages** – Although not required for post-closure safety under undisturbed conditions, longer-lived waste forms and/or waste packages would contribute to waste isolation and multi-barrier capability of the DBD system. NWTRB (2016) recommended that DOE explicitly analyze the potential safety benefits of using more robust waste forms and waste packages as part of assessing the feasibility of the DBD concept. Waste package design is a part of the DBFT (SNL 2016b).
- **Robustness of Seals** – Seals are primarily needed during the first few hundred years of maximum heat production from ^{137}Cs and ^{90}Sr decay in the borehole. Further seal performance is desirable until re-establishment of the natural salinity gradient, which tends to oppose upward flow; this period is assumed to be approximately 1,000 years. NWTRB (2016) recommended further research to demonstrate emplacement of potential seals and to test the efficacy of seal materials in dealing with breakouts and evolving damage zones around the borehole when exposed to in situ thermal, hydrogeologic, geomechanical, microbiological, and chemical conditions. Appendix D provides a borehole sealing R&D plan that addresses sealing requirements and research needs, including laboratory testing.
- **Characterization of the Heterogeneous Subsurface Conditions** – The robustness of the DBD concept relies in large part on the subsurface hydrogeology and geochemistry, specifically: low permeability and porosity in the host rock; lack of significant vertical connectivity in the DRZ; chemically reducing, high salinity, and density stratified groundwater at depth, and evidence of isolation of deep groundwater. The measurement and confirmation of these heterogeneous properties and conditions poses technical challenges. NWTRB (2016) recommended that DOE address the technical and scientific

issues related to the potential heterogeneity of the subsurface geology and the complex in situ conditions at depth and carefully consider the key parameters for the safety case that need to be measured during sampling and testing in the 2- to 5-km depth range encompassing the seal and emplacement zones. A strategy to address these issues during the DBFT is documented in SNL (2016c).

- **Hydrogen Gas Generation from Corrosion of Waste Package and Casing Materials** – Concentrated chloride brines at elevated temperature are highly corrosive to steel components (e.g., iron) and certain other metals in casing and packaging materials. Corrosion causes reduction of aqueous hydrogen ions, producing H_2 gas. If H_2 gas were contained to a sufficient degree by the host rock and seals, the gas pressure could increase significantly, potentially leading to the formation of new fractures or dilation of pre-existing fractures. However, sustained corrosion would require transport of water from the host rock because the borehole initially contains only enough water to corrode a small fraction of the steel present. If there is sufficient permeability for water influx, then hydrogen can disperse outward through the same permeability in dissolved or gaseous form. To address this concern of H_2 gas generation and pressurization, an understanding of the gas generation process and the potential effects will be built on site-specific characterization, and can be addressed in selection of materials for casing and packages, and selection of an EZ completion option. (SNL 2016b, Section 2.2)
- **Microbial Activity** – Microbial activity in disposal boreholes is possible, because there are organisms that can survive and grow at high temperature in concentrated brines. However, the combination of thermophilic and halophilic behavior is rare. Further, the available metabolic pathways are limited. For example, there would be a scarcity of electron acceptors such as sulfate and organic compounds in cement; when these are expended growth will stop. Ultimately, the safety case for DBD does not depend on long-term containment in packages, or on radionuclide sorption, so microbial processes may not be important. (SNL 2016b, Section 2.2)
- **Radiolysis** – The radioactive waste will emit some combination of alpha, beta, gamma, and neutron radiation, depending on its composition. Irradiation of water and other molecules can cause changes in chemical reactivity (e.g., redox potential, pH, radiolysis, and concentrations of reactive radicals), and possibly gas generation, that have the potential to affect the performance of the DBD system. (SNL 2016b, Section 2.2)
- **Regulatory Framework –** The current U.S. regulatory framework for the disposal of high-activity waste was not originally intended to be applied to DBD facilities. Specific regulatory topics that may benefit from clarification for DBD are summarized in Section 2.1.3.

Current pre-closure safety analysis (Section 5.1) is limited to a preliminary wireline emplacement hazard analysis (Section 5.1). Future iterations of the DBD safety case will develop the pre-closure safety analyses more fully, with consideration of:

- **Pre-Closure Activities** – Identify event sequences and probabilities for the full range of pre-closure activities.
- **Pre-Closure Dose Calculations** – Estimate radiological doses to members of the public and to workers.

Current post-closure PA (Section 5.2) includes representation of selected FEPs for undisturbed scenarios. Future iterations of the DBD safety case will further develop the post-closure PA basis, including consideration of:

- **Disruptive Events** – Examine the effects of human intrusion and disruptive events such as tectonics, seismicity, volcanism, erosion, hydrothermal activity, climate change, glaciation, and other hydrologic changes. The effects of some of these disruptive events can be minimized as part of the siting guidelines and criteria.
- **Biosphere –** Develop a reference case biosphere more fully. Determination of biosphere model parameter values will depend on the characteristics of the biosphere (e.g., climate) and the habits of the population (receptor) in that biosphere. A biosphere model will permit calculation of post-closure doses.
- **Discrete Fractures** – Develop a reference case representation of discrete fractures in the crystalline basement that have the potential to enhance connectivity between the EZ and the accessible environment.
- **Mechanistic Corrosion** – Develop a mechanistic model for corrosion and subsequent breach of waste packages under downhole conditions. If necessary, the corrosion model could also include gas generation from corrosion of waste packages and other metal components.
- **Gas Phase and/or Colloidal Transport** – Examine the effects of radionuclide transport in the gas phase and/or by colloids.
- **Density Stratification and Salinity** – Explicitly model the evolution of fluid (brine) density due to salinity, including the time it takes to re-establish the ambient density/salinity gradient in and around the borehole following the perturbations from drilling and waste emplacement.

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APPENDIX A – POTENTIALLY APPLICABLE REGULATIONS

This Appendix contains excerpts from the following regulations, which are potentially applicable to DBD and/or could be expected to inform future DBD regulations:

- *10 CFR Part 60 (Disposal of High-Level Radioactive Wastes in Geologic Repositories)* – The purpose and scope is described in 10 CFR 60.1, "This part prescribes rules governing the licensing (including issuance of a construction authorization) of the U.S. Department of Energy to receive and possess source, special nuclear, and byproduct material at a geologic repository operations area sited, constructed, or operated in accordance with the Nuclear Waste Policy Act of 1982, as amended. This part does not apply to any activity licensed under another part of this chapter. This part does not apply to the licensing of the U.S. Department of Energy to receive and possess source, special nuclear, and byproduct material at a geologic repository operations area sited, constructed, or operated at Yucca Mountain, Nevada, in accordance with the Nuclear Waste Policy Act of 1992, as amended, and the Energy Policy Act of 1992, subject to part 63 of this chapter."

  This is the existing general NRC regulation for disposal of high-activity waste[4]. 10 CFR 60 makes reference to the EPA standards at *40 CFR Part 191 (Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes)*.

- *10 CFR Part 63 (Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada)* – The purpose and scope is described in 10 CFR 60.1, "This part prescribes rules governing the licensing (including issuance of a construction authorization) of the U.S. Department of Energy to receive and possess source, special nuclear, and byproduct material at a geologic repository operations area sited, constructed, or operated at Yucca Mountain, Nevada, in accordance with the Nuclear Waste Policy Act of 1982, as amended, and the Energy Policy Act of 1992. As provided in 10 CFR 60.1, the regulations in part 60 of this chapter do not apply to any activity licensed under another part of this chapter."

  This is the site-specific regulation for disposal of high-activity waste[5] at Yucca Mountain. 10 CFR 63 makes reference to the EPA standards at *40 CFR Part 197 (Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada)*.

[4] 10 CFR 60.2 defines "high-level radioactive waste" as "(1) irradiated reactor fuel, (2) liquid wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel, and (3) solids into which such liquid wastes have been converted." This definition is different from the NWPA definition (NWPA 1983, Sec. 2) in that it refers to SNF (part (1) of the 10 CFR 60.2 definition) and HLW (parts (2) and (3) of the 10 CFR 60.2 definition) collectively as high-level radioactive waste.

40 CFR 191.02 defines SNF and HLW separately, and is consistent with the NWPA definition.

[5] 10 CFR 63.2 defines "high-level radioactive waste" as (1) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; (2) Irradiated reactor fuel; and (3) Other highly radioactive material that the Commission, consistent with existing law, determines by rule requires permanent isolation." This definition is different from the NWPA definition (NWPA 1983, Sec. 2) in that it refers to SNF (part (2) of the 10 CFR 63.2 definition) and HLW (parts (1) and (3) of the 10 CFR 63.2 definition) collectively as high-level radioactive waste.

40 CFR 197.2 defines SNF and HLW separately, and is consistent with the NWPA definition.

A number of the current regulations were published before the early 1990s when the NRC (and other Federal agencies) began using current knowledge about radiation risks and internal dosimetry. These older regulations generally have two or three limits associated with them. They tend to have separate limits for the dose to the whole body, the organs, and possibly, a specific limit for the thyroid. In the early 1990s, the Federal government began using a newer dosimetry system that accounted for how radiosensitive the various organ systems are. In addition to being able to compare the doses between organs, one can calculate what whole body dose would result in the same cancer risk. This whole body dose is known as an effective dose equivalent. (10 CFR 63, 66 FR 55752)

The effective dose equivalent is defined as “the sum of the products of the dose equivalent received by specified tissues following an exposure of, or an intake of radionuclides into, specified tissues of the body, multiplied by appropriate weighting factors” (40 CFR 191.12; 40 CFR 197.2). This allows the various tissue-specific health risks to be summed into an overall health risk. Using this approach, not only the whole body but each of the organs are protected from an increased chance of cancer, and they are all protected at the same level of risk, which was not true of the earlier system (10 CFR 63, 66 FR 55752).

In the regulations and standards excerpted in the remainder of this Appendix, radiological safety is addressed through the use of annual dose limits, based on the effective dose equivalent concept. However, the EPA (in 40 CFR 191 and 40 CFR 197) and the NRC (in 10 CFR 60 and 10 CFR 63) use different approaches to assess the total dose to individuals.

In the EPA standards, “annual dose” is represented by the annual committed effective dose equivalent (annual CEDE), defined as the “sum of the committed effective dose equivalent from internal doses resulting from one year’s exposure to radioactive materials, and the effective dose equivalent from external radiation exposure during the year” (10 CFR 63, 66 FR 55734; see also 10 CFR 191.12 and 40 CFR 197.2).

In the NRC regulations, “annual dose” is represented by the annual total effective dose equivalent (annual TEDE). Similar to the CEDE, the TEDE is defined as the “sum of the effective dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures)” (10 CFR 63.2).

The differences between the CEDE and the TEDE stem from the determination of the external dose component. External exposure for the TEDE may be determined using a “deep-dose equivalent”, a point measurement that does not sum the doses to the organs or tissue through use of weighting factors (10 CFR 63, 66 FR 55734; see also 10 CFR 63.102(o)). This is different from the external exposure component for the CEDE, determined using the effective dose equivalent, which involves summing the products of organ doses and weighting factors. As discussed in 10 CFR 63 (66 FR 55735), the deep-dose equivalent is only used in the determination TEDE external dose component for pre-closure occupational dose. For post-closure dose (i.e., the individual protection standard), the NRC “intends to use effective dose equivalent for assessing external exposure” (10 CFR 63, 66 FR 55735).

It should also be noted (10 CFR 63, 66 FR 55752): “Because each of the organs had the same limit under the older system even though each had a different level of radiosensitivity, it is very difficult to directly compare the old standards with the new standards. As noted in the proposed rule, the Commission considers 0.25 mSv/yr (25 mrem/yr) TEDE as the appropriate dose limit to compare with the range of potential doses represented by the older limits that had whole body dose limits of 0.25 mSv/yr (25 mrem/yr). However, to conform to the EPA standard, the Commission has incorporated a dose limit of 0.15 mSv/yr (15 mrem/yr) in final part 63."

A.1 Pre-Closure

A.1.1 Pre-Closure Performance Objectives

The following regulations are excerpted here:

- Pre-closure performance objectives - 10 CFR 60.111 and 10 CFR 63.111
- Referenced dose limits and standards - 10 CFR 20.1201, 10 CFR 63.204, and 40 CFR 191.03
- Supporting definitions - 10 CFR 63.2 and 10 CFR 60.2

10 CFR 60.111 – Performance of the geologic repository operations area through permanent closure

(a) Protection against radiation exposures and releases of radioactive material. The geologic repository operations area shall be designed so that until permanent closure has been completed, radiation exposures and radiation levels, and releases of radioactive to unrestricted areas, will be maintained within the limits specified in part 20 of this chapter and such generally applicable environmental standards for radioactivity as may have been established by the Environmental Protection Agency.

(b) Retrievability of waste.

(1) The geologic repository operations area shall be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced and, thereafter, until the completion of a performance confirmation program and Commission review of the information obtained from such a program. To satisfy this objective, the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after the waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission. This different time period may be established on a case-by-case basis consistent with the emplacement schedule and the planned performance confirmation program.

(2) This requirement shall not preclude decisions by the Commission to allow backfilling part or all of, or permanent closure of, the geologic repository operations area prior to the end of the period of design for retrievability.

10 CFR 63.111 – Performance objectives for the geologic repository operations area through permanent closure

(a) Protection against radiation exposures and releases of radioactive material.

(1) The geologic repository operations area must meet the requirements of part 20 of this chapter.

(2) During normal operations, and for Category 1 event sequences, the annual TEDE (hereafter referred to as "dose") to any real member of the public located beyond the boundary of the site may not exceed the preclosure standard specified at § 63.204.

(b) Numerical guides for design objectives.

(1) The geologic repository operations area must be designed so that, taking into consideration Category 1 event sequences and until permanent closure has been completed, the aggregate radiation exposures and the aggregate radiation levels in both restricted and unrestricted areas, and the aggregate releases of radioactive materials to unrestricted areas, will be maintained within the limits specified in paragraph (a) of this section.

(2) The geologic repository operations area must be designed so that, taking into consideration any single Category 2 event sequence and until permanent closure has been completed, no individual located on, or beyond, any point on the boundary of the site will receive, as a result of the single Category 2 event sequence, the more limiting of a TEDE of 0.05 Sv (5 rem), or the sum of the deep dose equivalent and the committed dose equivalent to any individual organ or tissue (other than the lens of the eye) of 0.5 Sv (50 rem). The lens dose equivalent may not exceed 0.15 Sv (15 rem), and the shallow dose equivalent to skin may not exceed 0.5 Sv (50 rem).

(c) Preclosure safety analysis. A preclosure safety analysis of the geologic repository operations area that meets the requirements specified at § 63.112 must be performed. This analysis must demonstrate that:

(1) The requirements of § 63.111(a) will be met; and

(2) The design meets the requirements of § 63.111(b).

(d) Performance confirmation. The geologic repository operations area must be designed so as to permit implementation of a performance confirmation program that meets the requirements of subpart F of this part.

(e) Retrievability of waste.

(1) The geologic repository operations area must be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced and thereafter, until the completion of a performance confirmation program and Commission review of the information obtained from such a program. To satisfy this objective, the geologic repository operations area must be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission. This different time period may be established on a case-by-case basis consistent with the emplacement schedule and the planned performance confirmation program.

(2) This requirement may not preclude decisions by the Commission to allow backfilling part, or all of, or permanent closure of the geologic repository operations area, before the end of the period of design for retrievability.

10 CFR 20.1201 – Occupational dose limits for adults

(a) The licensee shall control the occupational dose to individual adults, except for planned special exposures under § 20.1206, to the following dose limits.

(1) An annual limit, which is the more limiting of--

(i) The total effective dose equivalent being equal to 5 rems (0.05 Sv); or

(ii) The sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than the lens of the eye being equal to 50 rems (0.5 Sv).

(2) The annual limits to the lens of the eye, to the skin of the whole body, and to the skin of the extremities, which are:

(i) A lens dose equivalent of 15 rems (0.15 Sv), and

(ii) A shallow-dose equivalent of 50 rem (0.5 Sv) to the skin of the whole body or to the skin of any extremity.

10 CFR 63.204 – Preclosure standard

DOE must ensure that no member of the public in the general environment receives more than an annual dose of 0.15 mSv (15 mrem) from the combination of:

(a) Management and storage (as defined in 40 CFR 191.2) of radioactive material that:

(1) Is subject to 40 CFR 191.3(a); and

(2) Occurs outside of the Yucca Mountain repository but within the Yucca Mountain site; and

(b) Storage (as defined in § 63.202) of radioactive material inside the Yucca Mountain repository.

[10 CFR 63.204 is based on, and consistent with, 40 CFR 197.4 (Public Health and Environmental Standards for Storage)]

40 CFR 191.03 – Standards

(a) Management and storage of spent nuclear fuel or high-level or transuranic radioactive wastes at all facilities regulated by the Commission or by Agreement States shall be conducted in such a manner as to provide reasonable assurance that the combined annual dose equivalent to any member of the public in the general environment resulting from: (1) Discharges of radioactive material and direct radiation from such management and storage and (2) all operations covered by Part 190; shall not exceed 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other critical organ.

(b) Management and storage of spent nuclear fuel or high-level or transuranic radioactive wastes at all facilities for the disposal of such fuel or waste that are operated by the Department and that are not regulated by the Commission or Agreement States shall be conducted in such a manner as to provide reasonable assurance that the combined annual dose equivalent to any member of the public in the general environment resulting from discharges of radioactive material and direct radiation from such management and storage shall not exceed 25 millirems to the whole body and 75 millirems to any critical organ.

10 CFR 63.2 – Definitions

Geologic repository operations area means a high-level radioactive waste facility that is part of a geologic repository, including both surface and subsurface areas, where waste handling activities are conducted. [10 CFR 60.2 contains the same definition]

Event sequence means a series of actions and/or occurrences within the natural and engineered components of a geologic repository operations area that could potentially lead to exposure of individuals to radiation. An event sequence includes one or more initiating events and associated combinations of repository system component failures, including those produced by the action or inaction of operating personnel. Those event sequences that are expected to occur one or more times before permanent closure of the geologic repository operations area are referred to as *Category 1 event sequences*. Other event sequences that have at least one chance in 10,000 of occurring before permanent closure are referred to as *Category 2 event sequences*.

10 CFR 60.2 – Definitions

Design basis events means:

> (1)(i) Those natural and human-induced events that are reasonably likely to occur regularly, moderately frequently, or one or more times before permanent closure of the geologic repository operations area; and (ii) Other natural and man-induced events that are considered unlikely, but sufficiently credible to warrant consideration, taking into account the potential for significant radiological impacts on public health and safety.
>
> (2) The events described in paragraph (1)(i) of this definition are referred to as "Category 1" design basis events. The events described in paragraph (1)(ii) of this definition are referred to as "Category 2" design basis events.

A.1.2 Pre-Closure Safety Analysis

The following regulations are excerpted here:

- Pre-closure safety analysis requirements - 10 CFR 63.112
- Supporting definitions - 10 CFR 63.2 and 10 CFR 63.102

10 CFR 63.112 – Requirements for preclosure safety analysis of the geologic repository operations area

The preclosure safety analysis of the geologic repository operations area must include:

(a) A general description of the structures, systems, components, equipment, and process activities at the geologic repository operations area;

(b) An identification and systematic analysis of naturally occurring and human-induced hazards at the geologic repository operations area, including a comprehensive identification of potential event sequences;

(c) Data pertaining to the Yucca Mountain site, and the surrounding region to the extent necessary, used to identify naturally occurring and human-induced hazards at the geologic repository operations area;

(d) The technical basis for either inclusion or exclusion of specific, naturally occurring and human-induced hazards in the safety analysis;

(e) An analysis of the performance of the structures, systems, and components to identify those that are important to safety. This analysis identifies and describes the controls that are relied on to limit or prevent potential event sequences or mitigate their consequences. This analysis also identifies measures taken to ensure the availability of safety systems.

(f) A description and discussion of the design, both surface and subsurface, of the geologic repository operations area, including—

> (1) The relationship between design criteria and the requirements specified at § 63.111(a) and (b); and
>
> (2) The design bases and their relation to the design criteria.

10 CFR 63.2 – Definitions

Design bases means that information that identifies the specific functions to be performed by a *structure, system, or component* of a facility and the specific values or ranges of values chosen for controlling parameters as reference bounds for design.

Important to safety, with reference to *structures, systems, and components*, means those engineered features of the geologic repository operations area whose function is:

> (1) To provide reasonable assurance that high-level waste can be received, handled, packaged, stored, emplaced, and retrieved without exceeding the requirements of § 63.111(b)(1) for Category 1 event sequences; or
>
> (2) To prevent or mitigate Category 2 event sequences that could result in radiological exposures exceeding the values specified at § 63.111(b)(2) to any individual located on or beyond any point on the boundary of the site.

10 CFR 63.102 – Concepts

(f) *Preclosure safety analysis*. Section 63.111 includes performance objectives for the geologic repository operations area for the period before permanent closure and decontamination or permanent closure, decontamination, and dismantlement of surface facilities. The preclosure safety analysis is a systematic examination of the site; the design; and the potential hazards, initiating events and their resulting event sequences and potential radiological exposures to workers and the public. Initiating events are to be considered for inclusion in the preclosure safety analysis for determining event sequences only if they are reasonable (i.e., based on the characteristics of the geologic setting and the human environment, and consistent with precedents adopted for nuclear facilities with comparable or higher risks to workers and the public). The analysis identifies structures, systems, and components important to safety.

A.2 Post-Closure

A.2.1 Post-Closure Performance Objectives

The following regulations are excerpted here:

- Post-closure performance objectives - 10 CFR 60.112 and 10 CFR 63.113
- Referenced individual protection standards and dose limits - 40 CFR 191.15, 10 CFR 63.311, and 10 CFR 63.341
- Referenced ground water protection standards - 40 CFR 191.24 and 10 CFR 63.331
- Referenced human intrusion standards and dose limits - 40 CFR 191 Appendix C, 10 CFR 63.321, and 10 CFR 63.322
- Referenced containment requirements - 40 CFR 191.13
- Referenced multiple barrier requirements - 10 CFR 60.113 and 10 CFR 63.115
- Supporting definitions - 40 CFR 191.12, 10 CFR 63.302, 10 CFR 63.2, and 10 CFR 63.102

10 CFR 60.112 – Overall system performance objective for the geologic repository after permanent closure

The geologic setting shall be selected and the engineered barrier system and the shafts, boreholes and their seals shall be designed to assure that releases of radioactive materials to the accessible environment following permanent closure conform to such generally applicable environmental standards for radioactivity as may have been established by the Environmental Protection Agency[6] with respect to both anticipated processes and events and unanticipated processes and events.

10 CFR 63.113 – Performance objectives for the geologic repository after permanent closure

(a) The geologic repository must include multiple barriers, consisting of both natural barriers and an engineered barrier system.

(b) The engineered barrier system must be designed so that, working in combination with natural barriers, radiological exposures to the reasonably maximally exposed individual are within the limits specified at § 63.311 of subpart L of this part. Compliance with this paragraph must be demonstrated through a performance assessment that meets the requirements specified at § 63.114 of this subpart, and §§ 63.303, 63.305, 63.312 and 63.342 of Subpart L of this part.

(c) The engineered barrier system must be designed so that, working in combination with natural barriers, releases of radionuclides into the accessible environment are within the limits specified at § 63.331 of subpart L of this part. Compliance with this paragraph must be demonstrated through a performance assessment that meets the requirements specified at § 63.114 of this subpart and §§ 63.303, 63.332 and 63.342 of subpart L of this part.

(d) The ability of the geologic repository to limit radiological exposures to the reasonably maximally exposed individual, in the event of human intrusion into the engineered barrier system, must be demonstrated through an analysis that meets the requirements at §§ 63.321 and 63.322 of subpart L of this part. Estimating radiological exposures to the reasonably maximally exposed

[6] The corresponding EPA Standards are 40 CFR 191.

individual requires a performance assessment that meets the requirements specified at § 63.114 of this subpart, and §§ 63.303, 63.305, 63.312 and 63.342 of subpart L of this part.

40 CFR 191.15 – Individual protection requirements

(a) Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance[7] of the disposal system shall not cause the annual committed effective dose, received through all potential pathways from the disposal system, to any member of the public in the accessible environment, to exceed 15 millirems (150 microsieverts).

10 CFR 63.311 – Individual protection standard after permanent closure

(a) DOE must demonstrate, using performance assessment, that there is a reasonable expectation that the reasonably maximally exposed individual receives no more than the following annual dose from releases from the undisturbed Yucca Mountain disposal system[8]:

(1) 0.15 mSv (15 mrem) for 10,000 years following disposal; and

(2) 1.0 mSv (100 mrem) after 10,000 years, but within the period of geologic stability[9].

(b) DOE's performance assessment must include all potential pathways of radionuclide transport and exposure.

[10 CFR 63.311 is based on, and consistent with, 40 CFR 197.20 (Individual-Protection Standard)]

10 CFR 63.341 - Projections of peak dose

To complement the results of § 63.311, DOE must calculate the peak dose of the reasonably maximally exposed individual that would occur after 10,000 years following disposal but within the period of geologic stability. No regulatory standard applies to the results of this analysis; however, DOE must include the results and their bases in the environmental impact statement for Yucca Mountain as an indicator of long-term disposal system performance.

40 CFR 191.24 – Disposal standards (for Ground-Water Protection)

(a) Disposal systems.

(1) *General.* Disposal systems for waste and any associated radioactive material shall be designed to provide a reasonable expectation that 10,000 years of undisturbed performance after disposal shall not cause the levels of radioactivity in any underground source of drinking water, in the accessible environment, to exceed the limits specified in 40 CFR part 141 as they exist on January 19, 1994.

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[7] *Undisturbed performance* means the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events (40 CFR 191.12). However, to assess the containment requirements at 40 CFR 191.13, performance assessments shall include "all significant processes and events that might affect the disposal system".

[8] The *undisturbed Yucca Mountain disposal system* is defined as "the Yucca Mountain disposal system is not affected by human intrusion" (10 CFR 63.302). The undisturbed system may include the effects of "disruptive" FEPs in accordance with 10 CFR 63.342.

[9] The *period of geologic stability* is defined as "the time during which the variability of geologic characteristics and their future behavior in and around the Yucca Mountain site can be bounded, that is, they can be projected within a reasonable range of possibilities. This period is defined to end at 1 million years after disposal." (10 CFR 63.302)

10 CFR 63.331 – Separate standards for protection of ground water

DOE must demonstrate that there is a reasonable expectation that, for 10,000 years of undisturbed performance after disposal, releases of radionuclides from waste in the Yucca Mountain disposal system into the accessible environment will not cause the level of radioactivity in the representative volume of ground water to exceed the limits [for combined radium-226 and radium-228, gross alpha activity (including radium-226 but excluding radon and uranium), and combined beta and photon emitting radionuclides]

[10 CFR 63.331 is based on, and consistent with, 40 CFR 197.30 (Ground Water Protection Standards)]

40 CFR 191 Appendix C – Consideration of Inadvertent Human Intrusion into Geologic Repositories.

The Agency believes that the most productive consideration of inadvertent intrusion concerns those realistic possibilities that may be usefully mitigated by repository design, site selection, or use of passive controls (although passive institutional controls should not be assumed to completely rule out the possibility of intrusion). Therefore, inadvertent and intermittent intrusion by exploratory drilling for resources (other than any provided by the disposal system itself) can be the most severe intrusion scenario assumed by the implementing agencies. Furthermore, the implementing agencies can assume that passive institutional controls or the intruders' own exploratory procedures are adequate for the intruders to soon detect, or be warned of, the incompatibility of the area with their activities.

40 CFR 191 Appendix C – Frequency and Severity of Inadvertent Human Intrusion into Geologic Repositories.

The implementing agencies should consider the effects of each particular disposal system's site, design, and passive institutional controls in judging the likelihood and consequences of such inadvertent exploratory drilling. However, the Agency assumes 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. Furthermore, the Agency assumes that the consequences of such inadvertent drilling need not be assumed to be more severe than: (1) Direct release to the land surface of all the ground water in the repository horizon that would promptly flow through the newly created borehole to the surface due to natural lithostatic pressure—or (if pumping would be required to raise water to the surface) release of 200 cubic meters of ground water pumped to the surface if that much water is readily available to be pumped; and (2) creation of a ground water flow path with a permeability typical of a borehole filled by the soil or gravel that would normally settle into an open hole over time—not the permeability of a carefully sealed borehole.

10 CFR 63.321 – Individual protection standard for human intrusion

(a) DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion (see § 63.322) could occur without recognition by the drillers.

(b) DOE must demonstrate that there is a reasonable expectation that the reasonably maximally exposed individual receives, as a result of the human intrusion, no more than the following annual dose:

(1) 0.15 mSv (15 mrem) for 10,000 years following disposal; and

(2) 1.0 mSv (100 mrem) after 10,000 years, but within the period of geologic stability.

(c) DOE's analysis must include all potential environmental pathways of radionuclide transport and exposure, subject to the requirements of § 63.322.

[10 CFR 63.321 is based on, and consistent with, 40 CFR 197.25 (Human-Intrusion Standard)]

10 CFR 63.322 – Human intrusion scenario

For the purposes of the analysis of human intrusion, DOE must make the following assumptions:

(a) There is a single human intrusion as a result of exploratory drilling for ground water;

(b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository;

(c) The drillers use the common techniques and practices that are currently employed in exploratory drilling for ground water in the region surrounding Yucca Mountain;

(d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole;

(e) No particulate waste material falls into the borehole;

(f) The exposure scenario includes only those radionuclides transported to the saturated zone by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the saturated zone); and

(g) No releases are included which are caused by unlikely natural processes and events.

40 CFR 191.13 – Containment requirements.

(a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall: (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (appendix A); and (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (appendix A).

[Table 1 (appendix A) – Release Limits for Containment Requirements (Cumulative releases to the accessible environment for 10,000 years after disposal). This table provides release limits (curies) per 1,000 MTHM or other unit of waste for selected radionuclides.]

10 CFR 60.113 - Performance of particular barriers after permanent closure.

(a) General provisions –

(1) *Engineered barrier system*.

(i) The engineered barrier system shall be designed so that assuming anticipated processes and events: (A) Containment of HLW will be substantially complete during the period when radiation and thermal conditions in the engineered barrier system are dominated by fission product decay; and (B) any release of radionuclides from the engineered barrier system shall be a gradual process which results in small fractional releases to the geologic setting over long times. For disposal in the saturated zone, both the partial and complete filling with groundwater of available void spaces in the underground facility shall be appropriately considered and analysed among the anticipated processes and events in designing the engineered barrier system.

(ii) In satisfying the preceding requirement, the engineered barrier system shall be designed, assuming anticipated processes and events, so that: (A) Containment of HLW within the waste packages will be substantially complete for a period to be determined by the Commission taking into account the factors specified in § 60.113(b) provided, that such period shall be not less than 300 years nor more than 1,000 years after permanent closure of the geologic repository; and (B) The release rate of any radionuclide from the engineered barrier system following the containment period shall not exceed one part in 100,000 per year of the inventory of that radionuclide calculated to be present at 1,000 years following permanent closure, or such other fraction of the inventory as may be approved or specified by the Commission; provided, that this requirement does not apply to any radionuclide which is released at a rate less than 0.1% of the calculated total release rate limit. The calculated total release rate limit shall be taken to be one part in 100,000 per year of the inventory of radioactive waste, originally emplaced in the underground facility, that remains after 1,000 years of radioactive decay.

(2) *Geologic setting*. The geologic repository shall be located so that pre-waste-emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years or such other travel time as may be approved or specified by the Commission.

(b) On a case-by-case basis, the Commission may approve or specify some other radionuclide release rate, designed containment period or pre-waste-emplacement groundwater travel time, provided that the overall system performance objective, as it relates to anticipated processes and events, is satisfied. Among the factors that the Commission may take into account are:

(1) Any generally applicable environmental standard for radioactivity established by the Environmental Protection Agency;

(2) The age and nature of the waste, and the design of the underground facility, particularly as these factors bear upon the time during which the thermal pulse is dominated by the decay heat from the fission products;

(3) The geochemical characteristics of the host rock, surrounding strata and groundwater; and

(4) Particular sources of uncertainty in predicting the performance of the geologic repository.

(c) Additional requirements may be found to be necessary to satisfy the overall system performance objective as it relates to unanticipated processes and events.

10 CFR 63.115 - Requirements for multiple barriers.

Demonstration of compliance with § 63.113(a) must:

(a) Identify those design features of the engineered barrier system, and natural features of the geologic setting, that are considered barriers important to waste isolation.

(b) Describe the capability of barriers, identified as important to waste isolation, to isolate waste, taking into account uncertainties in characterizing and modeling the behavior of the barriers.

(c) Provide the technical basis for the description of the capability of barriers, identified as important to waste isolation, to isolate waste. The technical basis for each barrier's capability shall be based on and consistent with the technical basis for the performance assessments used to demonstrate compliance with § 63.113(b) and (c).

40 CFR 191.12 – Definitions

Accessible environment means: (1) The atmosphere; (2) land surfaces; (3) surface waters; (4) oceans; and (5) all of the lithosphere that is beyond the controlled area.

Controlled area means: (1) a surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location.

10 CFR 63.302 – Definitions for Subpart L

Accessible environment means any point outside of the controlled area, including: (1) the atmosphere (including the atmosphere above the surface area of the controlled area); (2) land surfaces; (3) surface waters; (4) oceans; and (5) the lithosphere. [40 CFR 197.12 contains the same definition]

Controlled area means:

(1) The surface area, identified by passive institutional controls, that encompasses no more than 300 square kilometers. It must not extend farther:

(i) south than 36°40'13.6661" North latitude, in the predominant direction of ground-water flow; and

(ii) than five kilometers from the repository footprint in any other direction; and

(2) The subsurface underlying the surface area.

[40 CFR 197.12 contains the same definition]

10 CFR 63.2 – Definitions

Important to waste isolation, with reference to design of the engineered barrier system and characterization of natural barriers, means those engineered and natural barriers whose function is to provide a reasonable expectation that high-level waste can be disposed of without exceeding the requirements of § 63.113(b) and (c).

10 CFR 63.102 – Concepts

(i) Characteristics of the reference biosphere and the reasonably maximally exposed individual are to be based on current human behavior and biospheric conditions in the region, as described in § 63.305 and § 63.312.

A.2.2 Post-Closure Performance Assessment

The following regulations are excerpted here:

- Post-closure performance assessment requirements - 10 CFR 63.114
- Limits on and scope of performance assessment - 10 CFR 63.342 and 40 CFR 191 Appendix C
- Supporting definitions - 10 CFR 63.102

10 CFR 63.114 – Requirements for performance assessment.

(a) Any performance assessment used to demonstrate compliance with § 63.113 for 10,000 years after disposal must:

(1) Include data related to the geology, hydrology, and geochemistry (including disruptive processes and events) of the Yucca Mountain site, and the surrounding region to the extent necessary, and information on the design of the engineered barrier system used to define, for 10,000 years after disposal, parameters and conceptual models used in the assessment.

(2) Account for uncertainties and variabilities in parameter values, for 10,000 years after disposal, and provide for the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment.

(3) Consider alternative conceptual models of features and processes, for 10,000 years after disposal, that are consistent with available data and current scientific understanding and evaluate the effects that alternative conceptual models have on the performance of the geologic repository.

(4) Consider only features, events, and processes consistent with the limits on performance assessment specified at § 63.342.

(7) Provide the technical basis for models used to represent the 10,000 years after disposal in the performance assessment, such as comparisons made with outputs of detailed process-level models and/or empirical observations (e.g., laboratory testing, field investigations, and natural analogs).

(b) The performance assessment methods used to satisfy the requirements of paragraph (a) of this section are considered sufficient for the performance assessment for the period of time after 10,000 years and through the period of geologic stability.

10 CFR 63.342 - Limits on performance assessments.

(a) DOE's performance assessments conducted to show compliance with §§ 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 100,000,000 per year of occurring. In addition, DOE's performance assessments need not evaluate the impacts resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurring if the results of the performance assessments would not be changed significantly in the initial 10,000-year period after disposal.

(b) For performance assessments conducted to show compliance with §§ 63.321(b)(1) and 63.331, DOE's performance assessments shall exclude the unlikely features, events, and processes, or sequences of events and processes, i.e., those that are estimated to have less than one chance in 100,000 per year of occurring and at least one chance in 100,000,000 per year of occurring.

(c) For performance assessments conducted to show compliance with §§ 63.311(a)(2) and 63.321(b)(2), DOE's performance assessments shall project the continued effects of the features, events, and processes included in paragraph (a) of this section beyond the 10,000-year post-disposal period through the period of geologic stability. DOE must evaluate all of the features, events, or processes included in paragraph (a) of this section, and also:

(1) DOE must assess the effects of seismic and igneous activity scenarios, subject to the probability limits in paragraph (a) of this section for very unlikely features, events, and processes, or sequences of events and processes. Performance assessments conducted to show compliance with § 63.321(b)(2) are also subject to the probability limits in paragraph (b) of this section for unlikely features, events, and processes, or sequences of events and processes.

(i) The seismic analysis may be limited to the effects caused by damage to the drifts in the repository, failure of the waste packages, and changes in the elevation of the water table under Yucca Mountain (i.e., the magnitude of the water table rise under Yucca Mountain).

(ii) The igneous activity analysis may be limited to the effects of a volcanic event directly intersecting the repository. The igneous event may be limited to that causing damage to the waste packages directly, causing releases of radionuclides to the biosphere, atmosphere, or ground water.

(2) DOE must assess the effects of climate change. The climate change analysis may be limited to the effects of increased water flow through the repository as a result of climate change, and the resulting transport and release of radionuclides to the accessible environment. The nature and degree of climate change may be represented by constant-in-time climate conditions. The analysis may commence at 10,000 years after disposal and shall extend through the period of geologic stability.

(3) DOE must assess the effects of general corrosion on engineered barriers. DOE may use a constant representative corrosion rate throughout the period of geologic stability or a distribution of corrosion rates correlated to other repository parameters.

40 CFR 191 Appendix C – Scope of Performance Assessments

Section 191.13 requires the implementing agencies to evaluate compliance through performance assessments as defined in § 191.12(q). The Agency assumes that such performance assessments need not consider categories of events or processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years. Furthermore, the performance assessments need not evaluate in detail the releases from all events and processes estimated to have a greater likelihood of occurrence. Some of these events and processes may be omitted from the performance assessments if there is a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changed by such omissions.

10 CFR 63.102 – Concepts

(j) *Performance assessment*. Demonstrating compliance with the postclosure performance objective specified at § 63.113(b) requires a performance assessment to quantitatively estimate radiological exposures to the reasonably maximally exposed individual at any time during the compliance period. The performance assessment is a systematic analysis that identifies the features, events, and processes (i.e., specific conditions or attributes of the geologic setting, degradation, deterioration, or alteration processes of engineered barriers, and interactions between the natural and engineered barriers) that might affect performance of the geologic repository; examines their effects on performance; and estimates the radiological exposures to the reasonably maximally exposed individual. The features, events, and processes considered in the performance assessment should represent a wide range of both beneficial and potentially adverse effects on performance (e.g., beneficial effects of radionuclide sorption; potentially adverse effects of fracture flow or a criticality event). Those features, events, and processes expected to materially affect compliance with § 63.113(b) or be potentially adverse to performance are included, while events (event classes or scenario classes) that are very unlikely (less than one chance in 10,000 over 10,000 years) can be excluded from the analysis. An event class consists of all possible specific initiating events that are caused by a common natural process (e.g., the event class for seismicity includes the range of credible earthquakes for the Yucca Mountain site). Radiological exposures to the reasonably maximally exposed individual are estimated using the selected features, events, and processes, and incorporating the probability that the estimated exposures will occur. Additionally, performance assessment methods are appropriate for use in demonstrating compliance with the postclosure performance objectives for ground-water protection and human intrusion, and are subject to the requirements for performance assessments specified at § 63.114 and applicable criteria in Subpart L (e.g., criteria for evaluating compliance with ground-water protection and individual protection standards).

APPENDIX B – HISTORICAL SITING GUIDELINES AND CRITERIA

This Appendix includes excerpts from various documents and regulations that contain siting guidelines and criteria for high-activity waste repositories. These excerpts, presented chronologically, provide insights into potentially applicable siting guidelines and criteria for DBD facilities.

B.1 Early Generic Siting Criteria (1980 and Earlier)

The U.S. Geological Survey (USGS), in response to the U.S. Atomic Energy Commission (AEC), produced a report in 1974 that included several optimal considerations for a site for geologic disposal of HLW (Stuckless and Levich 2016). These considerations are summarized in Table B-1.

Table B-1. Summary of Optimal Considerations for Placing HLW in Geologic Formations

Category	Optimal Considerations
Hydrologic	• Hydrologic isolation is paramount, requiring low-permeability rock and a virtually fault-free site
Seismic	• Low seismic risk
Flooding	• Low possibility of flooding by rising sea level
Climate	• Low potential hazard for surface water or groundwater in glacial or rainy climates
Erosion	• Low potential for exhumation by erosion

Source: Ekren et al. (1974), as summarized in Stuckless and Levich (2016)

The National Academy of Sciences – National Research Council developed an early set of geological criteria for repositories (NAS 1978) that includes and geo-economic, geologic, hydrologic, and geochemical criteria. These criteria are summarized in Table B-2. A full listing of the criteria can be found in Freeze et al. (2013a, Section 2.3.2.1).

Table B-2. Summary of Geological Criteria for Repositories for HLW (from NAS 1978)

Category	Summary of Criteria
Geo-Economic	• No areas with resource potential • No areas near dam sites
Geological – Geometric	• Sufficient depth • Adequate size for repository and buffer zone • Available information on host rock properties
Geologic – Long-Term Stability	• Structurally stable • Avoid faults and tectonic boundaries • Avoid high geothermal gradients and recent volcanic activity • Geophysical properties and stress state assure stability during operations • Backfilling and sealing can be soon after waste emplacement
Hydrologic	• No fluid transport to biosphere above prescribed limits • Geology permits satisfactory plugging, sealing, and monitoring • Geologic record suggests favorable long-term hydrological isolation
Geochemical	• Geochemical reactions, radioactive heat, and/or radiation should not increase permeability or compromise geological containment • Geochemical properties of waste, host rock, and water should minimize waste form dissolution and restrict mobility of radionuclides

In 1980, a subgroup of the Earth Science Technical Plan Working Group of the DOE and the USGS prepared a list of screening criteria for identification and geological characterization of sites for mined radioactive waste repositories (USGS 1980). These criteria are summarized in Table B-3. A full listing of the criteria can be found in Freeze et al. (2013a, Section 2.3.2.1).

Table B-3. Summary of Plan for Identification and Geological Characterization of Sites for Mined Radioactive Waste Repositories (from USGS 1980)

Category	Summary of Criteria
Repository Host Rock	• Adequate mineability • High enough thermal conductivity to accommodate thermal stresses • Minimal fractures • Low hydraulic conductivity • Sufficient dimensions and geometry • Sufficient depth • Sufficient rock homogeneity • High radionuclide sorption capacity • Geochemical properties and reactions should not facilitate radionuclide transport
Groundwater Flow System	• Long travel/residence time along flow path to discharge area • Strong downward or lateral flow, no upward flow • Sufficient uniformity of hydraulic characteristics along flow path to discharge area, minimal fracture porosity • High sorptive capacity • Nonpotable water overlying and underlying host rock
Tectonic Conditions	• Avoid areas of tectonic activity (known active faults, high seismic intensity, recent volcanic activity, persistent uplift)
Mineral Resources	• Avoid mineralized zones below repository to minimize potential for drilling penetrations into repository
General Considerations	• Need site-specific geologic criteria

Also in 1980, in support of a national planning strategy for developing mined geologic repositories, the DOE published a Final Environmental Impact Statement for the Management of Commercially Generated Radioactive Waste (DOE 1980) that included general considerations for the design and location of geologic repositories. These are summarized in Table B-4.

Table B-4. Suggested Repository Site Selection Criteria (from DOE 1980, Section 5.1.1)

Factors Relevant to Geologic Disposal	Criteria
Depth of Repository – provides a barrier between the waste and the biosphere and protects the repository from human activities	• be located in a geologic environment with geometry adequate for repository placement
Properties of Host Rock – physical, chemical, and thermal properties determine the rock's capability to isolate and contain the waste and reduce unwanted interactions between the rock and waste	• have geologic characteristics compatible with waste isolation • have subsurface hydrologic and geochemical characteristics compatible with waste isolation
Hydrologic Regime – surface water and groundwater considerations are important because the existence of connected water channels could provide potential pathways for waste transport away from the repository	• be located so that the surficial hydrologic system, both during anticipated climatic cycles and during extreme natural phenomena, shall not cause unacceptable adverse impact on repository performance
Tectonic Stability – consideration will reduce the likelihood of deformation or disruption of host rock	• be located in a geologic setting that is known to have been stable or free from major disturbances such as faulting, deformation and volcanic activity for long time periods
Resource Potential – low resource potential is desirable to avoid loss of any economic resource and reduce the likelihood of future exploration activities	• be located in an area that does not contain desirable or needed mineral resources, or to the extent presently determinable, resources that may become valuable in the future
Multi-barrier Safety – redundant isolation features provided by the rock properties, geologic setting, and engineered barriers give overall added confidence that the waste will remain isolated	

In parallel with the U.S. efforts, the IAEA published a set of site selection factors for repositories in geological formations (IAEA 1977). These are summarized in Table B-5.

Table B-5. Site Selection Factors (from IAEA 1977, Section 4)

Category	Factors
Topography	• Surficial features, relief and terrain
Tectonics and Seismicity	• Areas of fault movement and earthquakes
Subsurface Conditions	• Depth of disposal zone • Formation configuration – thickness and extent • Consistency, uniformity, homogeneity or purity • Nature and extent of overlying, underlying and flanking beds
Structure	• Dip or inclination • Faults and joints • Diapirism
Physical and Chemical Properties	• Permeability, porosity and dispersiveness • Inclusions of gases and liquids • Rock mechanical behavior • Thermal effects • Sorption capacity • Mineral sources of water • Radiation effects
Hydrology	• Surface waters • Groundwaters (nature and occurrence of flow, direction, velocity, and volume of flow)
Future Geological Events	• Faulting and related earthquakes • Volcanic activity • Glaciation
General Geological and Engineering Conditions	• Site area and buffer zone • Pre-existing boreholes and excavations • Exploration boreholes, shafts, tunnels and excavations • Spoil disposal • Waste transportation • Ecological effects
Economic and Social Considerations	• Resource potential • Land value and use • Population density • Jurisdiction of the land and existing rights • Accessibility and services

B.2 NWPA

The NWPA (NWPA 1983, Section 112(a) (Guidelines)) states that "general guidelines for the recommendation of sites for repositories" shall be issued, that "such guidelines shall specify detailed geologic considerations that shall be primary criteria for the selection of sites in various geologic media", and that "the Secretary shall use guidelines established under this subsection in considering candidate sites for recommendation under subsection (b)". The NWPA further states that such guidelines shall:

- specify factors that qualify or disqualify any site from development as a repository, including factors pertaining to the location of valuable natural resources, hydrology, geophysics, seismic activity, and atomic energy defense activities, proximity to water supplies, proximity to populations, the effect upon the rights of users of water, and proximity to components of the National Park System, the National Wildlife Refuge System, the National Wild and Scenic Rivers System, the National Wilderness Preservation System, or National Forest Lands.
- take into consideration the proximity to sites where high-level radioactive waste and spent nuclear fuel is generated or temporarily stored and the transportation and safety factors involved in moving such waste to a repository.
- specify population factors that will disqualify any site from development as a repository if any surface facility of such repository would be located (1) in a highly populated area; or (2) adjacent to an area 1 mile by 1 mile having a population of not less than 1,000 individuals.
- require the Secretary to consider the cost and impact of transporting to the repository site the solidified high-level radioactive waste and spent fuel to be disposed of in the repository and the advantages of regional distribution in the siting of repositories.
- require the Secretary to consider the various geologic media in which sites for repositories may be located and, to the extent practicable, to recommend sites in different geologic media.

B.3 10 CFR Part 60

10 CFR 60 Subpart E, originally promulgated in 1983, contains generic siting criteria for geologic repositories in the form of favorable conditions that could provide reasonable assurance of waste isolation. 10 CFR 60 is the existing general NRC regulation for disposal of high-activity waste. These siting criteria were developed based on the recommendations of Section 112(a) of the NWPA (see Section B.2).

10 CFR 60.122 – Siting criteria

(a)

(1) A geologic setting shall exhibit an appropriate combination of the conditions specified in paragraph (b) of this section so that, together with the engineered barriers system, the favorable conditions present are sufficient to provide reasonable assurance that the performance objectives relating to isolation of the waste will be met.

(2) If any of the potentially adverse conditions specified in paragraph (c) of this section is present, it may compromise the ability of the geologic repository to meet the performance objectives relating to isolation of the waste.

(b) *Favorable conditions*

(1) The nature and rates of tectonic, hydrogeologic, geochemical, and geomorphic processes (or any of such processes) operating within the geologic setting during the Quaternary Period, when projected, would not affect or would favorably affect the ability of the geologic repository to isolate the waste.

(2) For disposal in the saturated zone, hydrogeologic conditions that provide:

(i) A host rock with low horizontal and vertical permeability;

(ii) Downward or dominantly horizontal hydraulic gradient in the host rock and immediately surrounding hydrogeologic units; and

(iii) Low vertical permeability and low hydraulic gradient between the host rock and the surrounding hydrogeologic units.

(3) Geochemical conditions that:

(i) Promote precipitation or sorption of radionuclides;

(ii) Inhibit the formation of particulates, colloids, and inorganic and organic complexes that increase the mobility of radionuclides; or

(iii) Inhibit the transport of radionuclides by particulates, colloids, and complexes.

(4) Mineral assemblages that, when subjected to anticipated thermal loading, will remain unaltered or alter to mineral assemblages having equal or increased capacity to inhibit radionuclide migration.

(5) Conditions that permit the emplacement of waste at a minimum depth of 300 meters from the ground surface. (The ground surface shall be deemed to be the elevation of the lowest point on the surface above the disturbed zone.)

(6) A low population density within the geologic setting and a postclosure controlled area that is remote from population centers.

(7) Pre-waste-emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment that substantially exceeds 1,000 years.

(8) For disposal in the unsaturated zone, hydrogeologic conditions that provide--

(i) Low moisture flux in the host rock and in the overlying and underlying hydrogeologic units;

(ii) A water table sufficiently below the underground facility such that fully saturated voids contiguous with the water table do not encounter the underground facility;

(iii) A laterally extensive low-permeability hydrogeologic unit above the host rock that would inhibit the downward movement of water or divert downward moving water to a location beyond the limits of the underground facility;

(iv) A host rock that provides for free drainage; or

(v) A climatic regime in which the average annual historic precipitation is a small percentage of the average annual potential evapotranspiration.

(c) *Potentially adverse conditions.* The following conditions are potentially adverse conditions if they are characteristic of the postclosure controlled area or may affect isolation within the controlled area.

(1) Potential for flooding of the underground facility, whether resulting from the occupancy and modification of floodplains or from the failure of existing or planned man-made surface water impoundments.

(2) Potential for foreseeable human activity to adversely affect the groundwater flow system, such as groundwater withdrawal, extensive irrigation, subsurface injection of fluids, underground pumped storage, military activity or construction of large scale surface water impoundments.

(3) Potential for natural phenomena such as landslides, subsidence, or volcanic activity of such a magnitude that large-scale surface water impoundments could be created that could change the regional groundwater flow system and thereby adversely affect the performance of the geologic repository.

(4) Structural deformation, such as uplift, subsidence, folding, or faulting that may adversely affect the regional groundwater flow system.

(5) Potential for changes in hydrologic conditions that would affect the migration of radionuclides to the accessible environment, such as changes in hydraulic gradient, average interstitial velocity, storage coefficient, hydraulic conductivity, natural recharge, potentiometric levels, and discharge points.

(6) Potential for changes in hydrologic conditions resulting from reasonably foreseeable climatic changes.

(7) Groundwater conditions in the host rock, including chemical composition, high ionic strength or ranges of Eh-pH, that could increase the solubility or chemical reactivity of the engineered barrier system.

(8) Geochemical processes that would reduce sorption of radionuclides, result in degradation of the rock strength, or adversely affect the performance of the engineered barrier system.

(9) Groundwater conditions in the host rock that are not reducing.

(10) Evidence of dissolutioning such as breccia pipes, dissolution cavities, or brine pockets.

(11) Structural deformation such as uplift, subsidence, folding, and faulting during the Quaternary Period.

(12) Earthquakes which have occurred historically that if they were to be repeated could affect the site significantly.

(13) Indications, based on correlations of earthquakes with tectonic processes and features, that either the frequency of occurrence or magnitude of earthquakes may increase.

(14) More frequent occurrence of earthquakes or earthquakes of higher magnitude than is typical of the area in which the geologic setting is located.

(15) Evidence of igneous activity since the start of the Quaternary Period.

(16) Evidence of extreme erosion during the Quaternary Period.

(17) The presence of naturally occurring materials, whether identified or undiscovered, within the site, in such form that:

> (i) Economic extraction is currently feasible or potentially feasible during the foreseeable future; or
>
> (ii) Such materials have greater gross value or net value than the average for other areas of similar size that are representative of and located within the geologic setting.

(18) Evidence of subsurface mining for resources within the site.

(19) Evidence of drilling for any purpose within the site.

(20) Rock or groundwater conditions that would require complex engineering measures in the design and construction of the underground facility or in the sealing of boreholes and shafts.

(21) Geomechanical properties that do not permit design of underground opening that will remain stable through permanent closure.

(22) Potential for the water table to rise sufficiently so as to cause saturation of an underground facility located in the unsaturated zone.

(23) Potential for existing or future perched water bodies that may saturate portions of the underground facility or provide a faster flow path from an underground facility located in the unsaturated zone to the accessible environment.

(24) Potential for the movement of radionuclides in a gaseous state through air-filled pore spaces of an unsaturated geologic medium to the accessible environment.

B.4 10 CFR Part 960

10 CFR 960 (General Guidelines for the Preliminary Screening of Potential Sites for a Nuclear Waste Repository), originally promulgated in 1984, contains a set of site suitability guidelines that were developed in accordance with Section 112(a) of the NWPA (see Section B.2) and were intended to complement 10 CFR 60 (see Section B.3) and 40 CFR 191.

10 CFR 960.3 – Implementation guidelines

The guidelines of this subpart establish the procedure and basis for applying the postclosure and the preclosure guidelines of subparts C and D, respectively, to evaluations of the suitability of sites. As may be appropriate during the siting process, this procedure requires consideration of a variety of geohydrologic settings and rock types, regionality, and environmental impacts and consultation with affected States, affected Indian tribes, and Federal agencies.

10 CFR 960.3–1–4–1 Site identification as potentially acceptable

The evidence for the identification of a potentially acceptable site shall be the types of information specified in appendix IV of this part. Such evidence will be relatively general and less detailed than that required for the nomination of a site as suitable for characterization. Because the gathering of detailed geologic data will not take place until after the recommendation of a site for characterization, the levels of information may be relatively greater for the evaluation of those guidelines in subparts C and D that pertain to surface-identifiable factors for such site. The sources of information shall include the literature in the public domain and the private sector, when available, and will be supplemented in some instances by surface investigations and conceptual engineering design studies conducted by the DOE. Geologic surface investigations may include the mapping of identifiable rock masses, fracture and joint characteristics, and fault zones. Other surface investigations will consider the aquatic and terrestrial ecology; water rights and uses; topography; potential offsite hazards; natural resource concentrations; national or State protected resources; existing transportation systems; meteorology and climatology; population densities, centers, and distributions; and general socioeconomic characteristics.

10 CFR 960.3–2–1 Site screening for potentially acceptable sites

To identify potentially acceptable sites for the development of other than the first repository, the process shall begin with site-screening activities that consider large land masses that contain rock formations of suitable depth, thickness, and lateral extent and have structural, hydrologic, and tectonic features favorable for waste containment and isolation. Within those large land masses, subsequent site-screening activities shall focus on successively smaller and increasingly more suitable land units. This process shall be developed in consultation with the States that contain land units under consideration. It shall be implemented in a sequence of steps that first applies the applicable disqualifying conditions to eliminate land units on the basis of the evidence specified in § 960.3–1–4–1 and in accordance with the application requirements set forth in appendix III of this part. After the disqualifying conditions have been applied, the favorable and potentially adverse conditions, as identified for each remaining land unit, shall be evaluated. The presence of favorable conditions shall favor a given land unit, while the presence of potentially adverse conditions shall penalize that land unit.

__10 CFR 960.4 Postclosure guidelines (Subpart C)__

The guidelines in this subpart specify the factors to be considered in evaluating and comparing sites on the basis of expected repository performance after closure. The postclosure guidelines are separated into a system guideline and eight technical guidelines.

__10 CFR 960.4–1 System guideline__

(a) *Qualifying Condition.* The geologic setting at the site shall allow for the physical separation of radioactive waste from the accessible environment after closure in accordance with the requirements of 40 CFR part 191, subpart B, as implemented by the provisions of 10 CFR part 60. The geologic setting at the site will allow for the use of engineered barriers to ensure compliance with the requirements of 40 CFR part 191 and 10 CFR part 60 (see appendix I of this part)

__10 CFR 960.4–2 Technical guidelines__

The technical guidelines in this subpart set forth qualifying, favorable, potentially adverse, and, in five guidelines, disqualifying conditions on the characteristics, processes, and events that may influence the performance of a repository system after closure. The favorable conditions and the potentially adverse conditions under each guideline are not listed in any assumed order of importance.

__10 CFR 960.4-2-1 Geohydrology__

(a) *Qualifying condition*. The present and expected geohydrologic setting of a site shall be compatible with waste containment and isolation. The geohydrologic setting, considering the characteristics of and the processes operating within the geologic setting, shall permit compliance with (1) the requirements specified in § 960.4-1 for radionuclide releases to the accessible environment and (2) the requirements specified in 10 CFR 60.113 for radionuclide releases from the engineered-barrier system using reasonably available technology.

(b) *Favorable conditions.*

(1) Site conditions such that the pre-waste-emplacement ground-water travel time along any path of likely radionuclide travel from the disturbed zone to the accessible environment would be more than 10,000 years.

(2) The nature and rates of hydrologic processes operating within the geologic setting during the Quaternary Period would, if continued into the future, not affect or would favorably affect the ability of the geologic repository to isolate the waste during the next 100,000 years.

(3) Sites that have stratigraphic, structural, and hydrologic features such that the geohydrologic system can be readily characterized and modeled with reasonable certainty.

(4) For disposal in the saturated zone, at least one of the following pre-waste-emplacement conditions exists:

(i) A host rock and immediately surrounding geohydrologic units with low hydraulic conductivities.

(ii) A downward or predominantly horizontal hydraulic gradient in the host rock and in the immediately surrounding geohydrologic units.

(iii) A low hydraulic gradient in and between the host rock and the immediately surrounding geohydrologic units.

(iv) High effective porosity together with low hydraulic conductivity in rock units along paths of likely radionuclide travel between the host rock and the accessible environment.

(5) For disposal in the unsaturated zone, at least one of the following pre-waste-emplacement conditions exists:

(i) A low and nearly constant degree of saturation in the host rock and in the immediately surrounding geohydrologic units.

(ii) A water table sufficiently below the underground facility such that the fully saturated voids continuous with the water table do not encounter the host rock.

(iii) A geohydrologic unit above the host rock that would divert the downward infiltration of water beyond the limits of the emplaced waste.

(iv) A host rock that provides for free drainage.

(v) A climatic regime in which the average annual historical precipitation is a small fraction of the average annual potential evapotranspiration.

NOTE: The DOE will, in accordance with the general principles set forth in § 960.1 of these regulations, revise the guidelines as necessary, to ensure consistency with the final NRC regulations on the unsaturated zone, which were published as a proposed rule on February 16, 1984, in 49 FR 5934.

(c) *Potentially adverse conditions*.

(1) Expected changes in geohydrologic conditions—such as changes in the hydraulic gradient, the hydraulic conductivity, the effective porosity, and the ground-water flux through the host rock and the surrounding geohydrologic units—sufficient to significantly increase the transport of radionuclides to the accessible environment as compared with pre-waste-emplacement conditions.

(2) The presence of ground-water sources, suitable for crop irrigation or human consumption without treatment, along ground-water flow paths from the host rock to the accessible environment.

(3) The presence in the geologic setting of stratigraphic or structural features—such as dikes, sills, faults, shear zones, folds, dissolution effects, or brine pockets—if their presence could significantly contribute to the difficulty of characterizing or modeling the geohydrologic system.

(d) *Disqualifying condition*. A site shall be disqualified if the pre-waste-emplacement ground-water travel time from the disturbed zone to the accessible environment is expected to be less than 1,000 years along any pathway of likely and significant radionuclide travel.

10 CFR 960.4-2-2 Geochemistry

(a) *Qualifying condition*. The present and expected geochemical characteristics of a site shall be compatible with waste containment and isolation. Considering the likely chemical interactions among radionuclides, the host rock, and the ground water, the characteristics of and the processes operating within the geologic setting shall permit compliance with (1) the requirements specified in § 960.4-1 for radionuclide releases to the accessible environment and (2) the requirements specified in 10 CFR 60.113 for radionuclide releases from the engineered-barrier system using reasonably available technology.

(b) *Favorable conditions*.

(1) The nature and rates of the geochemical processes operating within the geologic setting during the Quaternary Period would, if continued into the future, not affect or would favorably affect the ability of the geologic repository to isolate the waste during the next 100,000 years.

(2) Geochemical conditions that promote the precipitation, diffusion into the rock matrix, or sorption of radionuclides; inhibit the formation of particulates, colloids, inorganic complexes, or organic complexes that increase the mobility of radionuclides; or inhibit the transport of radionuclides by particulates, colloids, or complexes.

(3) Mineral assemblages that, when subjected to expected repository conditions, would remain unaltered or would alter to mineral assemblages with equal or increased capability to retard radionuclide transport.

(4) A combination of expected geochemical conditions and a volumetric flow rate of water in the host rock that would allow less than 0.001 percent per year of the total radionuclide inventory in the repository at 1,000 years to be dissolved.

(5) Any combination of geochemical and physical retardation processes that would decrease the predicted peak cumulative releases of radionuclides to the accessible environment by a factor of 10 as compared to those predicted on the basis of ground-water travel time without such retardation.

(c) *Potentially adverse conditions*.

(1) Ground-water conditions in the host rock that could affect the solubility or the chemical reactivity of the engineered-barrier system to the extent that the expected repository performance could be compromised.

(2) Geochemical processes or conditions that could reduce the sorption of radionuclides or degrade the rock strength.

(3) Pre-waste-emplacement ground-water conditions in the host rock that are chemically oxidizing.

10 CFR 960.4-2-3 Rock characteristics

(a) *Qualifying condition*. The present and expected characteristics of the host rock and surrounding units shall be capable of accommodating the thermal, chemical, mechanical, and radiation stresses expected to be induced by repository construction, operation, and closure and by expected interactions among the waste, host rock, ground water, and engineered components. The characteristics of and the processes operating within the geologic setting shall permit compliance with (1) the requirements specified in § 960.4-1 for radionuclide releases to the accessible environment and (2) the requirements set forth in 10 CFR 60.113 for radionuclide releases from the engineered-barrier system using reasonably available technology.

(b) *Favorable Conditions*.

(1) A host rock that is sufficiently thick and laterally extensive to allow significant flexibility in selecting the depth, configuration, and location of the underground facility to ensure isolation.

(2) A host rock with a high thermal conductivity, a low coefficient of thermal expansion, or sufficient ductility to seal fractures induced by repository construction, operation, or closure or by interactions among the waste, host rock, ground water, and engineered components.

(c) *Potentially adverse conditions*.

(1) Rock conditions that could require engineering measures beyond reasonably available technology for the construction, operation, and closure of the repository, if such measures are necessary to ensure waste containment or isolation.

(2) Potential for such phenomena as thermally induced fractures, the hydration or dehydration of mineral components, brine migration, or other physical, chemical, or radiation-related phenomena that could be expected to affect waste containment or isolation.

(3) A combination of geologic structure, geochemical and thermal properties, and hydrologic conditions in the host rock and surrounding units such that the heat generated by the waste could significantly decrease the isolation provided by the host rock as compared with pre-waste-emplacement conditions.

10 CFR 960.4-2-4 Climatic changes

(a) *Qualifying condition*. The site shall be located where future climatic conditions will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in § 960.4-1. In predicting the likely future climatic conditions at a site, the DOE will consider the global, regional, and site climatic patterns during the Quaternary Period, considering the geomorphic evidence of the climatic conditions in the geologic setting.

(b) Favorable conditions.

(1) A surface-water system such that expected climatic cycles over the next 100,000 years would not adversely affect waste isolation.

(2) A geologic setting in which climatic changes have had little effect on the hydrologic system throughout the Quaternary Period.

(c) Potentially adverse conditions.

(1) Evidence that the water table could rise sufficiently over the next 10,000 years to saturate the underground facility in a previously unsaturated host rock.

(2) Evidence that climatic changes over the next 10,000 years could cause perturbations in the hydraulic gradient, the hydraulic conductivity, the effective porosity, or the ground-water flux through the host rock and the surrounding geohydrologic units, sufficient to significantly increase the transport of radionuclides to the accessible environment.

10 CFR 960.4-2-5 Erosion

(a) *Qualifying condition*. The site shall allow the underground facility to be placed at a depth such that erosional processes acting upon the surface will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in § 960.4-1. In predicting the likelihood of potentially disruptive erosional processes, the DOE will consider the climatic, tectonic, and geomorphic evidence of rates and patterns of erosion in the geologic setting during the Quaternary Period.

(b) Favorable conditions.

(1) Site conditions that permit the emplacement of waste at a depth of at least 300 meters below the directly overlying ground surface.

(2) A geologic setting where the nature and rates of the erosional processes that have been operating during the Quaternary Period are predicted to have less than one chance in 10,000 over the next 10,000 years of leading to releases of radionuclides to the accessible environment.

(3) Site conditions such that waste exhumation would not be expected to occur during the first one million years after repository closure.

(c) Potentially adverse conditions.

(1) A geologic setting that shows evidence of extreme erosion during the Quaternary Period.

(2) A geologic setting where the nature and rates of geomorphic processes that have been operating during the Quaternary Period could, during the first 10,000 years after closure, adversely affect the ability of the geologic repository to isolate the waste.

(d) *Disqualifying condition*. The site shall be disqualified if site conditions do not allow all portions of the underground facility to be situated at least 200 meters below the directly overlying ground surface.

10 CFR 960.4-2-6 Dissolution

(a) *Qualifying condition*. The site shall be located such that any subsurface rock dissolution will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in § 960.4-1. In predicting the likelihood of dissolution within the geologic setting at a site, the DOE will consider the evidence of dissolution within that setting during the Quaternary Period, including the locations and characteristics of dissolution fronts or other dissolution features, if identified.

(b) *Favorable condition*. No evidence that the host rock within the site was subject to significant dissolution during the Quaternary Period.

(c) *Potentially adverse condition*. Evidence of dissolution within the geologic setting—such as breccia pipes, dissolution cavities, significant volumetric reduction of the host rock or surrounding strata, or any structural collapse—such that a hydraulic interconnection leading to a loss of waste isolation could occur.

(d) *Disqualifying condition*. The site shall be disqualified if it is likely that, during the first 10,000 years after closure, active dissolution, as predicted on the basis of the geologic record, would result in a loss of waste isolation.

10 CFR 960.4-2-7 Tectonics

(a) *Qualifying condition*. The site shall be located in a geologic setting where future tectonic processes or events will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in § 960.4-1. In predicting the likelihood of potentially disruptive tectonic processes or events, the DOE will consider the structural, stratigraphic, geophysical, and seismic evidence for the nature and rates of tectonic processes and events in the geologic setting during the Quaternary Period.

(b) *Favorable condition*. The nature and rates of igneous activity and tectonic processes (such as uplift, subsidence, faulting, or folding), if any, operating within the geologic setting during the Quaternary Period would, if continued into the future, have less than one chance in 10,000 over the first 10,000 years after closure of leading to releases of radionuclides to the accessible environment.

(c) *Potentially adverse conditions*.

(1) Evidence of active folding, faulting, diapirism, uplift, subsidence, or other tectonic processes or igneous activity within the geologic setting during the Quaternary Period.

(2) Historical earthquakes within the geologic setting of such magnitude and intensity that, if they recurred, could affect waste containment or isolation.

(3) Indications, based on correlations of earthquakes with tectonic processes and features, that either the frequency of occurrence or the magnitude of earthquakes within the geologic setting may increase.

(4) More-frequent occurrences of earthquakes or earthquakes of higher magnitude than are representative of the region in which the geologic setting is located.

(5) Potential for natural phenomena such as landslides, subsidence, or volcanic activity of such magnitudes that they could create large-scale surface-water impoundments that could change the regional ground-water flow system.

(6) Potential for tectonic deformations—such as uplift, subsidence, folding, or faulting—that could adversely affect the regional ground-water flow system.

(d) *Disqualifying condition*. A site shall be disqualified if, based on the geologic record during the Quaternary Period, the nature and rates of fault movement or other ground motion are expected to be such that a loss of waste isolation is likely to occur.

10 CFR 960.4-2-8 Human interference

The site shall be located such that activities by future generations at or near the site will not be likely to affect waste containment and isolation. In assessing the likelihood of such activities, the DOE will consider the estimated effectiveness of the permanent markers and records required by 10 CFR part 60, taking into account site-specific factors, as stated in §§ 960.4-2-8-1 and 960.4-2-8-2, that could compromise their continued effectiveness.

10 CFR 960.4-2-8-1 Natural resources

(a) *Qualifying condition*. This site shall be located such that—considering permanent markers and records and reasonable projections of value, scarcity, and technology—the natural resources, including ground water suitable for crop irrigation or human consumption without treatment, present at or near the site will not be likely to give rise to interference activities that would lead to radionuclide releases greater than those allowable under the requirements specified in § 960.4-1.

(b) *Favorable conditions*.

(1) No known natural resources that have or are projected to have in the foreseeable future a value great enough to be considered a commercially extractable resource.

(2) Ground water with 10,000 parts per million or more of total dissolved solids along any path of likely radionuclide travel from the host rock to the accessible environment.

(c) *Potentially adverse condition*s.

(1) Indications that the site contains naturally occurring materials, whether or not actually identified in such form that (i) economic extraction is potentially feasible during the foreseeable future or (ii) such materials have a greater gross value, net value, or commercial potential than the average for other areas of similar size that are representative of, and located in, the geologic setting.

(2) Evidence of subsurface mining or extraction for resources within the site if it could affect waste containment or isolation.

(3) Evidence of drilling within the site for any purpose other than repository-site evaluation to a depth sufficient to affect waste containment and isolation.

(4) Evidence of a significant concentration of any naturally occurring material that is not widely available from other sources.

(5) Potential for foreseeable human activities—such as ground-water withdrawal, extensive irrigation, subsurface injection of fluids, underground pumped storage, military activities, or the construction of large-scale surface-water impoundments—that could adversely change portions of the ground-water flow system important to waste isolation.

(d) *Disqualifying conditions.* A site shall be disqualified if—

(1) Previous exploration, mining, or extraction activities for resources of commercial importance at the site have created significant pathways between the projected underground facility and the accessible environment; or

(2) Ongoing or likely future activities to recover presently valuable natural mineral resources outside the controlled area would be expected to lead to an inadvertent loss of waste isolation.

10 CFR 960.4-2-8-2 Site ownership and control

(a) *Qualifying condition*. The site shall be located on land for which the DOE can obtain, in accordance with the requirements of 10 CFR part 60, ownership, surface and subsurface rights, and control of access that are required in order that potential surface and subsurface activities as the site will not be likely to lead to radionuclide releases greater than those allowable under the requirements specified in § 960.4-1.

(b) *Favorable condition*. Present ownership and control of land and all surface and subsurface rights by the DOE.

(c) *Potentially adverse condition*. Projected land-ownership conflicts that cannot be successfully resolved through voluntary purchase-sell agreements, nondisputed agency-to-agency transfers of title, or Federal condemnation proceedings.

10 CFR 960.5 Preclosure guidelines (Subpart D)

The guidelines in this subpart specify the factors to be considered in evaluating and comparing sites on the basis of expected repository performance before closure. The preclosure guidelines are separated into three system guidelines and eleven technical guidelines.

10 CFR 960.5–1 System guidelines

(a) *Qualifying conditions* –

(1) *Preclosure radiological safety*. Any projected radiological exposures of the general public and any projected releases of radioactive materials to restricted and unrestricted areas during repository operation and closure shall meet the applicable safety requirements set forth in 10 CFR part 20, 10 CFR part 60, and 40 CFR 191, subpart A (see appendix II of this part).

(2) *Environment, socioeconomics, and transportation*. During repository siting, construction, operation, closure, and decommissioning the public and the environment shall be adequately protected from the hazards posed by the disposal of radioactive waste.

(3) *Ease and cost of siting, construction, operation, and closure*. Repository siting, construction, operation, and closure shall be demonstrated to be technically feasible on the basis of reasonably available technology, and the associated costs shall be demonstrated to be reasonable relative to other available and comparable siting options.

10 CFR 960.5–2 Technical guidelines

The technical guidelines in this subpart set forth qualifying, favorable, potentially adverse, and, in seven guidelines, disqualifying conditions for the characteristics, processes, and events that influence the suitability of a site relative to the preclosure system guidelines. These conditions are separated into three main groups: Preclosure radiological safety; environment, socioeconomics, and transportation; and ease and cost of siting, construction, operation, and closure. The first group includes conditions on population density and distribution, site ownership and control, meteorology, and offsite installations and operations. The second group includes conditions related to environmental quality and socioeconomic impacts in areas potentially affected by a repository and to the transportation of waste to a repository site. The third group includes conditions on the surface characteristics of the site, the characteristics of the host rock and surrounding strata, hydrology, and tectonics. The individual technical guidelines within each group, as well as the favorable conditions and the potentially adverse conditions under each guideline, are not listed in any assumed order of importance.

Preclosure Radiological Safety

10 CFR 960.5-2-1 Population density and distribution

(a) *Qualifying condition.* The site shall be located such that, during repository operation and closure, (1) the expected average radiation dose to members of the public within any highly populated area will not be likely to exceed a small fraction of the limits allowable under the requirements specified in § 960.5-1(a)(1), and (2) the expected radiation dose to any member of the public in an unrestricted area will not be likely to exceed the limit allowable under the requirements specified in § 960.5-1(a)(1).

(b) *Favorable conditions.*

(1) A low population density in the general region of the site.

(2) Remoteness of site from highly populated areas.

(c) *Potentially adverse conditions.*

(1) High residential, seasonal, or daytime population density within the projected site boundaries.

(2) Proximity of the site to highly populated areas, or to areas having at least 1,000 individuals in an area 1 mile by 1 mile as defined by the most recent decennial count of the U.S. census.

(d) *Disqualifying conditions.* A site shall be *disqualified* if—

(1) Any surface facility of a repository would be located in a highly populated area; or

(2) Any surface facility of a repository would be located adjacent to an area 1 mile by 1 mile having a population of not less than 1,000 individuals as enumerated by the most recent U.S. census; or

(3) The DOE could not develop an emergency preparedness program which meets the requirements specified in DOE Order 5500.3 (Reactor and Non-Reactor Facility Emergency Planning, Preparedness, and Response Program for Department of Energy Operations) and related guides or, when issued by the NRC, in 10 CFR part 60, subpart I, "Emergency Planning Criteria."

10 CFR 960.5-2-2 Site ownership and control

(a) *Qualifying condition.* The site shall be located on land for which the DOE can obtain, in accordance with the requirements of 10 CFR 60.121, ownership, surface and subsurface rights, and control of access that are required in order that surface and subsurface activities during repository operation and closure will not be likely to lead to radionuclide releases to an unrestricted area greater than those allowable under the requirements specified in § 960.5-1(a)(1).

(b) *Favorable condition.* Present ownership and control of land and all surface and subsurface mineral and water rights by the DOE.

(c) *Potentially adverse condition.* Projected land-ownership conflicts that cannot be successfully resolved through voluntary purchase-sell agreements, nondisputed agency-to-agency transfers of title, or Federal condemnation proceedings.

10 CFR 960.5-2-3 Meteorology

(a) *Qualifying condition.* The site shall be located such that expected meteorological conditions during repository operation and closure will not be likely to lead to radionuclide releases to an unrestricted area greater than those allowable under the requirements specified in § 960.5-1(a)(1).

(b) *Favorable condition.* Prevailing meteorological conditions such that any radioactive releases to the atmosphere during repository operation and closure would be effectively dispersed, thereby reducing significantly the likelihood of unacceptable exposure to any member of the public in the vicinity of the repository.

(c) *Potentially adverse conditions.*

(1) Prevailing meteorological conditions such that radioactive emissions from repository operation of closure could be preferentially transported toward localities in the vicinity of the repository with higher population densities than are the average for the region.

(2) History of extreme weather phenomena—such as hurricanes, tornadoes, severe floods, or severe and frequent winter storms—that could significantly affect repository operation or closure.

10 CFR 960.5-2-4 Offsite installations and operations

(a) *Qualifying condition.* The site shall be located such that present projected effects from nearby industrial, transportation, and military installations and operations, including atomic energy defense activities, (1) will not significantly affect repository siting, construction, operation, closure, or decommissioning or can be accommodated by engineering measures and (2), when considered together with emissions from repository operation and closure, will not be likely to lead to radionuclide releases to an unrestricted area greater than those allowable under the requirements specified in § 960.5-1(a)(1).

(b) *Favorable condition.* Absence of contributing radioactive releases from other nuclear installations and operations that must be considered under the requirements of 40 CFR 191, subpart A.

(c) *Potentially adverse conditions.*

(1) The presence of nearby potentially hazardous installations or operations that could adversely affect repository operation or closure.

(2) Presence of other nuclear installations and operations, subject to the requirements of 40 CFR part 190 or 40 CFR part 191, subpart A, with actual or projected releases near the maximum value permissible under those standards.

(d) *Disqualifying condition.* A site shall be disqualified if atomic energy defense activities in proximity to the site are expected to conflict irreconcilably with repository siting, construction, operation, closure, or decommissioning.

Environment, Socioeconomics, and Transportation

10 CFR 960.5-2-5 Environmental quality

(a) *Qualifying condition.* The site shall be located such that (1) the quality of the environment in the affected area during this and future generations will be adequately protected during repository siting, construction, operation, closure, and decommissioning, and projected environmental impacts in the affected area can be mitigated to an acceptable degree, taking into account programmatic, technical, social, economic, and environmental factors; and (2) the requirements specified in § 960.5-1(a)(2) can be met.

(b) *Favorable conditions.*

(1) Projected ability to meet, within time constraints, all Federal, State, and local procedural and substantive environmental requirements applicable to the site and the activities proposed to take place thereon.

(2) Potential significant adverse environmental impacts to present and future generations can be mitigated to an insignificant level through the application of reasonable measures, taking into account programmatic, technical, social, economic, and environmental factors.

(c) *Potentially adverse conditions.*

(1) Projected major conflict with applicable Federal, State, or local environmental requirements.

(2) Projected significant adverse environmental impacts that cannot be avoided or mitigated.

(3) Proximity to, or projected significant adverse environmental impacts of the repository or its support facilities on, a component of the National Park System, the National Wildlife Refuge System, the National Wild and Scenic Rivers System, the National Wilderness Preservation System, or National Forest Land.

(4) Proximity to, and projected significant adverse environmental impacts of the repository or its support facilities on, a significant State or regional protected resource area, such as a State park, a wildlife area, or a historical area.

(5) Proximity to, and projected significant adverse environmental impacts of the repository and its support facilities on, a significant Native American resource, such as a major Indian religious site, or other sites of unique cultural interest.

(6) Presence of critical habitats for threatened or endangered species that may be compromised by the repository or its support facilities.

(d) *Disqualifying conditions.* Any of the following conditions shall *disqualify* a site:

(1) During repository siting, construction, operation, closure, or decommissioning the quality of the environment in the affected area could not be adequately protected or projected environmental impacts in the affected area could not be mitigated to an acceptable degree, taking into account programmatic, technical, social, economic, and environmental factors.

(2) Any part of the restricted area or repository support facilities would be located within the boundaries of a component of the National Park System, the National Wildlife Refuge System, the National Wilderness Preservation System, or the National Wild and Scenic Rivers System.

(3) The presence of the restricted area or the repository support facilities would conflict irreconcilably with the previously designated resource-preservation use of a component of the National Park System, the National Wildlife Refuge System, the National Wilderness Preservation System, the National Wild and Scenic Rivers System, or National Forest Lands, or any comparably significant State protected resource that was dedicated to resource preservation at the time of the enactment of the Act.

10 CFR 960.5-2-6 Socioeconomic impacts

(a) *Qualifying condition.* The site shall be located such that (1) any significant adverse social and/or economic impacts induced in communities and surrounding regions by repository siting, construction, operation, closure, and decommissioning can be offset by reasonable mitigation or compensation, as determined by a process of analysis, planning, and consultation among the DOE, affected State and local government jurisdictions, and affected Indian tribes; and (2) the requirements specified in § 960.5-1(a)(2) can be met.

(b) *Favorable conditions.*

(1) Ability of an affected area to absorb the project-related population changes without significant disruptions of community services and without significant impacts on housing supply and demand.

(2) Availability of an adequate labor force in the affected area.

(3) Projected net increases in employment and business sales, improved community services, and increased government revenues in the affected area.

(4) No projected substantial disruption of primary sectors of the economy of the affected area.

(c) *Potentially adverse conditions.*

(1) Potential for significant repository-related impacts on community services, housing supply and demand, and the finances of State and local government agencies in the affected area.

(2) Lack of an adequate labor force in the affected area.

(3) Need for repository-related purchase or acquisition of water rights, if such rights could have significant adverse impacts on the present or future development of the affected area.

(4) Potential for major disruptions of primary sectors of the economy of the affected area.

(d) *Disqualifying condition.* A site shall be disqualified if repository construction, operation, or closure would significantly degrade the quality, or significantly reduce the quantity, of water from major sources of offsite supplies presently suitable for human consumption or crop irrigation and such impacts cannot be compensated for, or mitigated by, reasonable measures.

10 CFR 960.5-2-7 Transportation

(a) *Qualifying condition.* The site shall be located such that (1) the access routes constructed from existing local highways and railroads to the site (i) will not conflict irreconcilably with the previously designated use of any resource listed in § 960.5-2-5(d) (2) and (3); (ii) can be designed and constructed using reasonably available technology; (iii) will not require transportation system components to meet performance standards more stringent than those specified in the applicable DOT and NRC regulations, nor require the development of new packaging containment technology; (iv) will allow transportation operations to be conducted without causing an unacceptable risk to the public or unacceptable environmental impacts, taking into account programmatic, technical, social, economic, and environmental factors; and (2) the requirements of § 960.5-1(a)(2) can be met.

(b) *Favorable conditions.*

(1) Availability of access routes from local existing highways and railroads to the site which have any of the following characteristics:

(i) Such routes are relatively short and economical to construct as compared to access routes for other comparable siting options.

(ii) Federal condemnation is not required to acquire rights-of-way for the access routes.

(iii) Cuts, fills, tunnels, or bridges are not required.

(iv) Such routes are free of sharp curves or steep grades and are not likely to be affected by landslides or rock slides.

(v) Such routes bypass local cities and towns.

(2) Proximity to local highways and railroads that provide access to regional highways and railroads and are adequate to serve the repository without significant upgrading or reconstruction.

(3) Proximity to regional highways, mainline railroads, or inland waterways that provide access to the national transportation system.

(4) Availability of a regional railroad system with a minimum number of interchange points at which train crew and equipment changes would be required.

(5) Total projected life-cycle cost and risk for transportation of all wastes designated for the repository site which are significantly lower than those for comparable siting options, considering locations of present and potential sources of waste, interim storage facilities, and other repositories.

(6) Availability of regional and local carriers—truck, rail, and water—which have the capability and are willing to handle waste shipments to the repository.

(7) Absence of legal impediment with regard to compliance with Federal regulations for the transportation of waste in or through the affected State and adjoining States.

(8) Plans, procedures, and capabilities for response to radioactive waste transportation accidents in the affected State that are completed or being developed.

(9) A regional meteorological history indicating that significant transportation disruptions would not be routine seasonal occurrences.

(c) *Potentially adverse conditions.*

(1) Access routes to existing local highways and railroads that are expensive to construct relative to comparable siting options.

(2) Terrain between the site and existing local highways and railroads such that steep grades, sharp switchbacks, rivers, lakes, landslides, rock slides, or potential sources of hazard to incoming waste shipments will be encountered along access routes to the site.

(3) Existing local highways and railroads that could require significant reconstruction or upgrading to provide adequate routes to the regional and national transportation system.

(4) Any local condition that could cause the transportation-related costs, environmental impacts, or risk to public health and safety from waste transportation operations to be significantly greater than those projected for other comparable siting options.

Ease and Cost of Siting, Construction, Operation, and Closure

10 CFR 960.5-2-8 Surface characteristics

(a) *Qualifying condition.* The site shall be located such that, considering the surface characteristics and conditions of the site and surrounding area, including surface-water systems and the terrain, the requirements specified in § 960.5-1(a)(3) can be met during repository siting, construction, operation, and closure.

(b) *Favorable conditions.*

(1) Generally flat terrain.

(2) Generally well-drained terrain.

(c) *Potentially adverse condition.* Surface characteristics that could lead to the flooding of surface or underground facilities by the occupancy and modification of flood plains, the failure of existing or planned man-made surface-water impoundments, or the failure of engineered components of the repository.

10 CFR 960.5-2-9 Rock characteristics

(a) *Qualifying condition.* The site shall be located such that (1) the thickness and lateral extent and the characteristics and composition of the host rock will be suitable for accommodation of the underground facility; (2) repository construction, operation, and closure will not cause undue hazard to personnel; and (3) the requirements specified in § 960.5-1(a)(3) can be met.

(b) *Favorable conditions.*

(1) A host rock that is sufficiently thick and laterally extensive to allow significant flexibility in selecting the depth, configuration, and location of the underground facility.

(2) A host rock with characteristics that would require minimal or no artificial support for underground openings to ensure safe repository construction, operation, and closure.

(c) *Potentially adverse conditions.*

(1) A host rock that is suitable for repository construction, operation, and closure, but is so thin or laterally restricted that little flexibility is available for selecting the depth, configuration, or location of an underground facility.

(2) In situ characteristics and conditions that could require engineering measures beyond reasonably available technology in the construction of the shafts and underground facility.

(3) Geomechanical properties that could necessitate extensive maintenance of the underground openings during repository operation and closure.

(4) Potential for such phenomena as thermally induced fracturing, the hydration and dehydration of mineral components, or other physical, chemical, or radiation-related phenomena that could lead to safety hazards or difficulty in retrieval during repository operation.

(5) Existing faults, shear zones, pressurized brine pockets, dissolution effects, or other stratigraphic or structural features that could compromise the safety of repository personnel because of water inflow or construction problems.

(d) *Disqualifying condition.* The site shall be *disqualified* if the rock characteristics are such that the activities associated with repository construction, operation, or closure are predicted to cause significant risk to the health and safety of personnel, taking into account mitigating measures that use reasonably available technology.

10 CFR 960.5-2-10 Hydrology

(a) *Qualifying condition.* The site shall be located such that the geohydrologic setting of the site will (1) be compatible with the activities required for repository construction, operation, and closure; (2) not compromise the intended functions of the shaft liners and seals; and (3) permit the requirements specified in § 960.5-1(a)(3) to be met.

(b) *Favorable conditions.*

(1) Absence of aquifers between the host rock and the land surface.

(2) Absence of surface-water systems that could potentially cause flooding of the repository.

(3) Availability of the water required for repository construction, operation, and closure.

(c) *Potentially adverse condition.* Ground-water conditions that could require complex engineering measures that are beyond reasonably available technology for repository construction, operation, and closure.

(d) *Disqualifying condition.* A site shall be disqualified if, based on expected ground-water conditions, it is likely that engineering measures that are beyond reasonably available technology will be required for exploratory-shaft construction or for repository construction, operation, or closure.

10 CFR 960.5-2-11 Tectonics

(a) *Qualifying Conditions.* The site shall be located in a geologic setting in which any projected effects of expected tectonic phenomena or igneous activity on repository construction, operation, or closure will be such that the requirements specified in § 960.5-1(a)(3) can be met.

(b) *Favorable Condition.* The nature and rates of faulting, if any, within the geologic setting are such that the magnitude and intensity of the associated seismicity are significantly less than those generally allowable for the construction and operation of nuclear facilities.

(c) *Potentially Adverse Conditions.*

(1) Evidence of active faulting within the geologic setting.

(2) Historical earthquakes or past man-induced seismicity that, if either were to recur, could produce ground motion at the site in excess of reasonable design limits.

(3) Evidence, based on correlations of earthquakes with tectonic processes and features, (e.g., faults) within the geologic setting, that the magnitude of earthquakes at the site during repository construction, operation, and closure may be larger than predicted from historical seismicity.

(d) *Disqualifying Condition.* A site shall be disqualified if, based on the expected nature and rates of fault movement or other ground motion, it is likely that engineering measures that are beyond reasonably available technology will be required for exploratory-shaft construction or for repository construction, operation, or closure.

APPENDIX C – POTENTIALLY RELEVANT DESIGN CRITERIA

This Appendix includes excerpts from various documents and regulations that contain design criteria for high-activity waste repositories and DBD.

C.1 10 CFR Part 60

10 CFR 60 Subpart E, originally promulgated in 1983, contains general design criteria for the structures, systems, and components (SSCs) of a geologic repository. 10 CFR 60 is the existing general NRC regulation for disposal of high-activity waste.

SSCs are not explicitly defined in 10 CFR 60 (or in 10 CFR 63), but 10 CFR 63.2 defines "*Important to safety*, with reference to *structures, systems, and components"* as "those engineered features of the geologic repository operations area whose function is to provide reasonable assurance that high-level waste can be received, handled, packaged, stored, emplaced, and retrieved without exceeding the [pre-closure safety] requirements of [10 CFR 63.111]."

Similarly, IAEA (2007) provides the following definition:

Structures, Systems and Components (SSCs) – A general term encompassing all of the elements (items) of a facility or activity which contribute to protection and safety, except human factors.

- *Structures* are the passive elements: buildings, vessels, shielding, etc.
- A *system* comprises several components, assembled in such a way as to perform a specific (active) function.
- A *component* is a discrete element of a system. Examples of components are wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks and valves.

10 CFR 60.130 – General considerations

(a) Pursuant to the provisions of § 60.21(c)(2)(i), an application for construction authorization for a high-level radioactive waste repository at a geologic repository operations area, and an application for a license to receive, possess, store, and dispose of high-level radioactive waste in the geologic repository operations area, must include the principal design criteria for a proposed facility. The principal design criteria establish the necessary design, fabrication, construction, testing, maintenance, and performance requirements for structures, systems, and components important to safety and/or important to waste isolation. Sections 60.131 through 60.134 specify minimum requirements for the principal design criteria for the geologic repository operations area.

(b) These design criteria are not intended to be exhaustive. However, omissions in §§ 60.131 through 60.134 do not relieve DOE from any obligation to provide such features in a specific facility needed to achieve the performance objectives.

10 CFR 60.131 – General design criteria for the geologic repository operations area

(a) *Radiological protection*. The geologic repository operations area shall be designed to maintain radiation doses, levels, and concentrations of radioactive material in air in restricted areas within the limits specified in part 20 of this chapter. Design shall include:

(1) Means to limit concentrations of radioactive material in air;

(2) Means to limit the time required to perform work in the vicinity of radioactive materials, including, as appropriate, designing equipment for ease of repair and replacement and providing adequate space for ease of operation;

(3) Suitable shielding;

(4) Means to monitor and control the dispersal of radioactive contamination;

(5) Means to control access to high radiation areas or airborne radioactivity areas; and

(6) A radiation alarm system to warn of significant increases in radiation levels, concentrations of radioactive material in air, and of increased radioactivity released in effluents. The alarm system shall be designed with provisions for calibration and for testing its operability.

(b) *Protection against design basis events*. The structures, systems, and components important to safety shall be designed so that they will perform their necessary safety functions, assuming occurrence of design basis events.

(c) *Protection against dynamic effects of equipment failure and similar events*. The structures, systems, and components important to safety shall be designed to withstand dynamic effects such as missile impacts, that could result from equipment failure, and similar events and conditions that could lead to loss of their safety functions.

(d) *Protection against fires and explosions*.

(1) The structures, systems, and components important to safety shall be designed to perform their safety functions during and after credible fires or explosions in the geologic repository operations area.

(2) To the extent practicable, the geologic repository operations area shall be designed to incorporate the use of noncombustible and heat resistant materials.

(3) The geologic repository operations area shall be designed to include explosion and fire detection alarm systems and appropriate suppression systems with sufficient capacity and capability to reduce the adverse effects of fires and explosions on structures, systems, and components important to safety.

(4) The geologic repository operations area shall be designed to include means to protect systems, structures, and components important to safety against the adverse effects of either the operation or failure of the fire suppression systems.

(e) *Emergency capability*.

(1) The structures, systems, and components important to safety shall be designed to maintain control of radioactive waste and radioactive effluents, and permit prompt termination of operations and evacuation of personnel during an emergency.

(2) The geologic repository operations area shall be designed to include onsite facilities and services that ensure a safe and timely response to emergency conditions and that facilitate the use of available offsite services (such as fire, police, medical, and ambulance service) that may aid in recovery from emergencies.

(f) *Utility services*.

(1) Each utility service system that is important to safety shall be designed so that essential safety functions can be performed, assuming occurrence of the design basis events.

(2) The utility services important to safety shall include redundant systems to the extent necessary to maintain, with adequate capacity, the ability to perform their safety functions.

(3) Provisions shall be made so that, if there is a loss of the primary electric power source or circuit, reliable and timely emergency power can be provided to instruments, utility service systems, and operating systems, including alarm systems, important to safety.

(g) *Inspection, testing, and maintenance*. The structures, systems, and components important to safety shall be designed to permit periodic inspection, testing, and maintenance, as necessary, to ensure their continued functioning and readiness.

(h) *Criticality control*. All systems for processing, transporting, handling, storage, retrieval, emplacement, and isolation of radioactive waste shall be designed to ensure that nuclear criticality is not possible unless at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. Each system must be designed for criticality safety assuming occurrence of design basis events. The calculated effective multiplication factor (keff) must be sufficiently below unity to show at least a 5 percent margin, after allowance for the bias in the method of calculation and the uncertainty in the experiments used to validate the method of calculation.

(i) *Instrumentation and control systems.* The design shall include provisions for instrumentation and control systems to monitor and control the behavior of systems important to safety, assuming occurrence of design basis events.

(j) *Compliance with mining regulations*. To the extent that DOE is not subject to the Federal Mine Safety and Health Act of 1977, as to the construction and operation of the geologic repository operations area, the design of the geologic repository operations area shall nevertheless include provisions for worker protection necessary to provide reasonable assurance that all structures, systems, and components important to safety can perform their intended functions. Any deviation from relevant design requirements in 30 CFR, chapter I, subchapters D, E, and N will give rise to a rebuttable presumption that this requirement has not been met.

(k) *Shaft conveyances used in radioactive waste handling*.

(1) Hoists important to safety shall be designed to preclude cage free fall.

(2) Hoists important to safety shall be designed with a reliable cage location system.

(3) Loading and unloading systems for hoists important to safety shall be designed with a reliable system of interlocks that will fail safely upon malfunction.

(4) Hoists important to safety shall be designed to include two independent indicators to indicate when waste packages are in place and ready for transfer.

10 CFR 60.132 – Additional design criteria for surface facilities in the geologic repository operations area.

(a) *Facilities for receipt and retrieval of waste*. Surface facilities in the geologic repository operations area shall be designed to allow safe handling and storage of wastes at the geologic repository operations area, whether these wastes are on the surface before emplacement or as a result of retrieval from the underground facility.

(b) *Surface facility ventilation*. Surface facility ventilation systems supporting waste transfer, inspection, decontamination, processing, or packaging shall be designed to provide protection against radiation exposures and offsite releases as provided in § 60.111(a).

(c) *Radiation control and monitoring -*

(1) Effluent control. The surface facilities shall be designed to control the release of radioactive materials in effluents during Category 1 design basis events so as to meet the performance objectives of § 60.111(a).

(2) Effluent monitoring. The effluent monitoring systems shall be designed to measure the amount and concentration of radionuclides in any effluent with sufficient precision to determine whether releases conform to the design requirement for effluent control. The monitoring systems shall be designed to include alarms that can be periodically tested.

(d) *Waste treatment*. Radioactive waste treatment facilities shall be designed to process any radioactive wastes generated at the geologic repository operations area into a form suitable to permit safe disposal at the geologic repository operations area or to permit safe transportation and conversion to a form suitable for disposal at an alternative site in accordance with any regulations that are applicable.

(e) *Consideration of decommissioning*. The surface facility shall be designed to facilitate decontamination or dismantlement to the same extent as would be required, under other parts of this chapter, with respect to equivalent activities licensed thereunder.

10 CFR 60.133 – Additional design criteria for the underground facility

[only parts most relevant to DBD are listed]

(a) General criteria for the underground facility.

(1) The orientation, geometry, layout, and depth of the underground facility, and the design of any engineered barriers that are part of the underground facility shall contribute to the containment and isolation of radionuclides.

(2) The underground facility shall be designed so that the effects of credible disruptive events during the period of operations, such as flooding, fires and explosions, will not spread through the facility.

(c) Retrieval of waste. The underground facility shall be designed to permit retrieval of waste in accordance with the performance objectives of § 60.111.

(h) Engineered barriers. Engineered barriers shall be designed to assist the geologic setting in meeting the performance objectives for the period following permanent closure.

(i) Thermal loads. The underground facility shall be designed so that the performance objectives will be met taking into account the predicted thermal and thermomechanical response of the host rock, and surrounding strata, groundwater system.

10 CFR 60.134 – Design of seals for shafts and boreholes

(a) *General design criterion*. Seals for shafts and boreholes shall be designed so that following permanent closure they do not become pathways that compromise the geologic repository's ability to meet the performance objectives or the period following permanent closure.

(b) *Selection of materials and placement methods*. Materials and placement methods for seals shall be selected to reduce, to the extent practicable:

(1) The potential for creating a preferential pathway for groundwater to contact the waste packages or

(2) For radionuclide migration through existing pathways.

10 CFR 60.135 – Criteria for the waste package and its components

[only parts most relevant to DBD are listed]

(a) High-level-waste package design in general

(1) Packages for HLW shall be designed so that the in situ chemical, physical, and nuclear properties of the waste package and its interactions with the emplacement environment do not compromise the function of the waste packages or the performance of the underground facility or the geologic setting.

(2) The design shall include but not be limited to consideration of the following factors: solubility, oxidation/reduction reactions, corrosion, hydriding, gas generation, thermal effects, mechanical strength, mechanical stress, radiolysis, radiation damage, radionuclide retardation, leaching, fire and explosion hazards, thermal loads, and synergistic interactions.

10 CFR 60.136 – Preclosure controlled area

(a) A preclosure controlled area must be established for the geologic repository operations area.

(b) The geologic repository operations area shall be designed so that, for Category 2 design basis events, no individual located on or beyond any point on the boundary of the preclosure controlled area will receive the more limiting of a total effective dose equivalent of 0.05 Sv (5 rem), or the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue (other than the lens of the eye) of 0.5 Sv (50 rem). The eye dose equivalent shall not exceed 0.15 Sv (15 rem), and the shallow dose equivalent to skin shall not exceed 0.5 Sv (50 rem). The minimum distance from the surface facilities in the geologic repository operations area to the boundary of the preclosure controlled area must be at least 100 meters.

(c) The preclosure controlled area may be traversed by a highway, railroad, or waterway, so long as appropriate and effective arrangements are made to control traffic and to protect public health and safety.

C.2 Deep Borehole Conceptual Design Report

Specific design requirements and controlled assumptions for DBD disposal were initially developed in SNL (2015) and refined in the *Deep Borehole Field Test Conceptual Design Report* (SNL 2016b). Table C-1 summarizes the design requirements for DBD (from SNL 2016b, Table 2-3) and Table C-2 summarizes the controlled assumptions for DBD (from SNL 2016b, Table 2-4).

Table C-1. DBD Design Requirements

Category	Requirement(s)
Industrial Safety and Health	**Operational Safety Basis** – Requirements for radiological exposure and dose, nuclear criticality, nuclear quality assurance, nuclear material safeguards, etc. are TBD.
Radiological Protection	**Radiation Exposure to Workers and the Public** – Waste package loading, sealing, handling, transport, emplacement, and retrieval equipment and operations shall comply with applicable radiological dose standards (e.g., 10 CFR 20). Engineered measures shall maintain exposures as low as reasonably achievable.
Safeguards and Security	**Nuclear Material Safeguards** – Safeguards and security requirements for DBD of radioactive waste are TBD.
Quality Assurance	**Quality Assurance –** QA requirements for DBD are TBD.
Other Statutory and Regulatory	**NEPA** – The National Environmental Protection Act is applicable to borehole disposal activities but specific details are not yet determined.
	State/Local Administered Permits – Drilling, land use, and environmental permits are required, as appropriate, from cognizant jurisdictions.
	Injection Well Requirements – Applicability of injection well regulations such as 40 CFR 144 to DBD of radioactive wastes is TBD.
Functional	**Safe Disposal** – Radioactive waste disposal activities will be performed in a manner consistent with long-term waste isolation, in accordance with a safety strategy that depends on the waste type and site-specific factors.
	Nuclear Criticality – Design, handling, and emplacement of waste packages must preclude any possibility of nuclear criticality. (SNL 2015)
Operating	**Operational** – Operational requirements for waste disposal operations are TBD.
Performance Criteria	**Waste Handling and Emplacement System Performance** – Waste packages shall provide containment, and shall be maintained in control at all times during emplacement operations (and retrieval, if necessary).
	Drilling and Construction Methods – Drilling and construction of waste disposal boreholes shall be conducted using methods selected for successful completion, waste isolation performance, and achieving characterization objectives. Specific performance criteria have not yet been determined.
	Disposal Borehole Service Life – Borehole construction, completion, and associated surface facilities shall be designed with service lifetime sufficient to accommodate safe disposal operations and sealing. A specific lifetime has not yet been determined.

Category	Requirement(s)
Borehole Design and Construction	**Guidance Casing** – A casing of constant diameter shall be run from the surface to total depth of disposal boreholes (possibly in sections) for transit of waste packages to the emplacement zone. The manner of perforating the guidance casing is TBD.
	Borehole Deviation – Waste disposal boreholes shall be constructed so that: 1) horizontal deviation does not exceed 50 m; and 2) maximum dogleg severity specifications (TBD) are met.
	Casing Internally Flush for Emplacement – Guidance casing shall be internally flush with uniform diameter over the full borehole length.
	Disposal Borehole Diameter – Disposal borehole and casing diameters shall permit emplacement of waste packages with sufficient radial clearance.
	Thermal Expansion in the Emplacement Zone – Casing, cement, and other features of emplacement zone completion, shall accommodate thermal expansion of fluids and solids due to waste heating without breaching packages, plugs, casing, or seals.
	Sealing Zone – Permanent seal(s) shall be installed in a borehole interval directly above the emplacement zone.
	Seal Zone Casing Removal – Casing shall be removed from borehole seal zone, exposing the rock where seals are to be set.
	Emplacement Zone Plugging – Plugs shall be installed in the emplacement zone to stabilize stacks of waste packages and limit axial compressive loading of packages.
	Emplacement Zone Plug Removal – Plugs installed in the emplacement zone shall be designed for possible removal to facilitate waste retrieval.
	Blow-Out Preventers (BOPs) on Disposal Boreholes – The need for wellhead blowout prevention equipment in waste disposal boreholes is TBD.
Waste Packaging	**Waste Package Containment** – Waste packages shall prevent leakage of radioactive waste (solid, liquid or gaseous) throughout the operational phase including transport, handling, emplacement, and borehole sealing. Also, no leakage of borehole fluid into packages shall occur during these activities.
	Waste Package Containment Longevity – Containment lifetime after borehole sealing and closure shall be consistent with the licensed safety strategy.
	Waste Package Mechanical Integrity – Waste packages shall maintain mechanical integrity (structural, dimensional) during transport, handling, emplacement, plugging, and sealing. Mechanical load limits for waste package design are TBD.
	Emplacement Zone Pressure – Waste packages shall perform in borehole fluid (water or mud) with minimum pressure consistent with pure water density and borehole depth, and maximum pressure TBD.
	Waste Package Factor of Safety (FoS) – FoS for mechanical integrity calculations will be based in part on DBFT results and is TBD.

Category	Requirement(s)
	Waste Package Temperature During and After Emplacement – Waste packages shall perform at the maximum waste-heated package temperature assumed, 250°C.
	Waste Package Diameter and Radial Clearance – Disposal package radial clearance will be determined sufficient based on the DBFT results and are TBD.
	Waste Package Smooth Exterior – The exterior waste package surface, including connectors, shall be smooth and free of features that could hang up on casing joints, hangers, collars, etc., when moving upward or downward.
	Waste Package Connections – Waste packages connections will be determined partly on DBFT results are TBD.
	Waste Package Length – Waste package length for DBD is TBD.
	Waste Package Buoyancy – Waste packages, including the waste load, shall have negative buoyancy in borehole fluid (density TBD) to prevent packages floating.
	Downhole Instrumentation – Instrumentation to be used during DBD operations is TBD and will be based at least partly on DBFT experience.
	Waste Package Leakage – Leakage control requirements for waste packages during operations are TBD.
Package Surface Handling / Transfer	**Shielding** – Shielding is required for DBD operations, but the level of shielding depends on waste form characteristics and packaging and is TBD.
	Well Control for Disposal Boreholes – Well control functions for the transfer cask and attachments are TBD.
	Transport for DBD – The means of transport for DBD is TBD.
Package Emplacement and Retrieval	**Waste Package Emplacement** – Waste packages shall be emplaced at the intended positions in the emplacement zone, and shall not become stuck anywhere else in the disposal borehole.
	Waste Package Retrieval – Retrievability and reversibility (as applicable) for future DBD are TBD.
	Emplacement System Redundancy – Transfer and emplacement equipment shall have redundant means for holding waste packages at the surface during staging so that single-point failures cannot result in a dropped waste package.
	Emplacement Fluid Density – The minimum density of any fluid in the borehole at any location, when waste packages are being emplaced, shall be that of water, and the maximum density is TBD. These parameters control buoyant weight of packages, and borehole hydrostatic pressure.
	DBD Emplacement Fluid – Fluid composition for DBD emplacement is TBD, and will be determined on consideration of properties, stability, and waste isolation.
	Bottom-Hole Assembly Weight Limit – The weight of the bottom-hole assembly (waste package, tool string, etc.) shall not exceed the service limit of the emplacement equipment, including an appropriate FoS (TBD).

Category	Requirement(s)
Borehole Sealing	**Seal Permeability** – Seals shall form a low permeability barrier (less than 10^{-16} m^2) to fluid flow within the borehole.
	Seal-Borehole Contact – Seals shall form a low-permeability contact with the borehole walls to prevent bypass flow at the interface.
	Borehole Seal Durability – Seals shall perform at in situ temperature, or if installed proximal to the emplacement zone, at up to 200°C through the duration of the thermal period.
	Seals Environment – Borehole seals shall resist mechanical loading, retaining low-permeability properties.
	Redundant Seal Design – Seals and sealing materials shall be designed to provide redundant performance.

NOTE: Where information is TBD, the reasons include present lack of definition for: 1) future disposal mission with respect to waste forms; 2) siting and depths of boreholes; 3) future DBD project organization and scope; 4) regulations applicable to future DBD projects; 5) waste-specific and site-specific safety strategies; 6) confirmatory data collection associated with disposal boreholes; 7) future requirements that may be based on DBFT results; 8) long-term control and ownership of borehole sites; and 9) provisions for nuclear materials security and safeguards. It is expected that requirements and assumptions will be revisited when additional information is available in these areas.

Source: SNL (2016b, Table 2-3)

Table C-2. DBD Controlled Assumptions

Waste Forms for Disposal – Specific waste forms to be disposed of in deep bore-holes, at specific sites or in specific geologic settings, are TBD.
Disposal Borehole Depth – Borehole depth for DBD is TBD.
DBD Bottom-Hole Temperature and Temperature Rise – Bottom-hole temperature (and temperature rise dues to heat-generating waste) for DBD will depend on site-specific data, waste characteristics and packaging, etc. Peak WP temperature (e.g., for heat-generating waste) is assumed to be 250°C.
Disposal Package Weight – Waste package maximum weight for borehole disposal of radioactive waste is TBD.
Waste Package Strings – When test packages are emplaced in the borehole by any method, the number of WPs in a stack not interrupted by a cemented interval is limited to 40.
Disposal Site Ownership – Long-term ownership and condition of sites for deep borehole disposal of radioactive waste are beyond the scope of the DBFT.
Disposal Borehole Directional Drilling – The need for directional drilling for disposal boreholes is TBD.
DBD Emplacement Fluid Density - Density of borehole fluid when WPs are present is TBD.
Terminal Velocity – A limit on terminal velocity of a WP has not been determined.
Date of Waste Emplacement – The date of emplacement of waste in a DBD facility is TBD.
Permeability of Host Rock and DRZ – The permeability of the host rock and the surrounding DRZ is not yet determined.

Source: SNL (2016b, Table 2-4)

APPENDIX D – BOREHOLE SEALING R&D PLAN

Borehole sealing research aims to ensure that borehole seals have a low permeability, bind effectively to the surrounding DRZ, be relatively straightforward to emplace, and be resistant to chemical alteration which might affect permeability. Seals are primarily needed during the first few hundred years of maximum heat production from ^{137}Cs and ^{90}Sr decay in the borehole. After this period, borehole temperatures will return to ambient and there will be little driving force for upward movement of water. Further seal performance is desirable until re-establishment of the natural salinity gradient, which tends to oppose upward flow; this period is assumed to be approximately 1,000 years, subject to corroboration by R&D.

Borehole sealing research will largely focus on bentonite and cement behavior under downhole conditions, and on rock welding. Bentonite expands in contact with water, has a high surface area, is routinely used to seal oil and gas and geothermal boreholes, and has been extensively studied as an engineered barrier in mined repositories. There is likewise a long history of sealing oil and gas and geothermal boreholes with cement, though the great depth of a disposal borehole poses emplacement challenges. Rock welding is a more recently developed concept. Rock welding uses a resistance heater to melt crushed granite into a “weld” similar in makeup to the native crystalline rock. Rock welding might anneal shut any radially extensive flow paths in the DRZ. Note that asphalt, while routinely used to seal oil and gas boreholes, is an unlikely sealing material for deep boreholes because of its potential to leach organic acids. Organic acids might alter the pH of the downhole fluids and/or mobilize radionuclides.

Arnold et al. (2013) identified the following specific seals-affecting uncertainties that might be better understood through R&D:

- Downhole brine composition
- Impact of alkaline leachate from cement
- Pressure
- Temperature
- Wall-rock interaction
- Impact of waste form corrosion effluent

A more recent analysis in the U.K. (AMEC 2014) examined research needs for deep site investigation borehole seals at mined geologic repositories which are similar in many cases to DBD seals, and argued that optimization of seals, seals alteration, temperature effects on bentonite and cements, and radionuclide transport through the sealed borehole were already sufficiently well understood. The AMEC analysis instead identified the following key seal performance uncertainties:

- **Quantitative seals performance requirements**,
- Greater definition of seal support elements, filler material for transmissive zones,
- **Better understanding the evolution of the DRZ**,
- Demonstrating the quality of emplaced seals,
- Understanding how gas generation and re-saturation might affect seals,
- **Developing new seals emplacement approaches**,
- Understanding controls over bentonite erosion and longevity,
- Predicting long-term impacts of bentonite additives on performance,
- **Understanding bentonite-casing interactions**,
- Testing seals in URLs, and
- **Facilitating knowledge transfer from industry**.

The highlighted seal performance uncertainties are described in more detail below; these are research targets for DBD that are expected to be examined during the course of the DBFT. Several of the other seal performance uncertainties are being examined in parallel by other organizations. For example, gas generation and re-saturation effects on seals were explored in the recent European Commission-funded Fate Of Repository GasEs (FORGE) Project. Better understanding of bentonite erosion is the object of the European Union-funded Bentonite Erosion: effects on the Long term performance of the engineered Barrier and Radionuclide transport (BELBaR) effort.

Demonstrating seals performance under in situ conditions over the millennial time spans required for DBD of long-lived radioactive waste may be unnecessary (and probably impossible) because seals are primarily needed during the period of maximum heat production (the first few hundred years) and the subsequent re-establishment of a salinity gradient (up to ~ 1,000 years) in the borehole.

Quantitative Seals Performance Requirements

At a minimum, seals must prevent appreciable vertical fluid movement for a period of ~1,000 years. This performance minimum might be shortened if inflow of saline connate water can be shown to re-establish the salinity gradient in the borehole sooner. However, for the sake of public confidence, longer seals performance periods might be desired. A key research target is a series of calculations that constrains the time-scales of brine inflows and re-establishment of the salinity gradient in the borehole, and the corresponding effects on vertical fluid flow. Researchers at the University of Sheffield are developing the technical basis underlying performance requirements for seals in deep boreholes.

Better Understanding the Evolution of the DRZ

Thermomechanical calculations to predict the temporal evolution of DRZ permeability and porosity are key features of an overall estimate of borehole seals performance.

Developing New Seals Emplacement Approaches

Researchers at the University of Sheffield are highlighting the operational difficulties in emplacing cement in deep boreholes, and are examining alternative formulations specific to deep boreholes. Similarly, how to reliably deliver compacted, dehydrated clay/bentonite down a fluid-filled borehole to an open (uncased) sealing interval is an object of research. Some options are oil-based mixtures, highly compacted blocks wrapped in reactive membrane material, and pumped slurries. R&D activities could help to narrow the choice of delivery methods for specific clay/bentonite materials suitable for borehole sealing.

Understanding Bentonite-Casing Interactions

Experimental work Los Alamos National Laboratory seeks to quantify temperature-dependent conversion of bentonite to illite and/or chlorite, in the presence and absence of stainless steel and mild steel.

Facilitating Knowledge Transfer from Industry

Researchers at the University of Sheffield are producing an analysis of cement and bentonite seals performance in oil/gas/geothermal boreholes and in scientific deep boreholes. Because seals research considers multiple materials and is multi-disciplinary, there is a strong need for information sharing. This might be accomplished by setting up a DBD Seals Working Group made up of the relevant researchers and meeting annually to report progress and share relevant sealing advances being made in other industries.

Rock Welding

Rock welding involves partially melting crushed granite backfill and the granitic wall rock with a down-hole electric heater. The melt then recrystallizes to a holocrystalline rock identical to, and continuous with, the host rock in almost all its properties except grain size. In theory, the rock welds are calculated to be large enough to seal the borehole and locally eliminate the DRZ.

Some small scale tests have been done in the past to evaluate melting properties of rock welds (e.g., Gibb et al. 2008), but a greater effort is needed if a field-scale demonstration is to be done. A phased effort might involve small-scale laboratory melting experiments proceeding through a bench-scale test at in situ temperature and pressure conditions, culminating in a test design for field-scale demonstration. A parallel modelling effort to build a mechanistic understanding of the phenomena associated with melting and cooling might also be done.

APPENDIX E – DBD FEP LIST

FEPs are the features, events, and processes that could affect the performance of the repository during the post-closure period. They are identified by considering the features of the repository and the events and processes that could affect the post-closure performance of each of these features. Table E-1 shows the features of the DBD system (rows) and the processes and events that could affect their long-term performance (columns).

The rows in Table E-1 represent the features that are applicable to DBD. They are as follows:

- **Waste Form (WF)** includes the radionuclide waste inventory and the materials used to encapsulate or solidify the waste (e.g., spent fuel pellets, cladding, or borosilicate glass). Possible components are SNF, vitrified HLW, and Cs/Sr capsules.
- **Waste Package and Internals (WP)** includes the container materials used to encapsulate the waste form (e.g., stainless steel). Waste packaging typically consists of both external and internal structures. Components are specific to the waste form(s) and/or design of engineered components in the EZ and design of the seals and plugs.
- **Emplacement Zone Workings (EZ)** includes the materials emplaced in the excavated regions outside of the waste packages (i.e., in the emplacement zone and between stacks of waste packages). Components may include buffer and/or backfill, a liner, and cement plugs placed between stacks of waste packages. In the case of deep borehole disposal, the buffer or backfill would consist of fluid or cement. They would be designed and selected for their ability to either serve as a buffer (i.e., serve some chemical or mechanical buffering role (NEA 1999b)) or to serve as backfill (i.e., help control mechanical, thermal, or chemical conditions in the borehole). Steel liners that serve to minimize accidents during the pre-closure phase will remain in place and thus will be part of the EZ workings. Cement plugs would be placed between stacks of waste package to manage the axial load on the waste packages.
- **Seals and Plugs (SP)** includes materials used to seal repository openings and retard radionuclide transport. Components may include bentonite, cement plugs, ballast, and casing and casing cement. For the purpose of FEPs, the “SP” feature includes both the uncased Seal Zone (SZ) and the cased Upper Borehole Zone (UBZ) shown in Figure 3-2 and Figure 4-2.
- **Host Rock (HR)** includes the geologic unit(s) containing the borehole and emplaced waste. The vertical extent of the host rock and the stratigraphic distinction between Host Rock and Other Geologic Units is site- and geology-specific. Components include the DRZ and the crystalline basement. The DRZ is defined as the portion of the host rock adjacent to the borehole that experiences durable (but not necessarily permanent) changes due to the drilling/presence of the borehole (see Section 4.3.3). Immediately adjacent to the borehole, these induced changes are more likely to be permanent (e.g., mechanical alteration due to drilling), whereas further radially from the borehole the induced changes are more likely to be time-dependent but not permanent (e.g., thermal effects due to radioactive decay of waste). The crystalline basement is defined as the host rock that has not been significantly affected by the presence of the repository.

- **Other Geologic Units (OU)** include the surrounding geologic units not considered part of the Host Rock stratigraphy. Components may include overlying sediments, aquifers, and/or unsaturated units.
- **Biosphere (BP)** includes features that are necessary for calculating dose to the receptor, which may include radionuclide movement above the subsurface.
- **Repository System (RS)** is designed to capture FEPs that are potentially relevant to the repository system as a whole.

The columns in Table E-1 represent the processes and events that could affect postclosure performance of the deep borehole disposal system. They are as follows:

- **Characteristics (CP)** describe the properties of the features or components that need to be evaluated. Characteristics are not typical FEPs (i.e., they cannot be screened in or out), instead they contain characteristic information (and changes to that information) that influences the screening of the other FEPs. For example, the initial radionuclide inventory is considered a characteristic of the waste form, and rock properties are considered characteristics of the geosphere features.
- **Coupled Thermal Processes** (e.g., thermal-mechanical, thermal-chemical, and thermal-hydrologic) are included in the same column as the corresponding processes without thermal effects (e.g., mechanical, chemical, and hydrologic, respectively) because these latter "primary" processes are generally more impactful on system behavior, and determine the basic form of the associated process models and numerical models. Thermal effects on these primary processes are usually represented by a temperature dependency in the relevant constitutive models and equations of state. Generally, the reverse coupling, e.g., the effect of chemical conditions on the thermal environment, is significantly weaker than the forward coupling, but would be included here, also.
- **Mechanical Processes (TM)** include phenomena that affect borehole stability, that affect degradation of engineered features, and that change rock properties such as porosity. These mechanical processes include salt creep, borehole breakout, stress corrosion cracking, hydrogen embrittlement, buckling, floor heave, and non-chemical weathering, among others. **Thermal-Mechanical Processes (TM)** include thermal stresses, thermal acceleration of salt creep, and their corresponding effects on the strength and degradation of the engineered and natural features.
- **Hydrologic Processes (TH)** include precipitation, infiltration, runoff, unsaturated zone flow, flow diversion, capillarity, matrix imbibition, and saturated zone flow. **Thermal-Hydrologic Processes (TH)** include evaporation, condensation, vapor flow, and temperature-dependent property changes.
- **Chemical Processes (TC)** include phenomena affecting the chemical environment, degradation mechanisms of engineered features, and the chemical environment in the natural system. These chemical processes include dissolution and precipitation, reduction and oxidation, salt deliquescence, general corrosion, localized (or crevice) corrosion, alteration, and solubility. **Thermal-Chemical Processes (TC)** include temperature-dependent effects on chemical processes such as rates of mineral precipitation/dissolution and clay dehydration, as well as effects on chemical properties, such as the temperature

dependency of equilibrium constants.

- **Biological (and Microbiological) Processes (TB)** include the possible effects of microorganisms on other processes relevant to performance, such as microbial effects on chemical processes. **Thermal-Biological Processes (TB)** include temperature-dependent effects on biological systems
- **Transport Processes (TT)** include advection, diffusion, dispersion, matrix diffusion, sorption, and colloid stability and filtration. These processes may occur within any of the features. **Thermal-Transport Processes (TT)** include temperature-dependent effects. Transport processes are typically strongly dependent on the other THCMBR processes and couplings.
- **Thermal Processes (TL)** (i.e., conduction, radiation, convection) include only those temperature-related FEPs that do not include a coupling to other THCMBR processes.
- **Radiological Processes (RA)** include the possible effects of ionizing radiation from the decay of radioactive materials on other processes potentially relevant to performance, such as chemistry. Radiological processes include radiolysis and radiological exposure to the receptor and the resulting doses.
- **Long-Term Geologic Processes (LG)** include tectonic activity, diagenesis, metamorphism, diapirism, subsidence, and slow dissolution by groundwater (subrosion).
- **Climatic Processes (CL)** include natural effects that may produce changes in the regional and local climate.
- **Human Activities (Long Timescale) (HP)** includes human-initiated effects on the climate and the surface environment. An example is a surface disruption or contamination that eventually impacts the repository.
- **Other Processes (OP)** are reserved for processes that do not fit into any of the other categories. Examples include processes related to the calculation of the dose to the receptor such as ingestion, inhalation, and exposure.
- **Nuclear Criticality Events (NC)** include initiators of sequences of events or processes that could lead to configurations that have potential for criticality in the repository system. For a criticality event to occur, the appropriate combination of materials (neutron moderators, neutron absorbers, fissile materials, or isotopes) and geometric configurations favorable to criticality must exist. During design, criticality analyses are performed to demonstrate the initial emplaced configuration of the waste form remains subcritical, even under flooded conditions (since water is a good neutron moderator). For a configuration to have potential for criticality, all of the following conditions must occur: (1) sufficient mechanical or corrosive damage to the waste package outer corrosion barrier to cause a breach, (2) presence of a moderator, i.e., water, (3) separation of fissionable material from the neutron absorber material or an absorber material selection error during the canister fabrication process, and (4) the accumulation or presence of a critical mass of fissionable material.
- **Early Failure Events (EF)** include phenomena leading to the failure of a feature or component at a time significantly faster than the design basis. An example is the through-wall penetration of a waste package due to manufacturing- or handling-induced defects, at a time earlier than would be predicted by mechanistic degradation models for a defect-free waste package. Another example is the early failure of a shaft seal.

- **Seismic Events (SM)** include seismic activity that produces vibratory ground motion or fault displacement which affects the waste packages, the EZ, the borehole, and/or the natural system pathways.
- **Igneous Events (IG)** include igneous intrusion intersecting the repository, volcanic eruption from a volcanic vent that intersects the repository, and/or volcanic disturbance to the natural system pathways. Igneous intrusion considers the possibility that magma, in the form of a dike, could intrude into the EZ, damaging waste packages and exposing the waste forms for potential mobilization of radionuclides. Volcanic eruption considers that a volcanic conduit (or conduits) intersects the repository, damages waste packages, and erupts at the land surface. The volcanic eruption disperses volcanic tephra and entrained waste under atmospheric conditions, and deposits the contaminated tephra on land surfaces where the contaminated tephra becomes subject to redistribution by soil and near surface transport processes.
- **Human Activities (Short Timescale) (HE)** includes human intrusion events. Human intrusion is commonly addressed by a stylized calculation (typically specified by regulation) simulating a future drilling operation in which an intruder drills a borehole that directly intersects waste, causing a release of radionuclides that are subsequently transported into the natural system or up the borehole to the surface. Different regulatory requirements exist internationally with regard to the consideration of such FEPs within scenario development.
- **Other Events (OE)** are reserved for events that do not fit into any of the other categories. Examples include events such as meteor impacts, explosions, or crashes.

Table E-1. FEP Matrix Structure for DBD

Characteristics, Processes, and Events / Features / Components		Processes											Events					
	Characteristics	Mechanical and Thermal-Mechanical	Hydrological and Thermal-Hydrologic	Chemical and Thermal-Chemical	Biological and Thermal-Biological	Transport and Thermal-Transport	Thermal	Radiological	Long-Term Geologic	Climatic	Human Activities (Long Timescale)	Other	Nuclear Criticality	Early Failure	Seismic	Igneous	Human Activities (Short Timescale)	Other
	CP	TM	TH	TC	TB	TT	TL	RA	LG	CL	HP	OP	NC	EF	SM	IG	HE	OE
Waste and Engineered Features																		
(WF) Waste Form																		
(01) SNF and Cladding																		
(02) Vitrified HLW																		
(03) Cs and Sr HLW																		
(WP) Waste Package and Internals																		
(01) SNF																		
(02) Vitrified HLW																		
(03) Cs/Sr Capsules																		
(EZ) Emplacement Zone Workings																		
(01) EZ Buffer/Backfill																		
(02) EZ Liner																		
(03) EZ Cement Plugs																		
(SP) Seals and Plugs																		
(01) Bentonite Seals																		
(02) Cement Plugs																		
(03) Ballast																		
(04) Casing and Casing Cement																		
Geosphere Features																		
(HR) Host Rock																		
(01) Disturbed Rock Zone (DRZ)																		
(02) Crystalline Basement																		
(OU) Overlying Geologic Units																		
(01) Sedimentary Units																		
Surface Features																		
(BP) Biosphere																		
(01) Surface and Near-Surface Media and Materials																		
(02) Flora and Fauna																		
(03) Humans																		
(04) Food and Drinking Water																		
System Features																		
(RS) Repository System																		
(01) Assessment Basis																		
(02) Preclosure/Operational																		
(03) Other Global																		

Assumptions that form the basis for the preliminary DBD FEP screening include:

Table E-2 gives a preliminary list of FEPs for DBD. The DBD FEPs are identified according to the feature affected by the selected event or process. For example, a radiological process (RA in Table E-1) that affects the Cs and Sr waste forms (WF.03 in Table E-1) is identified as "WF.03.RA.01." If there are multiple processes of the same type that could affect the same features, the last number in the identifier indicates which of the multiple processes is being considered in the FEP. For example, if there are two distinct radiological processes that could affect the Cs and Sr waste forms, they would be identified as "WF.03.RA.01" and WF.03.RA.02". Each FEP in Table E-2 includes one or more Associated Processes, identified as (A), (B), etc. The Associated Processes provide the level of detail needed to define and/or represent specific phenomena.

Table E-2 also gives preliminary screening decisions for each of the FEPs. The categories of screening decisions (Included, Included (deferred), Excluded (consequence), Excluded (probability), and Excluded (by regulation)) are discussed in Section 5.2.1. FEP screening is done at the Associated Process level. As noted in Section 5.2.1, these preliminary screening decisions will be iteratively updated as design and site-specific information and the PA model all become more refined.

Assumptions that form the basis for the preliminary DBD FEP screening include:

- [Note #1] The waste form includes both the glass-like CsCl and the compacted, granular SrF_2. Waste form degradation is not explicitly represented in the PA model. Instead, the radionuclides in the waste are assumed to be available for instantaneous dissolution in the EZ fluid (Section 4.3.2.6). As a result, waste form degradation FEPs are generally "Included" because their effects are already captured by the assumption of instantaneous degradation.
- [Note #2] Waste package corrosion and other degradation mechanisms are not explicitly represented in the PA model. Instead, a waste package breach time of one year after closure is assumed (for the deterministic PA simulation) (Section 5.2.3.6). As a result, waste package degradation FEPs are generally "Included" because their effects are already captured by the assumption of near-instantaneous degradation.
- [Note #3] Several FEPs, particularly those dealing with the host rock and/or disruptive events (e.g., igneous events), were "Excluded (probability)" because their effects would be precluded by the site selection criteria, such as discussed in Sections 3.2.1.2 and 4.2.8.
- [Note #4] Single (liquid) phase fluid flow is assumed. FEPs related to the generation of H_2 (e.g., from corrosion) and other gases and FEPs related to the presence of a gas phase are screened out ("Excluded (consequence)") because it is assumed that the borehole design, DRZ, and host rock properties will permit dissipation of gas overpressurization and the gas phase.
- [Note #5] Microbial activity in the EZ is "Excluded (probability)" because the maximum temperature at which known microorganisms can exist in an active state is 110°C (Pedersen and Karlsson, 1994). However, microbial activity above the EZ is not necessarily excluded because temperatures at depths less than 4 km are expected to be less than 110°C (assuming a surface temperature of 10°C and a gradient of 25°C/km).

- [Note #6] Colloid formation and colloidal transport FEPs are "Included (deferred)" pending further study. Colloids are assumed to be able to form inside the waste package.
- [Note #7] Human intrusion FEPs are generally "Included (deferred)" because DBD-specific regulations for human intrusion have yet to be specified (see Section 2.1.3.5). However, DBD human intrusion scenario(s) are likely to be limited to inadvertent intrusions; deliberate intrusions have typically been excluded by regulation.
- [Note #8] EZ components (buffer/backfill and cement plugs) and SP components (SZ seals and plugs) are included in the PA model with material properties that are representative of degraded conditions, but do not vary over time. As a result, seal and plug degradation FEPs are generally "Included" because their effects are already captured by the degraded properties. Early failure FEPs for EZ and SP components are generally "Included (deferred)" because the possibility of more significant degradation from early failure requires further study.
- [Note #9] The EZ liner is not explicitly represented in the PA model. As a result, potentially important FEPs related to the EZ liner are "Included (deferred)".
- [Note #10] The PA model domain does not include the UBZ portion of the SP zone. As a result, screening of the SP FEPs considers only phenomena occurring in the SZ. Consideration of UBZ components (UBZ casing and casing cement) and UBZ phenomena that might differ from SZ phenomena (e.g., the uppermost portion of the UBZ might be unsaturated) is deferred to a future iteration, and potentially important UBZ FEPs are "Included (deferred)".
- [Note #11] The DRZ is included in the PA model with material properties that are representative of degraded conditions, but do not vary over time. As a result, DRZ degradation and evolution FEPs are generally "Included" because their effects are already captured by the degraded properties.
- [Note #12] The PA model domain does not include the Overlying Geologic Units. As a result, several OU FEPs are "Included (deferred)".
- [Note #13] The PA model domain does not include the Biosphere. As a result, several BP FEPs are "Included (deferred)".
- [Note #14] For FEPs that were difficult to screen one way or the other, the intent was to "err" on the side of inclusion, with the idea that further study would provide a basis for excluding them. Sometimes that is noted in the Discussion column, but not always.

These numbered assumptions are referenced, where applicable, in the Discussion column of Table E-2.

Table E-2. DBD FEP List and Screening

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WF.00.CP.01	Waste Characteristics Cs and Sr HLW Properties	-Waste form types -Geometry -Radionuclide inventory -Non-radionuclide inventory -Materials and properties (initial condition, damage, corrosion products) -Fluids, colloids, and their properties (initial saturation, initial water chemistry (pH, ionic strength, p_{CO2}) initial water composition (radionuclides and dissolved species), initial void chemistry (air/gas), initial colloidal concentrations) -Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's) -Properties of any flammable or pyrophoric materials -Spatial heterogeneity of waste forms (waste package scale, emplacement zone scale)	N/A	
WF.00.TM.01	Mechanical and Thermal-Mechanical Effects on Waste Form	(A) Salt creep	Excluded (probability)	Host rock is crystalline.
		(B) Thermally-induced expansion / stress / cracking	Included	Note #1
		(C) Swelling of corrosion products	Excluded (consequence)	No significant corrosion products in WF
		(D) Thermal conduction	Included	
		(E) Mechanical loading from borehole breakout	Excluded (consequence)	EZ liner provides protection.
		(F) Interaction of co-located waste forms	Included	Note #1
WF.00.TM.02	Mechanical Effects of Gas on Waste Forms	(A) EZ pressurization	Excluded (consequence)	Note #4
		(B) Mechanical damage to waste forms	Excluded (consequence)	Note #4
		(C) Internal gas pressure	Excluded (consequence)	Note #4
		(D) Pressure increases from pyrophoric materials or flammable gases	Excluded (probability)	No pyrophoric materials or ignition sources.
WF.00.TH.01	Pressure-Driven Darcy Flow Through Fractures and Porous Media in the Waste Forms	(A) Pressure-driven flow of liquid (wetting) phase	Included	
		(B) Pressure-driven flow of gas (non-wetting) phase	Excluded (consequence)	Note #4
		(C) Flow of any additional phases (e.g., hydrocarbons)	Excluded (probability)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WF.00.TH.02	Capillarity-Dominated Darcy Flow in the Waste Forms	(A) Wicking and imbibition (i.e., infiltration without gravity)	Excluded (consequence)	
		(B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation)	Excluded (probability)	WF is in a liquid-saturated environment.
		(C) Immiscible phase interaction and displacement	Excluded (probability)	WF is in a liquid-saturated environment.
		(D) Trapping, discontinuous blobs, or viscous fingering in non-wetting phase	Excluded (probability)	WF is in a liquid-saturated environment.
WF.00.TH.03	Gravity- and Density-Dominated Flow in the Waste Forms	(A) Free convection due to density variation (from temperature or salinity effects)	Included	
		(B) Infiltration and drainage	Included (deferred)	From SZ.
WF.00.TH.04	Adsorption-Dominated Flow in the Waste Forms (Water held by electrostatic, van der Waals, or hydration forces)	(A) Thin film flow below residual saturation (i.e., near liquid dry-out)	Excluded (probability)	WF is in a liquid-saturated environment.
		(B) Hygroscopy (equilibration of solid phase with humidity)	Excluded (probability)	WF is in a liquid-saturated environment.
		(C) Immobile water in nano-pores or in small-aperture fractures	Excluded (probability)	WF is in a liquid-saturated environment.
WF.00.TH.05	Diffusion or Dispersion in Miscible Phases in the Waste Forms	(A) Diffusion of vapor in air phase	Excluded (probability)	WF is in a liquid-saturated environment.
		(B) Diffusion of dissolved gas in liquid phase	Excluded (consequence)	Note #4
WF.00.TH.06	Non-Darcy Flow Through Fractures and Porous Media in the Waste Forms	(A) High Reynolds number fluid flow in large-aperture fractures	Excluded (probability)	
		(B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths	Included	
		(C) Threshold gradient flow in low-permeability matrix	Excluded (consequence)	
WF.00.TH.07	Thermal-Hydrological Effects on Flow in Waste Forms	(A) Convection and conduction of energy via liquid phase	Included	
		(B) Convection of energy via vapor (i.e., heat pipe)	Excluded (probability)	WF is in a liquid-saturated environment.
		(C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine)	Included	
		(D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation	Excluded (probability)	WF is in a liquid-saturated environment.
		(E) Release of water from hydrated minerals during heating	Excluded (consequence)	
		(F) Effects of pyrophoricity	Excluded (probability)	No pyrophoric materials in waste.
WF.00.TC.01	Chemical and Thermal-Chemical Gas Generation in Waste Forms	(A) Generation of H_2 from corrosion of metals or fuels	Excluded (consequence)	Note #4
		(B) Gas generation from pyrophoricity	Excluded (probability)	No pyrophoric materials in waste.
		(C) Generation of flammable gases	Excluded (probability)	No ignition sources in waste.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WF.00.TC.02	Chemical and Thermal-Chemical Degradation of Organic Materials in Waste	(A) Degradation of plastic or synthetic rubber compounds without microbial activity	Excluded (probability)	No organic materials in waste.
WF.00.TB.01	Microbial Activity in Waste Forms	(A) Microbial effects on corrosion	Excluded (probability)	Note #5
		(B) Formation of complexants (humates, fulvates, organic waste)	Excluded (probability)	Note #5
		(C) Formation of microbial colloids	Excluded (probability)	Note #5
		(D) Formation of biofilms	Excluded (probability)	Note #5
		(E) Biodegradation	Excluded (probability)	Note #5
		(F) Biomass production	Excluded (probability)	Note #5
		(G) Bioaccumulation	Excluded (probability)	Note #5
		(H) CO_2, CH_4, and H_2S generation from microbial degradation	Excluded (probability)	Note #5
		(I) Nitrification	Excluded (probability)	Note #5
		(J) Sulfurization	Excluded (probability)	Note #5
		(K) Methanogenesis	Excluded (probability)	Note #5
WF.00.TB.02	Thermal Effects on Microbial Activity in Waste Forms	(A) Thermal effects on microbial activity	Excluded (probability)	Note #5
WF.00.TT.01	Transport of Dissolved Radionuclides in the Liquid Phase in Waste Forms	(A) Advection	Included	
		(B) Dispersion	Included	
		(C) Diffusion	Included	
		(D) Matrix Diffusion	Excluded (consequence)	
		(E) Intra-aqueous complexation	Excluded (probability)	No complexing agents in waste.
		(F) Isotopic dilution	Included (deferred)	
		(G) Dilution by mixing with formation waters	Included	
		(H) Solubility of radionuclides and other species	Included	
WF.00.TT.02	Interaction of Dissolved Radionuclides with Stationary Phases in Waste Forms	(A) Reversible/irreversible physical sorption	Excluded (consequence)	Conservative assumption.
		(B) Surface complexation	Excluded (consequence)	Conservative assumption
		(C) Ion exchange	Excluded (consequence)	Conservative assumption
		(D) Precipitation / dissolution, including limited dissolution due to inclusion in secondary phases and enhanced dissolution due to alpha recoil	Included	No enhanced dissolution due to alpha recoil as there is no alpha-emitting waste.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WF.00.TT.03	Interaction of Dissolved Radionuclides with Other Mobile Phases (Colloids, Gas Phase) in Waste Forms	(A) Reversible/irreversible physical sorption	Excluded (consequence)	Conservative assumption
		(B) Interactions with organic complexants	Excluded (consequence)	Conservative assumption
		(C) Ion exchange	Excluded (consequence)	Conservative assumption
		(D) Precipitation / dissolution	Excluded (consequence)	Conservative assumption
		(E) Partitioning	Excluded (consequence)	Conservative assumption
WF.00.TT.04	Coupled Process Effects on Transport of Dissolved Radionuclides in Waste Forms	(A) Thermal diffusion (Soret effect)	Excluded (consequence)	Effect negligible compared to uncertainty in diffusion coefficient
		(B) Thermal osmosis	Excluded (consequence)	Effect negligible compared to advection
		(C) Thermal conduction within the waste form and waste package	Included	
		(D) Other thermal effects, such as other Onsager relationships	Excluded (consequence)	Effect negligible given small radius of WF
WF.00.TT.05	Transport of Radionuclides in the Gas Phase in Waste Forms	(A) Advection	Excluded (consequence)	Note #4
		(B) Diffusion	Excluded (consequence)	Note #4
WF.00.TT.06	Formation of Colloids in Waste Forms	(A) Intrinsic colloids	Included (deferred)	Note #6
		(B) Pseudo-colloids (host rock fragments, waste form fragments, corrosion products, microbes)	Included (deferred)	Note #6
		(C) Sorption of radionuclides to colloids	Included (deferred)	Note #6
WF.00.TT.07	Transport of Radionuclides on Colloids in Waste Forms	(A) Advection	Included (deferred)	Note #6
		(B) Dispersion	Included (deferred)	Note #6
		(C) Diffusion	Included (deferred)	Note #6
		(D) Matrix Diffusion	Excluded (consequence)	
		(E) Stability/flocculation (mechanical stability, chemical stability)	Excluded (consequence)	Conservative assumption.
		((F) Filtration (physical, electrostatic)	Excluded (consequence)	Conservative assumption.
		(G) Dilution by mixing with formation waters	Included (deferred)	
WF.00.TT.08	Interaction of Colloids with Other Phases in Waste Forms	(A) Reversible/irreversible physical sorption onto stationary phases	Excluded (consequence)	Conservative assumption
		(B) Sorption at air-water interfaces	Excluded (probability)	WF is in a liquid-saturated environment.
WF.00.TL.01	Heat Generation in Waste Forms	(A) Heat generation from radionuclide decay	Included	
WF.00.TL.02	Exothermic Reactions in Waste Forms	(A) Hydration of concrete	Excluded (probability)	No concrete in waste.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(B) Oxidation of waste form	Excluded (consequence)	
WF.00.RA.01	Radioactive Decay and Ingrowth	(A) Decay chains	Included	
		(B) Decay products	Included	
		(C) Neutron activation	Excluded (probability)	Neutron radiation not produced by waste.
WF.00.RA.02	Radiolysis in Waste Forms	(A) He generation from waste form alpha decay	Excluded (probability)	No alpha-emitting waste in WF.
		(B) H_2 generation from radiolysis	Excluded (consequence)	Note #4
		(C) Altered water chemistry	Included (deferred)	
WF.00.RA.03	Radiation Damage to Waste Form	(A) Enhanced waste form degradation	Included	Note #1
WF.00.CL.01	Climatic Effects on Waste Forms	(A) Variations in precipitation and temperature	Excluded (consequence)	
		(B) Melt water	Excluded (consequence)	
WF.00.SM.01	Seismic Activity Impacts Waste Forms	(A) Mechanical damage to waste forms from ground motion, borehole breakout, fault displacement	Excluded (consequence)	Note #1, #2, and #3
WF.00.IG.01	Igneous Activity Impacts Waste Forms	(A) Mechanical damage to waste forms from igneous intrusion	Excluded (probability)	Note #3
		(B) Chemical interaction with magmatic volatiles	Excluded (probability)	Note #3
		(C) Transport of radionuclides in magma, pyroclasts, vents	Excluded (probability)	Note #3
WF.01.CP.01	SNF and Cladding Properties	-Geometry -Radionuclide inventory -Non-radionuclide inventory -Materials and properties (initial condition, enrichment/burnup, damage) -Fluids, colloids, and their properties (initial saturation, initial water chemistry (pH, ionic strength, p_{CO2}) initial water composition (radionuclides and dissolved species), initial void chemistry (air/gas), initial colloidal concentrations) -Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's) -Instant release fraction (SNF only)	N/A	
WF.01.TM.01	Thermal-Mechanical SNF and Cladding Degradation and Failure	(A) Initial damage (B) Stress corrosion cracking (C) Unzipping (D) Creep (E) Internal pressure (F) Mechanical impact	Excluded (probability)	No SNF in WF.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WF.01.TC.01	Evolution of the Water Chemistry in SNF and Cladding	(A) Speciation (B) Oxidation/reduction processes, reaction kinetics (C) Dissolution, reaction kinetics (D) Precipitation, inclusion in secondary phase, reaction kinetics (E) Formation and filtration of colloids (F) Effect of sorption (G) Solubility of radionuclides and other species (H) Thermal-chemical interactions with waste form / WP components, including chemical effects on fluid density (I) Thermal-chemical interaction with corrosion products, including effects on fluid density (J) Thermal-chemical interaction with intruding fluids, including effects on fluid density (K) Chemical interaction with gas phase (L) Osmotic stress and osmotic binding	Excluded (probability)	No SNF in WF.
WF.01.TC.02	Fuel Degradation	(A) Thermal-chemical alteration processes (B) Oxidation/reduction processes, reaction kinetics, interaction with metals (C) Dissolution / leaching, including limited dissolution due to inclusion in secondary phases and enhanced dissolution due to alpha recoil (D) Thermal cracking (E) Thermally-enhanced corrosion (F) Radiolysis and altered water chemistry	Excluded (probability)	No SNF in WF.
WF.01.TC.03	Thermal-Chemical SNF Cladding Degradation and Failure	(A) Thermal-chemical alteration processes (B) Oxidation/reduction processes, reaction kinetics, interaction with metals (C) Dissolution / leaching, including enhanced dissolution due to alpha recoil (D) Thermal cracking (E) General Corrosion (F) Microbially-influenced corrosion (G) Localized corrosion and/or stress-corrosion cracking (H) Enhanced corrosion (silica, fluoride) (I) Hydride cracking (J) Radiolysis and altered water chemistry	Excluded (probability)	No SNF in WF.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WF.02.CP.01	Vitrified HLW Properties	-Geometry -Radionuclide inventory -Non-radionuclide inventory -Materials and properties (initial condition, enrichment/burnup, damage) -Fluids, colloids, and their properties (initial saturation, initial water chemistry (pH, ionic strength, p_{CO2}) initial water composition (radionuclides and dissolved species), initial void chemistry (air/gas), initial colloidal concentrations) -Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's) Instant release fraction (SNF only)	N/A	
WF.02.TC.01	Evolution of the Water Chemistry in Vitrified HLW	(A) Speciation (B) Oxidation/reduction processes, reaction kinetics (C) Dissolution, reaction kinetics (D) Precipitation, inclusion in secondary phase, reaction kinetics (E) Formation and filtration of colloids (F) Effect of sorption (G) Solubility of radionuclides and other species (H) Thermal-chemical interactions with waste form / WP components, including chemical effects on fluid density (I) Thermal-chemical interaction with corrosion products, including effects on fluid density (J) Thermal-chemical interaction with intruding fluids, including effects on fluid density (K) Chemical interaction with gas phase (L) Osmotic stress and osmotic binding	Excluded (probability)	No vitrified HLW in WF.
WF.02.TC.02	Glass Degradation	(A) Thermal-chemical alteration processes and recrystallization (B) Oxidation/reduction processes, reaction kinetics, interaction with metals (C) Dissolution / leaching, including enhanced dissolution due to alpha recoil and limited dissolution due to inclusion in secondary phases (D) Thermal cracking (E) Thermally-enhanced corrosion (F) Radiolysis and altered water chemistry	Excluded (probability)	No vitrified HLW in WF.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WF.03.CP.01	Cs and Sr HLW Properties	-Waste form types -Geometry -Radionuclide inventory -Non-radionuclide inventory -Materials and properties (initial condition, damage, corrosion products) -Fluids, colloids, and their properties (initial saturation, initial water chemistry (pH, ionic strength, p_{CO2}) initial water composition (radionuclides and dissolved species), initial void chemistry (air/gas), initial colloidal concentrations) -Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's) -Properties of any flammable or pyrophoric materials Spatial heterogeneity of waste forms (waste package scale, emplacement zone scale)	N/A	
WF.03.TC.01	Evolution of the Water Chemistry in Cs and Sr HLW	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included	
		(G) Solubility of radionuclides and other species	Included	
		(H) Thermal-chemical interactions with waste form / WP components, including chemical effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Included (deferred)	
		(J) Thermal-chemical interaction with intruding fluids, including effects on fluid density	Included	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
		(L) Osmotic stress and osmotic binding	Excluded (consequence)	
WF.03.TC.02	Degradation of Cs and Sr HLW	(A) Thermal-chemical alteration processes and recrystallization	Included	Note #1
		(B) Oxidation/reduction processes, reaction kinetics, interaction with metals	Included	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(C) Dissolution / leaching, including enhanced dissolution due to alpha recoil and limited dissolution due to inclusion in secondary phases	Included	No enhanced dissolution due to alpha recoil as there is no alpha-emitting waste.
		(D) Thermal cracking	Included	Note #1
		(E) Thermally-enhanced corrosion	Included	Note #1
		(F) Radiolysis and altered water chemistry	Included (deferred)	
WP.00.CP.01	Waste Package Characteristics	- Waste package types - Spatial heterogeneity of waste packages (emplacement zone scale) - Co-located waste forms	N/A	
WP.00.TM.01	Mechanical Impacts on Waste Packages	(A) Mechanical loading from borehole breakout	Excluded (consequence)	EZ liner provides protection.
		(B) Gas pressure from gas generation	Excluded (consequence)	Note #4
		(C) Swelling of corrosion products	Included	Note #2
		(D) Cracking	Included	Note #2
WP.00.TM.02	Thermal-Mechanical Effects on Waste Packages	(A) Thermal sensitization / phase changes	Excluded (consequence)	
		(B) Thermally-induced expansion / stress / cracking	Included	Note #2
		(C) Thermal conduction / thermal radiation	Included	
		(D) Salt creep	Excluded (probability)	Host rock is crystalline.
		(E) Waste package movement / lifting / sinking	Excluded (consequence)	
WP.00.TM.03	Thermal-Mechanical Effects on In-Package Components	(A) Cracking	Included	Note #2
		(B) Thermally-induced expansion / stress / cracking	Included	Note #2
		(C) Swelling corrosion products	Included	Note #2
		(D) Salt creep	Excluded (probability)	Host rock is crystalline.
WP.00.TM.04	Mechanical Effects of Gas on Waste Packages	(A) EZ pressurization	Excluded (consequence)	Note #4
		(B) Mechanical damage to waste packages	Excluded (consequence)	Note #4
		(C) Internal gas pressure	Excluded (consequence)	Note #4
		(D) Pyrophoricity or flammable gas from waste form	Excluded (probability)	No pyrophoric materials or ignition sources.
WP.00.TH.01	Pressure-Driven Darcy Flow Through Fractures and Porous Media in the Waste Packages	(A) Pressure-driven flow of liquid (wetting) phase	Included	
		(B) Pressure-driven flow of gas (non-wetting) phase	Excluded (consequence)	Note #4
		(C) Flow of any additional phases (e.g., hydrocarbons)	Excluded (probability)	
WP.00.TH.02	Capillarity-Dominated Darcy Flow in the	(A) Wicking and imbibition (i.e., infiltration without gravity)	Excluded (consequence)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
	Waste Packages	(B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation)	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
		(C) Immiscible phase interaction and displacement	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
		(D) Trapping, discontinuous blobs, or viscous fingering in non-wetting phase	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
WP.00.TH.03	Gravity- and Density-Dominated Flow in the Waste Packages	(A) Free convection due to density variation (from temperature or salinity effects)	Included	
		(B) Infiltration and drainage	Included (deferred)	From SZ
		(C) Dripping and ponding	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
WP.00.TH.04	Adsorption-Dominated Flow in the Waste Packages (Water held by electrostatic, van der Waals, or hydration forces)	(A) Thin film flow below residual saturation (i.e., near liquid dry-out)	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
		(B) Hygroscopy (equilibration of solid phase with humidity	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
		(C) Immobile water in nano-pores or in small-aperture fractures	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
WP.00.TH.05	Diffusion or Dispersion in Miscible Phases in the Waste Packages	(A) Diffusion of vapor in air phase	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
		(B) Diffusion of dissolved gas in liquid phase	Excluded (consequence)	Note #4
WP.00.TH.06	Non-Darcy Flow Through Fractures and Porous Media in the Waste Packages	(A) High Reynolds number fluid flow in large-aperture fractures	Excluded (probability)	
		(B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths	Included (deferred)	
		(C) Threshold gradient flow in low-permeability matrix	Excluded (probability)	No low permeability matrix in WP.
WP.00.TH.07	Thermal-Hydrological Effects on Flow in the Waste Packages	(A) Convection and conduction of energy via liquid phase	Included	
		(B) Convection of energy via vapor (i.e., heat pipe)	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
		(C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine)	Included	
		(D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation	Excluded (probability)	WP interior is fully liquid-saturated once WP is breached.
		(E) Release of water from hydrated minerals during heating	Excluded (consequence)	
		(F) Effects of pyrophoricity	Excluded (probability)	No pyrophoric materials in waste or WP.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WP.00.TC.01	Gas Generation Inside Waste Packages	(A) H_2 generation from corrosion of the inner waste package walls and internal supports	Excluded (consequence)	Note #4
		(B) Gas generation from pyrophoricity	Excluded (probability)	No pyrophoric materials in waste or WP.
		(C) Generation of flammable gases	Excluded (probability)	No ignition sources in waste or WP.
WP.00.TC.02	Gas Generation Outside Waste Packages	(A) Anoxic corrosion of metal	Excluded (consequence)	Note #4
		(B) Aerobic corrosion of metal	Excluded (consequence)	Note #4
		(C) Thermal-chemical degradation of organic material	Excluded (consequence)	Note #4
		(D) Generation of flammable gases	Excluded (probability)	No ignition source.
WP.00.TC.03	General Corrosion of Waste Packages	(A) Dry-air oxidation	Excluded (probability)	WP and EZ are fully liquid-saturated.
		(B) Humid-air corrosion	Excluded (probability)	WP and EZ are fully liquid-saturated.
		(C) Aqueous phase corrosion	Included	Note #2
		(D) Passive film formation and stability	Excluded (consequence)	
WP.00.TC.04	Stress Corrosion Cracking (SCC) of Waste Packages	(A) Crack initiation, growth and propagation	Included	Note #2
		(B) Stress distribution around cracks	Included	Note #2
WP.00.TC.05	Localized Corrosion of Waste Packages	(A) Pitting	Included	Note #2
		(B) Crevice corrosion	Included	Note #2
		(C) Salt deliquescence	Excluded (probability)	WP and EZ are fully liquid-saturated.
WP.00.TC.06	Hydride Cracking of Waste Packages	(A) Hydrogen diffusion through metal matrix	Excluded (consequence)	Note #2
		(B) Crack initiation and growth in metal hydride phases	Excluded (consequence)	Note #2
		(C) Hydrogen embrittlement	Excluded (consequence)	Note #2
WP.00.TC.07	Internal Corrosion of Waste Packages Prior to Breach	(A) Corrosion prior to breach	Excluded (consequence)	
WP.00.TC.08	Electrochemical Effects in Waste Packages	(A) Enhanced metal corrosion	Excluded (consequence)	
WP.00.TC.09	Chemical Interactions Between Co-Located Waste	-(A) Interaction of corrosion products, groundwater species, complexants, and actinides from multiple waste forms in the same waste package	Excluded (consequence)	
WP.00.TC.10	Evolution of the Water Chemistry in Waste Packages	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included	
		(G) Solubility of radionuclides and other species	Included	
		(H) Thermal-chemical interactions with waste forms / WP components, including chemical effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Included (deferred)	
		(J) Thermal-chemical interaction with intruding fluids, including effects on fluid density	Included	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
		(L) Osmotic stress and osmotic binding	Excluded (consequence)	
WP.00.TB.01	Microbial Activity in Waste Packages	(A) Microbial effects on corrosion	Excluded (probability)	Note #5
		(B) Formation of complexants (humates, fulvates, organic waste)	Excluded (probability)	Note #5
		(C) Formation of microbial colloids	Excluded (probability)	Note #5
		(D) Formation of biofilms	Excluded (probability)	Note #5
		(E) Biodegradation	Excluded (probability)	Note #5
		(F) Biomass production	Excluded (probability)	Note #5
		(G) Bioaccumulation	Excluded (probability)	Note #5
		(H) CO_2, CH_4, and H_2S generation from microbial degradation	Excluded (probability)	Note #5
		(I) Nitrification	Excluded (probability)	Note #5
		(J) Sulfurization	Excluded (probability)	Note #5
		(K) Methanogenesis	Excluded (probability)	Note #5
WP.00.TB.02	Thermal Effects on Microbial Activity in Waste Packages	(A) Thermal effects on microbial activity	Excluded (probability)	Note #5
WP.00.TT.01	Transport of Dissolved Radionuclides in the Liquid Phase in Waste Packages	(A) Advection	Included	
		(B) Dispersion	Included	
		(C) Diffusion	Included	
		(D) Matrix Diffusion	Excluded (consequence)	
		(E) Intra-aqueous complexation	Excluded (probability)	No complexing agents in waste or WP.
		(F) Isotopic dilution	Included (deferred)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(G) Dilution by mixing with formation waters	Included	
		(H) Solubility of radionuclides and other species	Included	
WP.00.TT.02	Interaction of Dissolved Radionuclides with Stationary Phases in Waste Packages	(A) Reversible/irreversible physical sorption	Excluded (consequence)	Conservative assumption
		(B) Surface complexation	Excluded (consequence)	Conservative assumption
		(C) Ion exchange	Excluded (consequence)	Conservative assumption
		(D) Precipitation / dissolution, including limited dissolution due to inclusion in secondary phases and enhanced dissolution due to alpha recoil	Included	No enhanced dissolution due to alpha recoil as there is no alpha-emitting waste.
WP.00.TT.03	Interaction of Dissolved Radionuclides with Other Mobile Phases (Colloids, Gas Phase) in Waste Packages	(A) Reversible/irreversible physical sorption	Excluded (consequence)	Conservative assumption
		(B) Interactions with organic complexants	Excluded (consequence)	Conservative assumption
		(C) Ion exchange	Excluded (consequence)	Conservative assumption
		(D) Precipitation / dissolution	Excluded (consequence)	Conservative assumption
		(E) Partitioning	Excluded (consequence)	Conservative assumption
WP.00.TT.04	Coupled Process Effects on Transport of Dissolved Radionuclides in Waste Packages	(A) Thermal diffusion (Soret effect)	Excluded (consequence)	Effect negligible compared to uncertainty in diffusion coefficient
		(B) Thermal osmosis	Excluded (consequence)	Effect negligible compared to advection
		(C) Thermal conduction to adjacent components (buffer/backfill/host rock)	Included	
		(D) Other thermal effects, such as other Onsager relationships	Excluded (consequence)	Effect negligible given small radius of WP
WP.00.TT.05	Transport of Radionuclides in the Gas Phase in Waste Packages	(A) Advection	Excluded (consequence)	Note #4
		(B) Diffusion	Excluded (consequence)	Note #4
WP.00.TT.06	Formation of Colloids in Waste Packages	(A) Intrinsic colloids	Included (deferred)	Note #6
		(B) Pseudo-colloids (host rock fragments, waste form fragments, corrosion products, microbes)	Included (deferred)	Note #6
		(C) Sorption of radionuclides to colloids	Included (deferred)	Note #6
WP.00.TT.07	Transport of Radionuclides on Colloids in Waste Packages	(A) Advection	Included (deferred)	Note #6
		(B) Dispersion	Included (deferred)	Note #6
		(C) Diffusion	Included (deferred)	Note #6
		(D) Matrix Diffusion	Excluded (consequence)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(E) Stability/flocculation (mechanical stability, chemical stability)	Excluded (consequence)	Conservative assumption.
		(F) Filtration (physical, electrostatic)	Excluded (consequence)	Conservative assumption.
		(G) Dilution by mixing with formation waters	Included (deferred)	
WP.00.TT.08	Interaction of Colloids with Other Phases in Waste Packages	(A) Reversible/irreversible physical sorption onto stationary phases	Excluded (consequence)	Conservative assumption
		(B) Sorption at air-water interfaces	Excluded (probability)	WP and EZ are fully liquid-saturated.
WP.00.TL.01	Exothermic Reactions in Waste Packages	(A) Hydration of concrete	Excluded (probability)_	No concrete in WP.
		(B) Reactions with waste package internals	Excluded (consequence)	Heat generated is negligible compared to decay heat from waste.
WP.00.TL.02	Heat Transfer in Waste Packages	(A) Conduction	Included	
		(B) Convection	Included	
		(C) Radiation	Excluded (consequence)	Effect is negligible compared to conduction and convection.
WP.00.RA.01	Radiolysis in Waste Packages	(A) He generation from alpha decay in waste packages	Excluded (probability)	No alpha-emitting waste in WF or WP.
		(B) H_2 generation from radiolysis	Excluded (consequence)	Note #4
		(C) Altered water chemistry	Included (deferred)	
WP.00.RA.02	Radiation Damage to Waste Package	(A) Enhanced waste package degradation	Included	Note #2
WP.00.RA.03	Radiological Mutation of Microbes	(A) Radiation-induced mutation of microbes within a waste package	Excluded (probability)	Note #5
WP.00.CL.01	Climatic Effects on Waste Packages	(A) Variations in precipitation and temperature	Excluded (consequence)	
		(B) Melt water	Excluded (consequence)	
WP.00.NC.01	Criticality In-Package	(A) Formation of critical configuration	Excluded (probability)	No fissile material in waste.
WP.00.EF.01	Early Failure of Waste Packages	(A) Manufacturing defects	Included (deferred)	Note #2
		(B) Improper sealing	Included (deferred)	Note #2
		(C) Error in emplacement	Included (deferred)	This includes a WP stuck above the EZ.
WP.00.SM.01	Seismic Activity Impacts Waste Packages	(A) Mechanical damage to waste packages from ground motion, borehole breakout, fault displacement	Excluded (consequence)	Note #2 and #3
WP.00.IG.01	Igneous Activity Impacts Waste Packages	(A) Mechanical damage to waste packages from igneous intrusion	Excluded (probability)	Note #3
		(B) Chemical interaction with magmatic volatiles	Excluded (probability)	Note #3
		(C) Transport of radionuclides in magma, pyroclasts, vents	Excluded (probability)	Note #3

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WP.00.HE.01	Human Intrusion (Deliberate or Inadvertent) Effects on Waste Packages	(A) Drilling (resource exploration, …)	Included (deferred)	Note #7
		(B) Mining / tunneling	Included (deferred)	Note #7
		(C) Nonintrusive site investigation (airborne, surface-based, …)	Excluded (consequence)	No effect because of depth of WPs.
WP.01.CP.01	Waste Package for SNF Design and Properties	-Geometry -Flow pathways -Materials and properties (initial condition / damage / corrosion products) (porosity, tortuosity, diffusion coefficients, sorption/surface complexation properties, chemical potential) -Fluids, colloids, and their properties (initial saturation, initial water chemistry (pH, ionic strength, p_{CO2}) initial water composition (radionuclides and dissolved species), initial void chemistry (air/gas), initial colloidal concentrations) -Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	
WP.02.CP.01	Waste Package for Vitrified HLW Design and Properties	-Geometry -Materials and properties (initial condition / damage / corrosion products) -Fluids, colloids, and their properties (initial saturation, initial water chemistry (pH, ionic strength, p_{CO2}) initial water composition (radionuclides and dissolved species), initial void chemistry (air/gas), initial colloidal concentrations) -Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
WP.03.CP.01	Waste Package for Cs/Sr Capsules Design and Properties	- Geometry - Materials and properties (initial condition / damage / corrosion products) - Fluids, colloids, and their properties (initial saturation, initial water chemistry (pH, ionic strength, p_{CO2}) initial water composition (radionuclides and dissolved species), initial void chemistry (air/gas), initial colloidal concentrations) - Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	
EZ.00.CP.01	EZ Workings Design and Properties	- Geometry - Components - Materials and properties (initial condition / damage / corrosion products) - Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	
EZ.00.TM.01	Rockfall	(A) Rockfall (dynamic loading) from borehole breakout	Excluded (consequence)	EZ liner provides protection from dynamic loading from borehole breakout.
		(B) Floor buckling	Excluded (probability)	DBD concept does not include a "floor"
EZ.00.TM.02	Borehole Convergence and/or Collapse	(A) Static loading (rubble volume) from borehole breakout or collapse	Excluded (consequence)	EZ liner provides protection from static loading from borehole breakout.
		(B) Alteration of seepage	Included (deferred)	
		(C) Alteration of flow pathways	Included (deferred)	
		(D) Alteration of thermal environment	Included (deferred)	
EZ.00.TC.01	Electrochemical Effects in EZ Workings	(A) Thermally-enhanced metal corrosion	Excluded (consequence)	
EZ.00.TC.02	Evolution of Water Chemistry in EZ Workings After Borehole Breakout	(A) Evolution of water chemistry in EZ due to altered seepage and altered rock contact with EZ components after borehole breakout	Included (deferred)	
		(B) Thermal-chemical reactions from waste-to-host rock contact, including effects on fluid density	Included (deferred)	
		(C) Thermal-chemical reactions from EZ component-to-host rock contact, including effects on fluid density	Included (deferred)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(D) Chemical effects on fluid density	Included (deferred)	
EZ.00.TB.01	Microbial Activity in EZ Workings	(A) Microbial effects on corrosion	Excluded (probability)	Note #5
		(B) Formation of complexants (humates, fulvates, organic waste)	Excluded (probability)	Note #5
		(C) Formation of microbial colloids	Excluded (probability)	Note #5
		(D) Formation of biofilms	Excluded (probability)	Note #5
		(E) Biodegradation	Excluded (probability)	Note #5
		(F) Biomass production	Excluded (probability)	Note #5
		(G) Bioaccumulation	Excluded (probability)	Note #5
		(H) CO_2, CH_4, and H_2S generation from microbial degradation	Excluded (probability)	Note #5
		(I) Nitrification	Excluded (probability)	Note #5
		(J) Sulfurization	Excluded (probability)	Note #5
		(K) Methanogenesis	Excluded (probability)	Note #5
EZ.00.TB.02	Thermal Effects on Microbial Activity in EZ Workings	(A) Thermal effects on microbial activity	Excluded (probability)	Note #5
EZ.00.TT.01	Transport of Dissolved Radionuclides in the Liquid Phase in EZ Workings	(A) Advection	Included	
		(B) Dispersion	Included	
		(C) Diffusion	Included	
		(D) Matrix Diffusion	Excluded (consequence)	
		(E) Intra-aqueous complexation	Excluded (consequence)	
		(F) Isotopic dilution	Included (deferred)	
		(G) Dilution by mixing with formation waters	Included	
		(H) Solubility of radionuclides and other species	Included	
EZ.00.TT.02	Interaction of Dissolved Radionuclides with Stationary Phases in EZ Workings	(A) Reversible/irreversible physical sorption	Included (deferred)	
		(B) Surface complexation	Included (deferred)	
		(C) Ion exchange	Included (deferred)	
		(D) Precipitation / dissolution, including limited dissolution due to inclusion in secondary phases and enhanced dissolution due to alpha recoil	Included	No enhanced dissolution due to alpha recoil as there is no alpha-emitting waste.
EZ.00.TT.03	Interaction of Dissolved Radionuclides with	(A) Reversible/irreversible physical sorption	Included (deferred)	Note #6

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
	Other Mobile Phases (Colloids, Gas Phase) in EZ Workings	(B) Interactions with organic complexants	Included (deferred)	Note #6
		(C) Ion exchange	Included (deferred)	Note #6
		(D) Precipitation / dissolution	Included (deferred)	Note #6
		(E) Partitioning	Included (deferred)	Note #6
EZ.00.TT.04	Coupled Process Effects on Transport of Dissolved Radionuclides in EZ Workings	(A) Thermal diffusion (Soret effect)	Excluded (consequence)	Effect is negligible compared to uncertainty in diffusion coefficient.
		(B) Thermal osmosis	Excluded (consequence)	Effect is negligible compared to advection.
		(C) Thermal conduction to adjacent components and the host rock	Included	
		(D) Other thermal effects, such as other Onsager relationships	Excluded (consequence)	Significant coupled processes accounted for by other FEPs.
EZ.00.TT.05	Transport of Radionuclides in the Gas Phase in EZ Workings	(A) Advection	Excluded (consequence)	Note #4
		(B) Diffusion	Excluded (consequence)	Note #4
EZ.00.TT.06	Formation of Colloids in EZ Workings	(A) Intrinsic colloids	Included (deferred)	Note #6
		(B) Pseudo-colloids (host rock fragments, waste form fragments, corrosion products, microbes)	Included (deferred)	Note #6
		(C) Sorption of radionuclides to colloids	Included (deferred)	Note #6
EZ.00.TT.07	Transport of Radionuclides on Colloids in EZ Workings	(A) Advection	Included (deferred)	Note #6
		(B) Dispersion	Included (deferred)	Note #6
		(C) Diffusion	Included (deferred)	Note #6
		(D) Matrix Diffusion	Excluded (consequence)	
		(E) Stability/flocculation (mechanical stability, chemical stability)	Included (deferred)	Note #6
		(F) Filtration (physical, electrostatic)	Included (deferred)	Note #6
		(G) Dilution by mixing with formation waters	Included (deferred)	
EZ.00.TT.08	Interaction of Colloids with Other Phases in EZ Workings	(A) Reversible/irreversible physical sorption onto stationary phases	Included (deferred)	Note #6
		(B) Sorption at air-water interfaces	Excluded (probability)	EZ is liquid-saturated.
EZ.00.TL.01	Exothermic Reactions in EZ Workings	(A) Hydration of concrete	Excluded (probability)	Hydration of concrete occurs prior to closure of the borehole, not during the postclosure period.
EZ.00.TL.02	Effects of Borehole Breakout on Thermal	(A) Thermal blanket	Included (deferred)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
	Environment in EZ Workings	(B) Condensation	Excluded (probability)	EZ is liquid-saturated.
		(C) Changes in influx may affect temperature and relative humidity	Included (deferred)	
		(C) Conduction	Included	
		(D) Convection	Included	
		(E) Radiation	Excluded (consequence)	Effect is negligible compared to conduction and convection.
EZ.00.RA.01	Radiolysis in EZ Workings	(A) He generation from alpha decay in the EZ workings	Excluded (probability)	No alpha-emitting radionuclides in EZ.
		(B) H_2 generation from radiolysis	Excluded (consequence)	Note #4
		(C) Altered water chemistry	Included (deferred)	
EZ.00.RA.02	Radiation Damage to EZ Workings	(A) Enhanced degradation of EZ components (liner and waste support structures)	Excluded (consequence)	
EZ.00.RA.03	Radiological Mutation of Microbes in EZ Workings	(A) Radiation-induced mutation of microbes within EZ workings	Excluded (probability)	Note #5
EZ.00.CL.01	Climatic Effects on EZ Workings	(A) Variations in precipitation and temperature	Excluded (consequence)	Negligible effects because of depth of EZ.
		(B) Melt water	Excluded (consequence)	Negligible effects because of depth of EZ.
EZ.00.NC.01	Criticality in EZ Workings	(A) Formation of critical configuration	Excluded (probability)	No fissile material in waste.
EZ.00.EF.01	Early Failure of EZ Workings	(A) Inadequate construction	Included (deferred)	Note #8
		(B) Error in emplacement of EZ components	Included (deferred)	Note #8
EZ.00.SM.01	Seismic Activity Impacts EZ Workings	(A) Mechanical damage to EZ components from ground motion, borehole breakout, fault displacement	Excluded (consequence)	EZ liner provides some protection.
EZ.00.IG.01	Igneous Activity Impacts EZ Workings	(A) Mechanical damage to EZ components from igneous intrusion	Excluded (probability)	Note #3
		(B) Chemical interaction with magmatic volatiles	Excluded (probability)	Note #3
		(C) Transport of radionuclides in magma, pyroclasts, vents	Excluded (probability)	Note #3
EZ.00.HE.01	Human Intrusion (Deliberate or Inadvertent) Effects on EZ Workings	(A) Drilling (resource exploration, …)	Included (deferred)	Note #7
		(B) Mining / tunneling	Included (deferred)	Note #7
		(C) Nonintrusive site investigation (airborne, surface-based, …)	Excluded (consequence)	No effect because of depth of the EZ.
EZ.01.CP.01	EZ Buffer/Backfill Design and Properties	-Geometry -Materials and properties -Fluids, colloids, and their properties -Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
EZ.01.TM.01	Mechanical Effects on EZ Buffer/Backfill	(A) Compaction or reconsolidation of buffer/backfill	Included	Note #8
		(B) Back-stress from buffer/backfill	Excluded (consequence)	
		(C) Non-thermally-induced volume changes (e.g., swelling, cracking, corrosion products)	Included (deferred)	Note #8
		(D) Mechanical loading from borehole breakout	Excluded (consequence)	EZ liner provides protection.
		(E) Protection of EZ components from borehole breakout	Excluded (consequence)	EZ liner provides protection.
		(F) Erosion / dissolution	Included	Note #8
EZ.01.TM.02	Thermal-Mechanical Effects on EZ Buffer/Backfill	(A) Thermally enhanced compaction or reconsolidation of buffer/backfill	Included (deferred)	Note #8
		(B) Thermal conduction	Included	
		(C) Thermally accelerated back-stress from buffer/backfill	Excluded (consequence)	
		(D) Thermally-induced volume changes(expansion/stress/cracking)	Included (deferred)	Note #8
		(E) Thermal alteration of buffer/backfill	Included (deferred)	Note #8
		(F) Thermally accelerated borehole breakout	Excluded (consequence)	EZ liner provides protection from borehole breakout.
		(G) Thermal blanket from borehole breakout	Included (deferred)	
EZ.01.TH.01	Pressure-Driven Darcy Flow Through Fractures and Porous Media in the EZ Buffer/Backfill	(A) Pressure-driven flow of liquid (wetting) phase	Included	
		(B) Pressure-driven flow of gas (non-wetting) phase	Excluded (consequence)	Note #4
		(C) Flow of any additional phases (e.g., hydrocarbons)	Excluded (probability)	
		(D) Pressure-driven flow between fractures and matrix (local non-equilibrium	Excluded (consequence)	
EZ.01.TH.02	Capillarity-Dominated Darcy Flow in the EZ Buffer/Backfill	(A) Wicking and imbibition (i.e., infiltration without gravity)	Excluded (consequence)	
		(B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation)	Excluded (probability)	EZ is liquid-saturated.
		(C) Immiscible phase interaction and displacement	Excluded (probability)	EZ is liquid-saturated.
		(D) Trapping, discontinuous blobs, or viscous fingering in non-wetting phase	Excluded (probability)	EZ is liquid-saturated.
EZ.01.TH.03	Gravity- and Density-Dominated Flow in the EZ Buffer/Backfill	(A) Free convection due to density variation (from temperature or salinity effects)	Included	
		(B) Infiltration and drainage	Included (deferred)	From SZ
		(C) Dripping through or ponding at the bottom of the borehole	Excluded (probability)	EZ is liquid-saturated.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
EZ.01.TH.04	Adsorption-Dominated Flow in the EZ Buffer/Backfill (Water held by electrostatic, van der Waals, or hydration forces)	(A) Thin film flow below residual saturation (i.e., near liquid dry-out)	Excluded (probability)	EZ is liquid-saturated.
		(B) Hygroscopy (equilibration of solid phase with humidity)	Excluded (probability)	EZ is liquid-saturated.
		(C) Immobile water in nano-pores or in small-aperture fractures	Excluded (probability)	EZ is liquid-saturated.
EZ.01.TH.05	Diffusion or Dispersion in Miscible Phases in the EZ Buffer/Backfill	(A) Diffusion of vapor in air phase	Excluded (probability)	EZ is liquid-saturated.
		(B) Diffusion of dissolved gas in liquid phase	Excluded (consequence)	Note #4
EZ.01.TH.06	Non-Darcy Flow Through Fractures and Porous Media in the EZ Buffer/Backfill	(A) High Reynolds number fluid flow in large-aperture fractures	Excluded (probability)	
		(B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths	Included (deferred)	
		(C) Threshold gradient flow in low-permeability matrix	Excluded (probability)	
EZ.01.TH.07	Thermal-Hydrological Effects on Flow in EZ Buffer/Backfill	(A) Convection and conduction of energy via liquid phase	Included	
		(B) Convection of energy via vapor (i.e., heat pipe)	Excluded (probability)	EZ is liquid-saturated.
		(C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine)	Included	
		(D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation	Excluded (probability)	EZ is liquid-saturated.
		(E) Release of water from hydrated minerals during heating	Excluded (consequence)	
		(F) Decrepitation, creation (during reconsolidation), and migration of fluid inclusions	Excluded (consequence)	Amount of water in fluid inclusions, if any, is insignificant.
EZ.01.TC.01	Evolution of the Water Chemistry in EZ Buffer/Backfill	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included (deferred)	
		(G) Solubility of radionuclides and other species	Included	
		(H) Thermal-chemical interactions with waste forms /WP components / EZ components, including chemical effects on fluid density	Included (deferred)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Included (deferred)	
		(J) Thermal-chemical interaction with intruding fluids and host rock, including effects on fluid density	Included	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
		(L) Osmotic stress and osmotic binding	Excluded (consequence)	
EZ.01.TC.02	Chemical and Thermal-Chemical Degradation of EZ Buffer/Backfill	(A) Thermal-chemical alteration processes	Included	Note #8
		(B) Oxidation/reduction processes, reaction kinetics, interaction with metals	Included (deferred)	
		(C) Dissolution / leaching	Included	Note #8
		(D) Thermal expansion/cracking	Included	Note #8
		(E) Thermally-enhanced corrosion	Excluded (probability)	No metal corrosion in buffer/backfill.
		(F) Radiolysis and altered water chemistry	Included (deferred)	
EZ.01.TL.01	Thermal Effects on EZ Buffer/Backfill	(A) Thermal blanket	Included (deferred)	
		(B) Condensation	Excluded (probability)	EZ is liquid-saturated.
		(C) Heat transfer via conduction, convection, or radiation	Included	
EZ.02.CP.01	EZ Liner Design and Properties	-Geometry -Materials and properties (initial condition / damage / corrosion products) Fluids and their properties	N/A	
EZ.02.TM.01	Mechanical Effects on EZ Liner	(A) Mechanical loading from borehole breakout	Included (deferred)	Note #9
		(B) Back-stress from liners	Excluded (consequence)	
		(C) Degradation from cracking or corrosion of liners	Included (deferred)	Note #9
		(D) Non-thermally-induced volume changes (corrosion products)	Included (deferred)	Note #9
EZ.02.TM.02	Thermal-Mechanical Effects on EZ Liner	(A) Thermal conduction / thermal radiation	Included (deferred)	Note #9
		(B) Thermally-accelerated borehole breakout	Included (deferred)	Note #9
		(C) Thermally-accelerated back-stress from liners	Excluded (consequence)	
		(D) Thermally-induced volume changes(expansion/stress/cracking)	Included (deferred)	Note #9
EZ.02.TH.01	Pressure-Driven Darcy Flow Through EZ Liner	(A) Pressure-driven flow of liquid (wetting) phase	Included (deferred)	Note #9
		(B) Pressure-driven flow of gas (non-wetting) phase	Excluded (consequence)	Note #4
		(C) Flow of any additional phases (e.g., hydrocarbons)	Excluded (probability)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
EZ.02.TH.02	Capillarity-Dominated Darcy Flow Through EZ Liner	(A) Wicking and imbibition (i.e., infiltration without gravity)	Excluded (probability)	EZ is liquid-saturated.
		(B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation)	Excluded (probability)	EZ is liquid-saturated.
		(C) Immiscible phase interaction and displacement	Excluded (probability)	EZ is liquid-saturated.
EZ.02.TH.03	Gravity- and Density-Dominated Flow Through EZ Liner	(A) Free convection due to density variation (from temperature or salinity effects)	Included	
		(B) Infiltration and drainage	Included (deferred)	From SZ
		(C) Dripping	Excluded (probability)	EZ is liquid-saturated.
EZ.02.TH.04	Adsorption-Dominated Flow Through EZ Liner (Water held by electrostatic, van der Waals, or hydration forces)	(A) Thin film flow below residual saturation (i.e., near liquid dry-out)	Excluded (probability)	EZ is liquid-saturated.
		(B) Hygroscopy (equilibration of solid phase with humidity)	Excluded (probability)	EZ is liquid-saturated.
EZ.02.TH.05	Diffusion or Dispersion in Miscible Phases Through EZ Liner	(A) Diffusion of vapor in air phase	Excluded (probability)	EZ is liquid-saturated.
		(B) Diffusion of dissolved gas in liquid phase	Excluded (consequence)	Note #4
EZ.02.TH.06	Non-Darcy Flow Through Fractures and Porous Media Through EZ Liner	(A) High Reynolds number fluid flow in large-aperture fractures	Excluded (probability)	
		(B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths	Included (deferred)	Note #9
EZ.02.TH.07	Thermal-Hydrological Effects on Flow Through EZ Liner	(A) Convection and conduction of energy via liquid phase	Included	
		(B) Convection of energy via vapor (i.e., heat pipe)	Excluded (probability)	EZ is liquid-saturated.
		(C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine)	Included	
		(D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation	Excluded (probability)	EZ is liquid-saturated.
EZ.02.TC.01	Evolution of the Water Chemistry in EZ Liner	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included (deferred)	
		(G) Solubility of radionuclides and other species	Included	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(H) Thermal-chemical interactions with waste forms /WP components / EZ components, including chemical effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Included (deferred)	
		(J) Thermal-chemical interaction with intruding fluids and host rock, including effects on fluid density	Included (deferred)	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
		(L) Osmotic stress and osmotic binding	Excluded (consequence)	
EZ.02.TC.02	Chemical and Thermal-Chemical Degradation of EZ Liner	(A) Thermal-chemical alteration processes	Included (deferred)	Note #9
		(B) Oxidation/reduction processes, reaction kinetics, interaction with metals	Included (deferred)	Note #9
		(C) Dissolution / leaching	Included (deferred)	Note #9
		(D) Thermal expansion/cracking	Included (deferred)	Note #9
		(E) Thermally-enhanced corrosion	Included (deferred)	Note #9
		(F) Radiolysis and altered water chemistry	Included (deferred)	Note #9
EZ.03.CP.01	Design of EZ Cement Plugs	- Geometry - Materials and properties (initial condition / damage / corrosion products) - Fluids and their properties	N/A	
EZ.03.TM.01	Mechanical Effects on EZ Cement Plugs	(A) Compaction or reconsolidation of Cement plugs	Included	Note #8
		(B) Back-stress from cement plugs	Excluded (consequence)	
		(C) Non-thermally-induced volume changes (e.g., swelling, cracking, corrosion products)	Included	Note #8
		(D) Mechanical loading from borehole breakout	Excluded (consequence)	EZ liner provides protection.
		(E) Protection of EZ components from borehole breakout	Excluded (consequence)	EZ liner provides protection.
		(F) Erosion / dissolution	Included	Note #8
EZ.03.TM.02	Thermal-Mechanical Effects on EZ Cement Plugs	(A) Thermally enhanced compaction or reconsolidation of cement plugs	Included (deferred)	Note #8
		(B) Thermal conduction	Included	
		(C) Thermally accelerated back-stress from cement plugs	Excluded (consequence)	
		(D) Thermally-induced volume changes(expansion/stress/cracking)	Included (deferred)	Note #8

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(E) Thermal alteration of cement plugs	Included (deferred)	Note #8
		(F) Thermally accelerated borehole breakout	Excluded (consequence)	EZ liner provides protection from borehole breakout.
EZ.03.TH.01	Pressure-Driven Darcy Flow Through EZ Cement Plugs	(A) Pressure-driven flow of liquid (wetting) phase	Included	
		(B) Pressure-driven flow of gas (non-wetting) phase	Excluded (consequence)	Note #4
		(C) Flow of any additional phases (e.g., hydrocarbons)	Excluded (probability)	
EZ.03.TH.02	Capillarity-Dominated Darcy Flow Through EZ Cement Plugs	-(A) Wicking and imbibition (i.e., infiltration without gravity)	Excluded (consequence)	
		-(B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation)	Excluded (probability)	EZ is liquid-saturated.
		(C) Immiscible phase interaction and displacement	Excluded (probability)	EZ is liquid-saturated.
EZ.03.TH.03	Gravity- and Density-Dominated Flow Through EZ Cement Plugs	-(A) Free convection due to density variation (from temperature or salinity effects)	Included	
		(B) Infiltration and drainage	Included (deferred)	From SZ
		(C) Dripping	Excluded (probability)	EZ is liquid-saturated.
EZ.03.TH.04	Adsorption-Dominated Flow Through EZ Cement Plugs (Water held by electrostatic, van der Waals, or hydration forces)	(A) Thin film flow below residual saturation (i.e., near liquid dry-out)	Excluded (probability)	EZ is liquid-saturated.
		(B) Hygroscopy (equilibration of solid phase with humidity)	Excluded (probability)	EZ is liquid-saturated.
		(C) Immobile water in nano-pores or in small-aperture fractures	Excluded (probability)	EZ is liquid-saturated.
EZ.03.TH.05	Diffusion or Dispersion in Miscible Phases Through EZ Cement Plugs	(A) Diffusion of vapor in air phase	Excluded (probability)	EZ is liquid-saturated.
		(B) Diffusion of dissolved gas in liquid phase	Excluded (consequence)	Note #4
EZ.03.TH.06	Non-Darcy Flow Through EZ Cement Plugs	(A) High Reynolds number fluid flow in large-aperture fractures	Excluded (probability)	
		(B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths	Included	Note #8
		(C) Threshold gradient flow in low-permeability matrix	Excluded (probability)	
EZ.03.TH.07	Thermal-Hydrological Effects on Flow in EZ Cement Plugs	(A) Convection and conduction of energy via liquid phase	Included	
		(B) Convection of energy via vapor (i.e., heat pipe)	Excluded (probability)	EZ is liquid-saturated.
		(C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine)	Included	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation	Excluded (probability)	EZ is liquid-saturated.
		(E) Release of water from hydrated minerals during heating	Excluded (consequence)	
EZ.03.TC.01	Evolution of the Water Chemistry in EZ Cement Plugs	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included (deferred)	
		(G) Solubility of radionuclides and other species	Included	
		(H) Thermal-chemical interactions with waste forms /WP components / EZ components, including chemical effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Included (deferred)	
		(J) Thermal-chemical interaction with intruding fluids and host rock, including effects on fluid density	Included	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
		(L) Osmotic stress and osmotic binding	Excluded (consequence)	
EZ.03.TC.02	Chemical and Thermal-Chemical Degradation of EZ Cement Plugs	(A) Thermal-chemical alteration processes	Included	Note #8
		(B) Oxidation/reduction processes, reaction kinetics, interaction with metals	Included (deferred)	
		(C) Dissolution / leaching	Included	Note #8
		(D) Thermal expansion/cracking	Included	Note #8
		(E) Thermally-enhanced corrosion	Included	Note #8
		(F) Radiolysis and altered water chemistry	Included (deferred)	
SP.00.CP.01	Design and Properties of Seals and Plugs	- Geometry - Materials and properties (initial condition / damage / corrosion products) - Fluids, colloids, and their properties - Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	
SP.00.TH.01	Pressure-Driven Darcy Flow Through Fractures	(A) Pressure-driven flow of liquid (wetting) phase	Included	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
	and Porous Media in Seals and Plugs	(B) Pressure-driven flow of gas (non-wetting) phase	Excluded (consequence)	Note #4
		(C) Flow of any additional phases (e.g., hydrocarbons)	Excluded (probability)	
		(D) Pressure-driven flow between fractures and matrix (local non-equilibrium)	Excluded (consequence)	
SP.00.TH.02	Capillarity-Dominated Darcy Flow in Seals and Plugs	(A) Wicking and imbibition (i.e., infiltration without gravity)	Excluded (consequence)	
		(B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation)	Excluded (probability)	SZ is liquid-saturated.
		(C) Immiscible phase interaction and displacement	Excluded (probability)	SZ is liquid-saturated.
		(D) Trapping, discontinuous blobs, or viscous fingering in non-wetting phase	Excluded (probability)	SZ is liquid-saturated.
SP.00.TH.03	Gravity- and Density-Dominated Flow in Seals and Plugs	(A) Free convection due to density variation (from temperature or salinity effects)	Included	
		(B) Infiltration and drainage	Included (deferred)	From UBZ
SP.00.TH.04	Adsorption-Dominated Flow in Seals and Plugs (Water held by electrostatic, van der Waals, or hydration forces)	(A) Thin film flow below residual saturation (i.e., near liquid dry-out)	Excluded (probability)	SZ is liquid-saturated.
		(B) Hygroscopy (equilibration of solid phase with humidity)	Excluded (probability)	SZ is liquid-saturated.
		(C) Immobile water in nano-pores or in small-aperture fractures	Excluded (probability)	SZ is liquid-saturated.
SP.00.TH.05	Diffusion or Dispersion in Miscible Phases in Seals and Plugs	(A) Diffusion of vapor in air phase	Excluded (probability)	SZ is liquid-saturated.
		(B) Diffusion of dissolved gas in liquid phase	Excluded (consequence)	Note #4
SP.00.TH.06	Non-Darcy Flow Through Fractures and Porous Media in Seals and Plugs	(A) High Reynolds number fluid flow in large-aperture fractures	Excluded (probability)	
		(B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths	Included	Note #8
		(C) Threshold gradient flow in low-permeability matrix	Excluded (probability)	
SP.00.TH.07	Thermal-Hydrological Effects on Flow in Seals and Plugs	(A) Convection and conduction of energy via liquid phase	Included	
		(B) Convection of energy via vapor (i.e., heat pipe)	Excluded (probability)	SZ is liquid-saturated.
		(C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine)	Included	
		(D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation	Excluded (probability)	SZ is liquid-saturated.
		(E) Release of water from hydrated minerals during heating	Excluded (consequence)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(F) Decrepitation, creation (during reconsolidation), and migration of fluid inclusions	Excluded (consequence)	Amount of water in fluid inclusions, if any, is insignificant.
SP.00.TB.01	Microbial Activity in Seals and Plugs	(A) Microbial effects on corrosion	Included (deferred)	Note #5
		(B) Formation of complexants	Included (deferred)	Note #5
		(C) Formation of microbial colloids	Included (deferred)	Note #5
		(D) Formation of biofilms	Included (deferred)	Note #5
		(E) Biodegradation	Included (deferred)	Note #5
		(F) Biomass production	Included (deferred)	Note #5
		(G) Bioaccumulation	Included (deferred)	Note #5
		(H) CO_2, CH_4, and H_2S generation from microbial degradation	Included (deferred)	Note #5
		(I) Nitrification	Included (deferred)	Note #5
		(J) Sulfurization	Included (deferred)	Note #5
		(K) Methanogenesis	Included (deferred)	Note #5
SP.00.TB.02	Thermal Effects on Microbial Activity in Seals and Plugs	(A) Thermal effects on microbial activity	Included (deferred)	Note #5
SP.00.TT.01	Transport of Dissolved Radionuclides in the Liquid Phase in Seals and Plugs	(A) Advection	Included	
		(B) Dispersion	Included	
		(C) Diffusion	Included	
		(D) Matrix Diffusion	Excluded (consequence)	
		(E) Intra-aqueous complexation	Excluded (consequence)	
		(F) Isotopic dilution	Included (deferred)	
		(G) Dilution by mixing with formation waters	Included	
		(H) Solubility of radionuclides and other species	Included	
SP.00.TT.02	Interaction of Dissolved Radionuclides with Stationary Phases (Rock Matrix, Fracture Surfaces) in Seals and Plugs	(A) Reversible/irreversible physical sorption	Included	
		(B) Surface complexation	Included	
		(C) Ion exchange	Included	
		(D) Precipitation / dissolution, including limited dissolution due to inclusion in secondary phases and enhanced dissolution due to alpha recoil	Included	No enhanced dissolution due to alpha recoil as there is no alpha-emitting waste.
SP.00.TT.03	Interaction of Dissolved Radionuclides with	(A) Reversible/irreversible physical sorption	Included (deferred)	Note #6

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
	Other Mobile Phases (Colloids, Gas Phase) in Seals and Plugs	(B) Interactions with organic complexants	Included (deferred)	Note #6
		(C) Ion exchange	Included (deferred)	Note #6
		(D) Precipitation / dissolution	Included (deferred)	Note #6
		(E) Partitioning	Included (deferred)	Note #6
SP.00.TT.04	Coupled Process Effects on Transport of Dissolved Radionuclides in Seals and Plugs	(A) Thermal diffusion (Soret effect)	Excluded (consequence)	Effect is negligible compared to uncertainty in diffusion coefficient.
		(B) Thermal osmosis	Excluded (consequence)	Effect is negligible compared to advection.
		(C) Thermal conduction to adjacent components and the host rock	Excluded (probability)	No heat generation in the seals and plugs.
		(D) Other thermal effects, such as other Onsager relationships	Excluded (consequence)	Significant coupled processes accounted for by other FEPs.
SP.00.TT.05	Transport of Radionuclides in the Gas Phase in Seals and Plugs	(A) Advection	Excluded (consequence)	Note #4
		(B) Diffusion	Excluded (consequence)	Note #4
SP.00.TT.06	Formation of Colloids in Seals and Plugs	(A) Intrinsic colloids	Included (deferred)	Note #6
		(B) Pseudo-colloids (host rock fragments, waste form fragments, corrosion products, microbes)	Included (deferred)	Note #6
		(C) Sorption of radionuclides to colloids	Included (deferred)	Note #6
SP.00.TT.07	Transport of Radionuclides on Colloids in Seals and Plugs	(A) Advection	Included (deferred)	Note #6
		(B) Dispersion	Included (deferred)	Note #6
		(C) Diffusion	Included (deferred)	Note #6
		(D) Matrix Diffusion	Excluded (consequence)	
		(E) Stability/flocculation (mechanical stability, chemical stability)	Included (deferred)	Note #6
		(F) Filtration (physical, electrostatic)	Included (deferred)	Note #6
		(G) Dilution by mixing with formation waters	Included (deferred)	
SP.00.TT.08	Interaction of Colloids with Other Phases (Rock Matrix, Fracture Surfaces) in Seals and Plugs	(A) Reversible/irreversible physical sorption onto stationary phases	Included (deferred)	Note #6
		(B) Sorption at air-water interfaces	Excluded (probability)	SZ is liquid-saturated.
SP.00.TL.01	Exothermic Reactions in Seals and Plugs	(A) Hydration of concrete	Excluded (probability)	Hydration of concrete occurs prior to closure of the borehole, not during the postclosure period.
SP.00.RA.01	Radiolysis in Seals and Plugs	(A) He generation from alpha decay in the seals and plugs	Excluded (probability)	No alpha-emitting radionuclides in SZ.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(B) H_2 generation from radiolysis	Excluded (consequence)	Note #4
		(C) Altered water chemistry	Excluded (consequence)	
SP.00.RA.02	Radiation Damage to Seals and Plugs	(A) Enhanced degradation of seals and plugs	Excluded (consequence)	
SP.00.CL.01	Climatic Effects on Seals and Plugs	(A) Variations in precipitation and temperature	Included (deferred)	Likely to be more significant at shallower depths.
		(B) Melt water	Included (deferred)	Likely to be more significant at shallower depths.
		(C) Seal erosion arising from glaciation	Included (deferred)	Likely to be more significant at shallower depths.
SP.00.NC.01	Criticality in Seals and Plugs	(A) Formation of critical configuration	Excluded (probability)	No fissile material in waste or SZ.
SP.00.EF.01	Early Failure of Seals and Plugs	(A) Error in emplacement	Included (deferred)	Note #8
		(B) Inadequate construction	Included (deferred)	Note #8
SP.00.SM.01	Seismic Activity Impacts Seals and Plugs	(A) Mechanical damage to seals and plugs from ground motion, borehole breakout, and fault displacement	Included (deferred)	
SP.00.IG.01	Igneous Activity Impacts Seals and Plugs	(A) Mechanical damage to EZ components from igneous intrusion	Excluded (probability)	Note #3
		(B) Chemical interaction with magmatic volatiles	Excluded (probability)	Note #3
		(C) Transport of radionuclides in magma, pyroclasts, vents	Excluded (probability)	Note #3
SP.00.HE.01	Human Intrusion (Deliberate or Inadvertent) Effects on Seals and Plugs	(A) Drilling (resource exploration, …)	Included (deferred)	Note #7
		(B) Mining / tunneling	Included (deferred)	Note #7
		(C) Nonintrusive site investigation (airborne, surface-based, …)	Excluded (consequence)	No effect because of depth of the SZ.
SP.01.CP.01	Bentonite Seal Design and Properties	- Geometry - Materials and properties (initial condition / damage / corrosion products) - Fluids, colloids, and their properties - Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	
SP.01.TM.01	Mechanical Effects on Bentonite Seals	(A) Compaction or reconsolidation of bentonite seals	Included	Note #8
		(B) Back-stress from seal components	Included	Note #8
		(C) Non-thermally-induced volume changes (e.g., swelling, cracking, corrosion products)	Included	Note #8

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(D) Mechanical loading from borehole breakout	Included	Note #8
		(E) Erosion / dissolution	Included	Note #8
SP.01.TM.02	Thermal-Mechanical Effects on Bentonite Seals	(A) Thermally enhanced compaction or reconsolidation of bentonite seals	Excluded (consequence)	Minimal temperature increase in SZ.
		(B) Thermal conduction	Excluded (consequence)	Minimal temperature increase in SZ.
		(C) Thermally accelerated back-stress from seal components	Excluded (consequence)	Minimal temperature increase in SZ.
		(D) Thermally-induced volume changes(expansion/stress/cracking)	Excluded (consequence)	Minimal temperature increase in SZ.
		(E) Thermal alteration of bentonite seals	Excluded (consequence)	Minimal temperature increase in SZ.
		(F) Thermally accelerated borehole breakout	Excluded (consequence)	Minimal temperature increase in SZ.
		(G) Thermal blanket from borehole breakout	Excluded (consequence)	Minimal temperature increase in SZ.
SP.01.TC.01	Evolution of Water Chemistry in Bentonite Seals	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included	
		(G) Solubility of radionuclides and other species	Included	
		(H) Thermal-chemical interactions with WP/EZ/seal components, including chemical effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Excluded (probability)	No corrosion products in SZ.
		(J) Thermal-chemical interaction with intruding fluids, including effects on fluid density	Included	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
		(L) Osmotic stress and osmotic binding	Excluded (consequence)	
SP.01.TC.02	Chemical and Thermal-Chemical Degradation of Bentonite Seals	(A) Thermal-chemical alteration processes	Included	Note #8
		(B) Oxidation/reduction processes, reaction kinetics, interaction with metals	Included (deferred)	
		(C) Dissolution / leaching	Included	Note #8
		(D) Cracking induced by thermal-chemical alteration	Included	Note #8

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(E) Enhanced corrosion	Excluded (probability)	No metal corrosion in SZ.
		(F) Radiolysis and altered water chemistry	Excluded (consequence)	
SP.02.CP.01	Cement Plug Design and Properties	- Geometry - Materials and properties (initial condition / damage / corrosion products) - Fluids, colloids, and their properties - Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	
SP.02.TM.01	Mechanical Effects on Cement Plugs	(A) Compaction or reconsolidation of cement plugs	Included	Note #8
		(B) Back-stress from cement plug components	Included	Note #8
		(C) Non-thermally-induced volume changes (e.g., swelling, cracking, corrosion products)	Included	Note #8
		(D) Mechanical loading from borehole breakout	Included	Note #8
		(E) Erosion / dissolution	Included	Note #8
SP.02.TM.02	Thermal-Mechanical Effects on Cement Plugs	(A) Thermally enhanced compaction or reconsolidation of cement plugs	Excluded (consequence)	Minimal temperature increase in SZ.
		(B) Thermal conduction	Excluded (consequence)	Minimal temperature increase in SZ.
		(C) Thermally accelerated back-stress from cement plugs components	Excluded (consequence)	Minimal temperature increase in SZ.
		(D) Thermally-induced volume changes(expansion/stress/cracking)	Excluded (consequence)	Minimal temperature increase in SZ.
		(E) Thermal alteration of cement plugs	Excluded (consequence)	Minimal temperature increase in SZ.
		(F) Thermally accelerated borehole breakout	Excluded (consequence)	Minimal temperature increase in SZ.
		(G) Thermal blanket from borehole breakout	Excluded (consequence)	Minimal temperature increase in SZ.
SP.02.TC.01	Evolution of Water Chemistry in Cement Plugs	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included (deferred)	
		(G) Solubility of radionuclides and other species	Included	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(H) Thermal-chemical interactions with WP/EZ/seal components, including chemical effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Excluded (probability)	No corrosion products in SZ.
		(J) Thermal-chemical interaction with intruding fluids, including effects on fluid density	Included	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
		(L) Osmotic stress and osmotic binding	Excluded (consequence)	
SP.02.TC.02	Chemical and Thermal-Chemical Degradation of Cement Plugs	(A) Thermal-chemical alteration processes	Included	Note #8
		(B) Oxidation/reduction processes, reaction kinetics, interaction with metals	Included (deferred)	
		(C) Dissolution / leaching	Included	Note #8
		(D) Cracking induced by thermal-chemical alteration	Included	Note #8
		(E) Enhanced corrosion	Excluded (probability)	No metal corrosion in SZ.
		(F) Radiolysis and altered water chemistry	Excluded (consequence)	
SP.03.CP.01	Ballast Design and Properties	-Geometry -Materials and properties (initial condition / damage / corrosion products) -Fluids, colloids, and their properties -Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	
SP.03.TM.01	Mechanical Effects on Ballast	(A) Compaction or reconsolidation of ballast	Included	Note #8
		(B) Back-stress from ballast components	Included	Note #8
		(C) Non-thermally-induced volume changes (e.g., swelling, cracking, corrosion products)	Included	Note #8
		(D) Mechanical loading from borehole breakout	Included	Note #8
		(E) Erosion / dissolution	Included	Note #8
SP.03.TM.02	Thermal-Mechanical Effects on Ballast	(A) Thermally enhanced compaction or reconsolidation of ballast	Excluded (consequence)	Minimal temperature increase in SZ.
		(B) Thermal conduction	Excluded (consequence)	Minimal temperature increase in SZ.
		(C) Thermally accelerated back-stress from ballast components	Excluded (consequence)	Minimal temperature increase in SZ.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(D) Thermally-induced volume changes(expansion/stress/cracking)	Excluded (consequence)	Minimal temperature increase in SZ.
		(E) Thermal alteration of ballast	Excluded (consequence)	Minimal temperature increase in SZ.
		(F) Thermally accelerated borehole breakout	Excluded (consequence)	Minimal temperature increase in SZ.
		(G) Thermal blanket from borehole breakout	Excluded (consequence)	Minimal temperature increase in SZ.
SP.03.TC.01	Evolution of Water Chemistry in Ballast	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included (deferred)	
		(G) Solubility of radionuclides and other species	Included	
		(H) Thermal-chemical interactions with WP/EZ/seal components, including chemical effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Excluded (probability)	No corrosion products in SZ.
		(J) Thermal-chemical interaction with intruding fluids, including effects on fluid density	Included	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
		(L) Osmotic stress and osmotic binding	Excluded (consequence)	
SP.03.TC.02	Chemical and Thermal-Chemical Degradation of Ballast	(A) Thermal-chemical alteration processes	Included	Note #8
		(B) Oxidation/reduction processes, reaction kinetics, interaction with metals	Included (deferred)	
		(C) Dissolution / leaching	Included	Note #8
		(D) Cracking induced by thermal-chemical alteration	Included	Note #8
		(E) Enhanced corrosion	Excluded (probability)	No metal corrosion in SZ.
		(F) Radiolysis and altered water chemistry	Excluded (consequence)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
SP.04.CP.01	Casing and Casing Cement Design and Properties	-Geometry -Materials and properties (initial condition / damage / corrosion products) -Fluids, colloids, and their properties -Flow and transport properties (flow type [i.e., porous medium vs. thin film], porosity, permeability, tortuosity, dispersion coefficients, surface complexation, and K_d's)	N/A	
SP.04.TM.01	Mechanical Effects on Casing and Casing Cement	(A) Compaction or reconsolidation of casing and casing cement	Included (deferred)	Note #10
		(B) Back-stress from casing and casing cement	Excluded (consequence)	
		(C) Non-thermally-induced volume changes (e.g., swelling, cracking, corrosion products)	Included (deferred)	Note #10
		(D) Mechanical loading from borehole breakout	Included (deferred)	Note #10
		(E) Erosion / dissolution	Included (deferred)	Note #10
SP.04.TM.02	Thermal-Mechanical Effects on Casing and Casing Cement	(A) Thermally enhanced compaction or reconsolidation of casing and casing cement	Excluded (consequence)	Minimal temperature increase in SZ.
		(B) Thermal conduction	Excluded (consequence)	Minimal temperature increase in SZ.
		(C) Thermally accelerated back-stress from casing and casing cement	Excluded (consequence)	Minimal temperature increase in SZ.
		(D) Thermally-induced volume changes(expansion/stress/cracking)	Excluded (consequence)	Minimal temperature increase in SZ.
		(E) Thermal alteration of casing and casing cement	Excluded (consequence)	Minimal temperature increase in SZ.
		(F) Thermally accelerated borehole breakout	Excluded (consequence)	Minimal temperature increase in SZ.
		(G) Thermal blanket from borehole breakout	Excluded (consequence)	Minimal temperature increase in SZ.
SP.04.TC.01	Evolution of Water Chemistry in Casing and Casing Cement	(A) Speciation	Included (deferred)	Note #10
		(B) Oxidation/reduction processes, reaction kinetics	Included (deferred)	Note #10
		(C) Dissolution, reaction kinetics	Included (deferred)	Note #10
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included (deferred)	Note #10
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included (deferred)	Note #10
		(G) Solubility of radionuclides and other species	Included (deferred)	Note #10
		(H) Thermal-chemical interactions with WP/EZ/seal components, including chemical effects on fluid density	Included (deferred)	Note #10

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Excluded (probability)	No corrosion products in SZ.
		(J) Thermal-chemical interaction with intruding fluids, including effects on fluid density	Included (deferred)	Note #10
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
		(L) Osmotic stress and osmotic binding	Excluded (consequence)	
SP.04.TC.02	Chemical and Thermal-Chemical Degradation of Casing and Casing Cement	(A) Thermal-chemical alteration processes	Included (deferred)	Note #10
		(B) Oxidation/reduction processes, reaction kinetics, interaction with metals	Included (deferred)	Note #10
		(C) Dissolution / leaching	Included (deferred)	Note #10
		(D) Cracking induced by thermal-chemical alteration	Included (deferred)	Note #10
		(E) Enhanced corrosion	Excluded (probability)	No metal corrosion in SZ.
		(F) Radiolysis and altered water chemistry	Excluded (consequence)	
HR.00.CP.01	Stratigraphic and Groundwater Properties of Host Rock	- Stratigraphy / component rock units and their properties - Regional features (e.g., fractures, faults, discontinuities, contacts) - Rock properties - Fluid properties - Groundwater chemistry - Presence or organic complexants (humates, fulvates, carbonates, …) in groundwater	N/A	
HR.00.TH.01	Effects of Recharge on Host Rock	(A) Pressure-driven flow from infiltration	Excluded (consequence)	Infiltration in overlying sediments will not significantly affect crystalline basement.
		(B) Water table rise/decline	Excluded (consequence)	Water table changes in overlying sediments will not significantly affect crystalline basement.
HR.00.TC.01	Thermal-Chemical Gas Generation in Host Rock	(A) Degassing (clathrates, deep gases)	Excluded (probability)	Clathrates and deep gases are found in polar and deep oceanic regions (DOE 2008).
		(B) Thermal-chemical degradation of organic materials	Excluded (consequence)	
HR.00.TB.01	Microbial Activity in Host Rock	(A) Microbial effects on corrosion	Included (deferred)	Note #5
		(B) Formation of complexants (humates, fulvates, organic waste)	Included (deferred)	Note #5
		(C) Formation of microbial colloids	Included (deferred)	Note #5
		(D) Formation of biofilms	Included (deferred)	Note #5

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(E) Biodegradation	Included (deferred)	Note #5
		(F) Biomass production	Included (deferred)	Note #5
		(G) Bioaccumulation	Included (deferred)	Note #5
		(H) CO_2, CH_4, and H_2S generation from microbial degradation	Included (deferred)	Note #5
		(I) Nitrification	Included (deferred)	Note #5
		(J) Sulfurization	Included (deferred)	Note #5
		(K) Methanogenesis	Included (deferred)	Note #5
HR.00.TB.02	Thermal Effects on Microbial Activity in Host Rock	(A) Thermal effects on microbial activity	Included (deferred)	Note #5
HR.00.LG.01	Tectonic Activity (Large Scale) in Host Rock	(A) Uplift	Excluded (probability)	Note #3
		(B) Folding	Excluded (probability)	Note #3
HR.00.LG.02	Subsidence in Host Rock	(A) Potential for subsidence to impact the integrity and performance of the borehole disposal system	Excluded (consequence)	No effect because of depth of the SZ and EZ.
HR.00.LG.03	Metamorphism in Host Rock	(A) Structural changes due to natural heating and/or pressure	Excluded (probability)	Note #3
HR.00.LG.04	Diagenesis in Host Rock	(A) Mineral alteration due to natural processes	Excluded (consequence)	Not significant in crystalline rock.
HR.00.LG.05	Diapirism in Host Rock	(A) Plastic flow of rocks under lithostatic loading	Excluded (consequence)	Not significant in crystalline rock.
		(B) Creep of salt / evaporites	Excluded (probability)	Not relevant to crystalline rock.
		(C) Clay phase transformations	Excluded (probability)	Not relevant to crystalline rock.
HR.00.LG.06	Large-Scale Dissolution in Host Rock	(A) Changes to host rock due to dissolution over geologic time scales	Excluded (consequence)	Not significant in crystalline rock.
HR.00.CL.01	Periglacial Effects on Host Rock	(A) Variations in precipitation and temperature	Excluded (consequence)	Negligible effects at depth of host rock.
		(B) Permafrost	Excluded (consequence)	Negligible effects at depth of host rock.
		(C) Seasonal freeze/thaw	Excluded (consequence)	Negligible effects at depth of host rock.
HR.00.CL.02	Glacial and Ice Sheet Effects on Host Rock	(A) Glaciation	Excluded (consequence)	Negligible effects at depth of host rock.
		(B) Glacial erosion and valleys	Excluded (consequence)	Negligible effects at depth of host rock.
		(C) Isostatic depression	Excluded (consequence)	Negligible effects at depth of host rock.
		(D) Melt water	Excluded (consequence)	Negligible effects at depth of host rock.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
HR.00.NC.01	Criticality in Far-Field	(A) Formation of critical configuration	Excluded (probability)	No fissile material in waste.
HR.00.SM.01	Seismic Activity Impacts Host Rock	(A) Altered flow pathways and properties after a seismic event	Included (deferred)	
		(B) Altered stress regimes (faults, fractures) after a seismic event	Included (deferred)	
HR.00.IG.01	Igneous Activity Impacts Host Rock	(A) Altered flow pathways and properties	Excluded (probability)	Note #3
		(B) Altered stress regimes (faults, fractures	Excluded (probability)	Note #3
		(C) Igneous intrusions	Excluded (probability)	Note #3
		(D) Altered thermal and chemical conditions	Excluded (probability)	Note #3
HR.00.HE.01	Human Intrusion (Deliberate or Inadvertent) - Effects on Host Rock	(A) Drilling (resource exploration, …	Included (deferred)	Note #7
		(B) Mining / tunneling	Included (deferred)	Note #7
		(C) Nonintrusive site investigation (airborne, surface-based, …)	Excluded (consequence)	No effect at depth of host rock.
HR.01.CP.01	Stratigraphy and Properties of the DRZ	-Stratigraphic units (thickness, lateral extent, heterogeneities) -Rock properties -Fluid properties -Fractures and fault properties	N/A	
HR.01.TM.01	Mechanical Effects on the Evolution of the DRZ	(A) Compaction or reconsolidation of DRZ from borehole breakout	Included	Note #11
		(B) Back-stress from waste, backfill or seals in the EZ or seals and plugs	Included	Note #11
		(C) Non-thermally-induced volume changes (closure of fractures)	Included	Note #11
		(D) Borehole pressurization from borehole breakout	Excluded (consequence)	EZ liner provides protection from borehole breakout.
		(E) Borehole breakout alters DRZ	Included	
HR.01.TM.02	Thermal-Mechanical Effects on the Evolution of the DRZ	(A) Thermally-enhanced borehole breakout (consolidation of buffer/backfill and expansion / contraction of DRZ fractures)	Included	Note #11
		(B) Thermal expansion / thermal stress	Included	Note #11
		(C) Thermal conduction	Included	Note #11
		(D) Thermally-induced volume changes(expansion/stress/cracking)	Included	Note #11
HR.01.TH.01	Pressure-Driven Darcy Flow Through Fractures and Porous Media in the DRZ	(A) Pressure-driven flow of liquid (wetting) phase	Included	
		(B) Pressure-driven flow of gas (non-wetting) phase	Excluded (consequence)	Note #4
		(C) Flow of any additional phases (e.g., hydrocarbons)	Excluded (consequence)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(D) Pressure-driven flow between fractures and matrix (local non-equilibrium)	Included (deferred)	
HR.01.TH.02	Capillarity-Dominated Darcy Flow in the DRZ	(A) Wicking and imbibition (i.e., infiltration without gravity)	Excluded (probability)	DRZ is liquid-saturated.
		(B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation)	Excluded (probability)	DRZ is liquid-saturated.
		(C) Immiscible phase interaction and displacement	Excluded (probability)	DRZ is liquid-saturated.
		(D) Trapping, discontinuous blobs, or viscous fingering in non-wetting phase	Excluded (probability)	DRZ is liquid-saturated.
HR.01.TH.03	Gravity- and Density-Dominated Flow in the DRZ	(A) Free convection due to density variation (from temperature or salinity effects)	Included	
		(B) Infiltration and drainage	Included (deferred)	From surrounding host rock and sediments.
		(C) Dripping or ponding	Excluded (probability)	DRZ is liquid-saturated.
HR.01.TH.04	Adsorption-Dominated Flow in the DRZ (Water held by electrostatic, van der Waals, or hydration forces)	(A) Thin film flow below residual saturation (i.e., near liquid dry-out)	Excluded (probability)	DRZ is liquid-saturated.
		(B) Hygroscopy (equilibration of solid phase with humidity)	Excluded (probability)	DRZ is liquid-saturated.
		(C) Immobile water in nano-pores or in small-aperture fractures	Excluded (probability)	DRZ is liquid-saturated.
HR.01.TH.05	Diffusion or Dispersion in Miscible Phases in the DRZ	(A) Diffusion of vapor in air phase	Excluded (probability)	DRZ is liquid-saturated.
		(B) Diffusion of dissolved gas in liquid phase	Excluded (consequence)	Note #4
HR.01.TH.06	Non-Darcy Flow Through Fractures and Porous Media in the DRZ	(A) High Reynolds number fluid flow in large-aperture fractures	Excluded (probability)	
		(B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths	Included	Note #11
		(C) Threshold gradient flow in low-permeability matrix	Excluded (consequence)	
HR.01.TH.07	Thermal-Hydrological Effects on Flow in the DRZ	(A) Convection and conduction of energy via liquid phase	Included	
		(B) Convection of energy via vapor (i.e., heat pipe)	Excluded (probability)	DRZ is liquid-saturated.
		(C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine)	Included	
		(D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation	Excluded (probability)	DRZ is liquid-saturated.
		(E) Release of water from hydrated minerals during heating	Excluded (consequence)	Amount of water released is insignificant.
		(F) Decrepitation, creation (during reconsolidation), and migration of fluid inclusions	Excluded (consequence)	Amount of water in fluid inclusions, if any, is insignificant.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
HR.01.TC.01	Evolution of Groundwater Chemistry in the DRZ	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included	
		(G) Solubility of radionuclides and other species	Included	
		(H) Thermal-chemical interactions with waste forms /WP components / EZ components, including chemical effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Included (deferred)	
		(J) Thermal-chemical interaction with intruding fluids and host rock, including effects on fluid density	Included	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
HR.01.TC.02	Chemical and Thermal-Chemical Evolution of the DRZ	(A) Thermal-chemical alteration processes for fractures, faults, rock matrix	Included	Note #11
		(B) Thermal-chemical alteration of minerals / volume changes	Included	Note #11
		(C) Thermal-chemical alteration of solubility, mineral precipitation / dissolution / leaching	Included	Note #11
		(D) Oxidation/reduction processes, reaction kinetics	Included	Note #11
		(E) Radiolysis and altered water chemistry	Included (deferred)	
HR.01.TT.01	Transport of Dissolved Radionuclides in the Liquid Phase in the DRZ	(A) Advection	Included	
		(B) Dispersion	Included	
		(C) Diffusion	Included	
		(D) Matrix Diffusion	Included (deferred)	
		(E) Intra-aqueous complexation	Excluded (consequence)	
		(F) Isotopic dilution	Included (deferred)	
		(G) Dilution by mixing with formation waters	Included	
		(H) Solubility of radionuclides and other species	Included	
HR.01.TT.02	Interaction of Dissolved Radionuclides with Stationary Phases (Rock Matrix, Fracture	(A) Reversible/irreversible physical sorption	Included	
		(B) Surface complexation	Included	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
	Surfaces) in the DRZ	(C) Ion exchange	Included	
		(D) Precipitation / dissolution, including limited dissolution due to inclusion in secondary phases and enhanced dissolution due to alpha recoil	Included	No enhanced dissolution due to alpha recoil as there is no alpha-emitting waste.
HR.01.TT.03	Interaction of Dissolved Radionuclides with Other Mobile Phases (Colloids, Gas Phase) in the DRZ	(A) Reversible/irreversible physical sorption	Included (deferred)	Note #6
		(B) Interactions with organic complexants	Included (deferred)	Note #6
		(C) Ion exchange	Included (deferred)	Note #6
		(D) Precipitation / dissolution	Included (deferred)	Note #6
		(E) Partitioning	Included (deferred)	Note #6
HR.01.TT.04	Coupled Process Effects on Transport of Dissolved Radionuclides in the DRZ	(A) Thermal diffusion (Soret effect)	Excluded (consequence)	Effect is negligible compared to uncertainty in diffusion coefficient.
		(B) Thermal osmosis	Excluded (consequence)	Effect is negligible compared to advection.
		(C) Thermal conduction to adjacent components and the host rock	Included	
		(D) Other thermal effects, such as other Onsager relationships	Excluded (consequence)	Significant coupled processes accounted for by other FEPs.
HR.01.TT.05	Transport of Radionuclides in the Gas Phase in the DRZ	(A) Advection	Excluded (consequence)	Note #4
		(B) Diffusion	Excluded (consequence)	Note #4
HR.01.TT.06	Formation of Colloids in the DRZ	(A) Intrinsic colloids	Included (deferred)	Note #6
		(B) Pseudo-colloids (host rock fragments, waste form fragments, corrosion products, microbes)	Included (deferred)	Note #6
		(C) Sorption of radionuclides to colloids	Included (deferred)	Note #6
HR.01.TT.07	Transport of Radionuclides on Colloids in the DRZ	(A) Advection	Included (deferred)	Note #6
		(B) Dispersion	Included (deferred)	Note #6
		(C) Diffusion	Included (deferred)	Note #6
		(D) Matrix Diffusion	Included (deferred)	Note #6
		(E) Stability/flocculation (mechanical stability, chemical stability)	Included (deferred)	Note #6
		(F) Filtration (physical, electrostatic)	Included (deferred)	Note #6
		(G) Dilution by mixing with formation waters	Included (deferred)	
HR.01.TT.08	Interaction of Colloids with Other Phases	(A) Reversible/irreversible physical sorption onto stationary phases	Included (deferred)	Note #6

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
	(Rock Matrix, Fracture Surfaces) in the DRZ	(B) Sorption at air-water interfaces	Excluded (probability)	DRZ is liquid-saturated.
HR.02.CP.01	Stratigraphy and Properties of Crystalline Basement	-Stratigraphic units (thickness, lateral extent, heterogeneities) -Rock properties -Fluid properties -Fractures and fault properties	N/A	
HR.02.TM.01	Thermal-Mechanical Effects in Crystalline Basement	(A) Natural deformation of crystalline basement	Included (deferred)	
		(B) Subsidence	Excluded (consequence)	No effect because of depth of the crystalline basement.
		(C) Thermal expansion / contraction and thermal stress	Included (deferred)	
HR.02.TH.01	Pressure-Driven Darcy Flow Through Fractures and Porous Media in Crystalline Basement	(A) Pressure-driven flow of liquid (wetting) phase	Included	
		(B) Pressure-driven flow of gas (non-wetting) phase	Excluded (consequence)	Note #4
		(C) Flow of any additional phases (e.g., hydrocarbons)	Excluded (consequence)	
		(D) Pressure-driven flow between fractures and matrix (local non-equilibrium)	Included (deferred)	
HR.02.TH.02	Capillarity-Dominated Darcy Flow in Crystalline Basement	(A) Wicking and imbibition (i.e., infiltration without gravity)	Excluded (probability)	Crystalline basement is liquid-saturated.
		(B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation)	Excluded (probability)	Crystalline basement is liquid-saturated.
		(C) Immiscible phase interaction and displacement	Excluded (probability)	Crystalline basement is liquid-saturated.
		(D) Trapping, discontinuous blobs, or viscous fingering in non-wetting phase	Excluded (probability)	Crystalline basement is liquid-saturated.
HR.02.TH.03	Gravity- and Density-Dominated Flow in Crystalline Basement	(A) Free convection due to density variation (from temperature or salinity effects)	Included	
		(B) Infiltration and drainage	Excluded (consequence)	Infiltration in overlying sediments will not significantly affect crystalline basement.
HR.02.TH.04	Adsorption-Dominated Flow in Crystalline Basement (Water held by electrostatic, van der Waals, or hydration forces)	(A) Thin film flow below residual saturation (i.e., near liquid dry-out)	Excluded (probability)	Crystalline basement is liquid-saturated.
		(B) Hygroscopy (equilibration of solid phase with humidity)	Excluded (probability)	Crystalline basement is liquid-saturated.
		(C) Immobile water in nano-pores or in small-aperture fractures	Excluded (probability)	Crystalline basement is liquid-saturated.
HR.02.TH.05	Diffusion or Dispersion in Miscible Phases in Crystalline Basement	(A) Diffusion of vapor in air phase	Excluded (probability)	Crystalline basement is liquid-saturated.
		(B) Diffusion of dissolved gas in liquid phase	Excluded (consequence)	Note #4
HR.02.TH.06	Non-Darcy Flow Through Fractures and	(A) High Reynolds number fluid flow in large-aperture fractures	Excluded (probability)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
	Porous Media in Crystalline Basement	(B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths	Excluded (consequence)	
		(C) Threshold gradient flow in low-permeability matrix	Excluded (consequence)	
HR.02.TH.07	Thermal-Hydrological Effects on Flow in Crystalline Basement	(A) Convection and conduction of energy via liquid phase	Included	
		(B) Convection of energy via vapor (i.e., heat pipe)	Excluded (probability)	Crystalline basement is liquid-saturated.
		(C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine)	Included	
		(D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation	Excluded (probability)	Crystalline basement is liquid-saturated.
		(E) Release of water from hydrated minerals during heating	Excluded (consequence)	Amount of water released is insignificant.
		(F) Decrepitation, creation (during reconsolidation), and migration of fluid inclusions	Excluded (consequence)	Amount of water in fluid inclusions, if any, is insignificant.
HR.02.TC.01	Evolution of Groundwater Chemistry in Crystalline Basement	(A) Speciation	Included	
		(B) Oxidation/reduction processes, reaction kinetics	Included	
		(C) Dissolution, reaction kinetics	Included	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included	
		(E) Formation and filtration of colloids	Included (deferred)	Note #6
		(F) Effect of sorption	Included	
		(G) Solubility of radionuclides and other species	Included	
		(H) Thermal-chemical interactions with disposal system components, including chemical effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with corrosion products, including effects on fluid density	Included (deferred)	
		(J) Thermal-chemical interaction with intruding fluids (from borehole or other units), including chemical effects on fluid density	Included	
		(K) Interaction with gas phase	Excluded (consequence)	Note #4
HR.02.TC.02	Chemical and Thermal-Chemical Evolution of Crystalline Basement	(A) Thermal-chemical alteration processes for fractures, faults, rock matrix	Included (deferred)	
		(B) Thermal-chemical alteration of minerals / volume changes	Included (deferred)	
		(C) Thermal-chemical alteration of solubility, mineral precipitation / dissolution / leaching	Included (deferred)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(D) Oxidation/reduction processes, reaction kinetics	Included	
		(E) Radiolysis and altered water chemistry	Included (deferred)	
HR.02.TT.01	Transport of Dissolved Radionuclides in the Liquid Phase in Crystalline Basement	(A) Advection	Included	
		(B) Dispersion	Included	
		(C) Diffusion	Included	
		(D) Matrix Diffusion	Included (deferred)	
		(E) Intra-aqueous complexation	Excluded (consequence)	
		(F) Isotopic dilution	Included (deferred)	
		(G) Dilution by mixing with formation waters	Included	
		(H) Solubility of radionuclides and other species	Included	
HR.02.TT.02	Interaction of Dissolved Radionuclides with Stationary Phases (Rock Matrix, Fracture Surfaces) in Crystalline Basement	(A) Reversible/irreversible physical sorption	Included	
		(B) Surface complexation	Included	
		(C) Ion exchange	Included	
		(D) Precipitation / dissolution, including limited dissolution due to inclusion in secondary phases and enhanced dissolution due to alpha recoil	Included	No enhanced dissolution due to alpha recoil as there is no alpha-emitting waste.
HR.02.TT.03	Interaction of Dissolved Radionuclides with Other Mobile Phases (Colloids, Gas Phase) in Crystalline Basement	(A) Reversible/irreversible physical sorption	Included (deferred)	Note #6
		(B) Interactions with organic complexants	Included (deferred)	Note #6
		(C) Ion exchange	Included (deferred)	Note #6
		(D) Precipitation / dissolution	Included (deferred)	Note #6
		(E) Partitioning	Included (deferred)	Note #6
HR.02.TT.04	Coupled Process Effects on Transport of Dissolved Radionuclides in Crystalline Basement	(A) Thermal diffusion (Soret effect)	Excluded (consequence)	Effect is negligible compared to uncertainty in diffusion coefficient.
		(B) Thermal osmosis	Excluded (consequence)	Effect is negligible compared to advection.
		(C) Thermal conduction to adjacent components and the host rock	Included	
		(D) Other thermal effects, such as other Onsager relationships	Excluded (consequence)	Significant coupled processes accounted for by other FEPs.
HR.02.TT.05	Transport of Radionuclides in the Gas Phase in Crystalline Basement	(A) Advection	Excluded (consequence)	Note #4
		(B) Diffusion	Excluded (consequence)	Note #4
HR.02.TT.06	Formation of Colloids in Crystalline Basement	(A) Intrinsic colloids	Included (deferred)	Note #6

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(B) Pseudo-colloids (host rock fragments, waste form fragments, corrosion products, microbes)	Included (deferred)	Note #6
		(C) Sorption of radionuclides to colloids	Included (deferred)	Note #6
HR.02.TT.07	Transport of Radionuclides on Colloids in Crystalline Basement	(A) Advection	Included (deferred)	Note #6
		(B) Dispersion	Included (deferred)	Note #6
		(C) Diffusion	Included (deferred)	Note #6
		(D) Matrix Diffusion	Included (deferred)	Note #6
		(E) Stability/flocculation (mechanical stability, chemical stability)	Included (deferred)	Note #6
		(F) Filtration (physical, electrostatic)	Included (deferred)	Note #6
		(G) Dilution by mixing with formation waters	Included (deferred)	
HR.02.TT.08	Interaction of Colloids with Other Phases (Rock Matrix, Fracture Surfaces) in Crystalline Basement	(A) Reversible/irreversible physical sorption onto stationary phases	Included (deferred)	Note #6
		(B) Sorption at air-water interfaces	Excluded (probability)	Crystalline basement is liquid-saturated.
OU.00.CP.01	Stratigraphic and Groundwater Properties of Overlying Geologic Units	-Stratigraphy / component rock units -Regional features (e.g., fractures, faults, discontinuities, contacts) -Rock Properties -Fluid properties -Groundwater chemistry Presence of organic complexants (humates, fulvates, carbonates, …) in groundwater	N/A	Note #12
OU.00.TH.01	Effects of Recharge on Overlying Geologic Units	(A) Pressure-driven flow from infiltration	Included (deferred)	
		(B) Water table rise/decline	Included (deferred)	
OU.00.TC.01	Thermal-Chemical Gas Generation in Overlying Geologic Units	(A) Degassing (clathrates, deep gases)	Excluded (probability)	Clathrates and deep gases are found in polar and deep oceanic regions (DOE 2008).
		(B) Thermal-chemical degradation of organic materials	Included (deferred)	
OU.00.LG.01	Tectonic Activity (Large Scale) in Overlying Geologic Units	(A) Uplift	Excluded (probability)	Note #3
		(B) Folding	Excluded (probability)	Note #3
OU.00.LG.02	Subsidence in Overlying Geologic Units	(A) Potential for subsidence to impact the integrity and performance of other geologic units	Excluded (consequence)	
OU.00.LG.03	Metamorphism in Overlying Geologic Units	(A) Structural changes due to natural heating and/or pressure	Excluded (probability)	Note #3

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
OU.00.LG.04	Diagenesis in Overlying Geologic Units	(A) Mineral alteration due to natural processes	Excluded (consequence)	Note #3
OU.00.LG.05	Diapirism in Overlying Geologic Units	(A) Plastic flow of rocks under lithostatic loading	Excluded (probability)	Note #3
		(B) Creep of salt / evaporites	Excluded (probability)	Note #3
		(C) Clay phase transformations	Excluded (probability)	Note #3
OU.00.LG.06	Large-Scale Dissolution in Overlying Geologic Units	(A) Changes to other geologic units due to dissolution over geologic time scales	Excluded (consequence)	Note #3
OU.00.HP.01	Human Influences on Climate (Intentional and Accidental) Effects on Geosphere	(A) Variations in precipitation and temperature	Included (deferred)	Likely to be more significant at shallower depths.
OU.00.SM.01	Seismic Activity Impacts Overlying Geologic Units	(A) Altered flow pathways and properties after a seismic event	Included (deferred)	
		(B) Altered stress regimes (faults, fractures) after a seismic event	Included (deferred)	
OU.00.IG.01	Igneous Activity Impacts Overlying Geologic Units	(A) Altered flow pathways and properties	Excluded (probability)	Note #3
		(B) Altered stress regimes (faults, fractures	Excluded (probability)	Note #3
		(C) Igneous intrusions	Excluded (probability)	Note #3
		(D) Altered thermal and chemical conditions	Excluded (probability)	Note #3
OU.00.HE.01	Human Intrusion (Deliberate or Inadvertent) Effects on Overlying Geologic Units	(A) Drilling (resource exploration, …	Included (deferred)	Note #7
		(B) Mining / tunneling	Included (deferred)	Note #7
		-(C) Nonintrusive site investigation (airborne, surface-based, …)	Excluded (consequence)	No effect because it is nonintrusive.
OU.01.CP.01	Stratigraphic and Groundwater Properties of Sedimentary Units	-Stratigraphic units (thickness, lateral extent, heterogeneities) -Rock properties -Fluid properties -Fractures and fault properties -Groundwater chemistry -Presence or organic complexants (humates, fulvates, carbonates, …) in groundwater	N/A	Note #12
OU.01.TM.01	Thermal-Mechanical Effects in Sedimentary Units	(A) Natural deformation	Excluded (consequence)	Not significant in sedimentary rocks.
		(B) Subsidence	Included (deferred)	
		(C) Thermal expansion / contraction and thermal stress	Excluded (consequence)	Not a significant process in unconsolidated sediments. Minimal temperature change in sedimentary units.
OU.01.TH.01	Pressure-Driven Darcy Flow Through Fractures and Porous Media in Sedimentary Units	(A) Pressure-driven flow of liquid (wetting) phase	Included (deferred)	
		(B) Pressure-driven flow of gas (non-wetting) phase	Included (deferred)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(C) Flow of any additional phases (e.g., hydrocarbons)	Excluded (consequence)	
		(D) Pressure-driven flow between fractures and matrix (local non-equilibrium)	Included (deferred)	
OU.01.TH.02	Capillarity-Dominated Darcy Flow in Sedimentary Units	(A) Wicking and imbibition (i.e., infiltration without gravity)	Included (deferred)	
		(B) Vapor barrier (i.e., reduction in relative liquid permeability at low saturation)	Included (deferred)	
		(C) Immiscible phase interaction and displacement	Included (deferred)	
		(D) Trapping, discontinuous blobs, or viscous fingering in non-wetting phase	Included (deferred)	
OU.01.TH.03	Gravity- and Density-Dominated Flow in Sedimentary Units	(A) Free convection due to density variation (from temperature or salinity effects)	Included (deferred)	
		(B) Infiltration and drainage	Included (deferred)	From surface
OU.01.TH.04	Adsorption-Dominated Flow in Sedimentary Units (Water held by electrostatic, van der Waals, or hydration forces)	(A) Thin film flow below residual saturation (i.e., near liquid dry-out)	Excluded (consequence)	
		(B) Hygroscopy (equilibration of solid phase with humidity)	Excluded (consequence)	
		(C) Immobile water in nano-pores or in small-aperture fractures	Excluded (consequence)	
OU.01.TH.05	Diffusion or Dispersion in Miscible Phases in Sedimentary Units	(A) Diffusion of vapor in air phase	Included (deferred)	
		(B) Diffusion of dissolved gas in liquid phase	Excluded (consequence)	
OU.01.TH.06	Non-Darcy Flow Through Fractures and Porous Media in Sedimentary Units	(A) High Reynolds number fluid flow in large-aperture fractures	Excluded (probability)	
		(B) Erosion or sedimentation (i.e., non-chemical plugging) of fractures and flow paths	Excluded (consequence)	
		(C) Threshold gradient flow in low-permeability matrix	Excluded (consequence)	
OU.01.TH.07	Thermal-Hydrological Effects on Flow in Sedimentary Units	(A) Convection and conduction of energy via liquid phase	Included (deferred)	
		(B) Convection of energy via vapor (i.e., heat pipe)	Excluded (consequence)	Minimal temperature change in sedimentary units.
		(C) Fluid density and viscosity changes due to temperature (e.g., thermal expansion of brine)	Included (deferred)	
		(D) Phase changes (i.e., condensation, boiling) leading to dry-out or resaturation	Excluded (consequence)	Minimal temperature change in sedimentary units.
		(E) Release of water from hydrated minerals during heating	Excluded (consequence)	Amount of water released is insignificant.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(F) Decrepitation, creation (during reconsolidation), and migration of fluid inclusions	Excluded (consequence)	Amount of water in fluid inclusions, if any, is insignificant.
OU.01.TH.08	Groundwater Discharge to Biosphere Boundary	(A) Infiltration and drainage at the surface (water table, capillary rise, surface water)	Included (deferred)	
		(B) Pressure-driven flow of liquid (wetting) phase	Included (deferred)	
		(C) Pressure-driven flow of gas (non-wetting) phase	Included (deferred)	
		(D) Flow of any additional phases (e.g., hydrocarbons)	Excluded (consequence)	
OU.01.TH.09	Groundwater Discharge to Well	(A) Human use (drinking water, bathing water, industrial)	Included (deferred)	
		(B) Agricultural use (irrigation, animal watering)	Included (deferred)	
OU.01.TC.01	Evolution of Groundwater Chemistry in Sedimentary Units	(A) Speciation	Included (deferred)	
		(B) Oxidation/reduction processes, reaction kinetics	Included (deferred)	
		(C) Dissolution, reaction kinetics	Included (deferred)	
		(D) Precipitation, inclusion in secondary phase, reaction kinetics	Included (deferred)	
		(E) Formation and filtration of colloids	Included (deferred)	
		(F) Effect of sorption	Included (deferred)	
		(G) Solubility of radionuclides and other species	Included (deferred)	
		(H) Thermal-chemical interaction with recharge water, including effects on fluid density	Included (deferred)	
		(I) Thermal-chemical interaction with intruding fluids (saline or fresh water), including effects on fluid density	Included (deferred)	
		(J) Interaction with gas phase	Included (deferred)	
OU.01.TC.02	Chemical and Thermal-Chemical Evolution of Sedimentary Units	(A) Thermal-chemical alteration processes for fractures, faults, rock matrix	Included (deferred)	
		(B) Thermal-chemical alteration of minerals / volume changes	Included (deferred)	
		(C) Thermal-chemical alteration of solubility, mineral precipitation / dissolution / leaching	Included (deferred)	
		(D) Oxidation/reduction processes, reaction kinetics	Included (deferred)	
OU.01.TB.01	Microbial Activity in Sedimentary Units	(A) Microbial effects on corrosion	Included (deferred)	
		(B) Formation of complexants (humates, fulvates, organic waste)	Included (deferred)	
		(C) Formation of microbial colloids	Included (deferred)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(D) Formation of biofilms	Included (deferred)	
		(E) Biodegradation	Included (deferred)	
		(F) Biomass production	Included (deferred)	
		(G) Bioaccumulation	Included (deferred)	
		(H) CO_2, CH_4, and H_2S generation from microbial degradation	Included (deferred)	
		(I) Nitrification	Included (deferred)	
		(J) Sulfurization	Included (deferred)	
		(K) Methanogenesis	Included (deferred)	
OU.01.TB.02	Thermal Effects on Microbial Activity in Sedimentary Units	(A) Thermal effects on microbial activity	Included (deferred)	
OU.01.TT.01	Transport of Dissolved Radionuclides in the Liquid Phase in Sedimentary Units	(A) Advection	Included (deferred)	
		(B) Dispersion	Included (deferred)	
		(C) Diffusion	Included (deferred)	
		(D) Matrix Diffusion	Included (deferred)	
		(E) Intra-aqueous complexation	Excluded (consequence)	
		(F) Isotopic dilution	Included (deferred)	
		(G) Dilution by mixing with formation waters	Included (deferred)	
		(H) Solubility of radionuclides and other species	Included (deferred)	
OU.01.TT.02	Interaction of Dissolved Radionuclides with Stationary Phases (Rock Matrix, Fracture Surfaces) in Sedimentary Units	(A) Reversible/irreversible physical sorption	Included (deferred)	
		(B) Surface complexation	Included (deferred)	
		(C) Ion exchange	Included (deferred)	
		(D) Precipitation / dissolution, including limited dissolution due to inclusion in secondary phases and enhanced dissolution due to alpha recoil	Included (deferred)	No enhanced dissolution due to alpha recoil as there is no alpha-emitting waste.
OU.01.TT.03	Interaction of Dissolved Radionuclides with Other Mobile Phases (Colloids, Gas Phase) in Sedimentary Units	(A) Reversible/irreversible physical sorption	Included (deferred)	
		(B) Interactions with organic complexants	Included (deferred)	
		(C) Ion exchange	Included (deferred)	
		(D) Precipitation / dissolution	Included (deferred)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(E) Partitioning	Included (deferred)	
OU.01.TT.04	Coupled Process Effects on Transport of Dissolved Radionuclides in Sedimentary Units	(A) Thermal diffusion (Soret effect)	Excluded (consequence)	Effect is negligible compared to uncertainty in diffusion coefficient.
		(B) Thermal osmosis	Excluded (consequence)	Effect is negligible compared to advection.
		(C) Thermal conduction to adjacent components and the host rock	Excluded (probability)	No heat generation in the sedimentary units.
		(D) Other thermal effects, such as other Onsager relationships	Excluded (consequence)	Significant coupled processes accounted for by other FEPs.
OU.01.TT.05	Transport of Radionuclides in the Gas Phase in Sedimentary Units	(A) Advection	Included (deferred)	
		(B) Diffusion	Included (deferred)	
OU.01.TT.06	Formation of Colloids in Sedimentary Units	(A) Intrinsic colloids	Included (deferred)	
		(B) Pseudo-colloids (host rock fragments, waste form fragments, corrosion products, microbes)	Included (deferred)	
		(C) Sorption of radionuclides to colloids	Included (deferred)	
OU.01.TT.07	Transport of Radionuclides on Colloids in Sedimentary Units	(A) Advection	Included (deferred)	
		(B) Dispersion	Included (deferred)	
		(C) Diffusion	Included (deferred)	
		(D) Matrix Diffusion	Included (deferred)	
		(E) Stability/flocculation (mechanical stability, chemical stability)	Included (deferred)	
		(F) Filtration (physical, electrostatic)	Included (deferred)	
		(G) Dilution by mixing with formation waters	Included (deferred)	
OU.01.TT.08	Interaction of Colloids with Other Phases (Rock Matrix, Fracture Surfaces) in Sedimentary Units	(A) Reversible/irreversible physical sorption onto stationary phases	Included (deferred)	
		(B) Sorption at air-water interfaces	Excluded (consequence)	
OU.01.CL.01	Periglacial Effects on Sedimentary Units	(A) Variations in precipitation and temperature	Included (deferred)	Likely to be more significant at shallower depths.
		(B) Permafrost	Excluded (consequence)	
		(C) Seasonal freeze/thaw	Excluded (consequence)	
OU.01.CL.02	Glacial and Ice Sheet Effects on Sedimentary Units	(A) Glaciation	Included (deferred)	
		(B) Glacial erosion and valleys	Included (deferred)	

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(C) Isostatic depression	Included (deferred)	
		(D) Melt water	Included (deferred)	Likely to be more significant at shallower depths.
BP.00.TB.01	Microbial Activity in Biosphere	(A) Effect on biosphere characteristics	Included (deferred)	
		(B) Effect on transport through biosphere	Included (deferred)	
BP.00.TL.01	Effects of Repository Heat on Biosphere	(A) Thermal effects on biosphere	Excluded (consequence)	Heat generated by the waste will not affect the biosphere because of the depth of burial and the half-lives of the heat-generating waste
BP.00.RA.01	Radionuclide Alteration in Biosphere	(A) Altered physical and chemical properties	Excluded (probability)	
		(B) Isotopic dilution	Included (deferred)	
BP.00.CL.01	Periglacial Effects on Biosphere	(A) Variations in precipitation and temperature	Included (deferred)	Note #13
		(B) Permafrost	Included (deferred)	Note #13
		(C) Seasonal freeze/thaw	Included (deferred)	Note #13
BP.00.CL.02	Glacial and Ice Sheet Effects on Biosphere	(A) Glaciation	Included (deferred)	Note #13
		(B) Glacial erosion and valleys	Included (deferred)	Note #13
		(C) Isostatic depression	Included (deferred)	Note #13
		(D) Melt water	Included (deferred)	Note #13
BP.00.CL.03	Climate Change (Natural and Anthropogenic)	(A) Long-term global effects (sea level, rain fall, …)	Included (deferred)	Note #13
		(B) Short-term regional and local effects	Included (deferred)	Note #13
		(C) Seasonal local effects (flooding, storms, …)	Included (deferred)	Note #13
BP.00.HP.01	Human Influences on Climate (Intentional and Accidental) Effects on Biosphere	(A) Variations in precipitation and temperature	Included (deferred)	Note #13
		(B) Global, regional, and/or local	Included (deferred)	Note #13
		(C) Greenhouse gases, ozone layer failure	Included (deferred)	Note #13
BP.00.OP.01	Radiation Doses	(A) Exposure rates (ingestion, inhalation, external exposure)	Included (deferred)	Note #13
		(B) Dose conversion factors	Included (deferred)	Note #13
BP.00.SM.01	Seismic Activity Impacts Biosphere	(A) Altered human behavior	Included (deferred)	Note #13
		(B) Altered surface characteristics	Included (deferred)	Note #13
		(C) Altered surface transport pathways	Included (deferred)	Note #13

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
		(D) Altered recharge	Included (deferred)	Note #13
BP.00.IG.01	Igneous Activity Impacts Biosphere	(A) Altered human behavior	Included (deferred)	Note #13
		(B) Altered surface characteristics	Included (deferred)	Note #13
		(C) Altered surface transport pathways	Included (deferred)	Note #13
		(D) Altered recharge	Included (deferred)	Note #13
		(E) Ash fall and ash redistribution	Included (deferred)	Note #13
BP.01.CP.01	Biosphere Surface Characteristics	-Climate -Soils (physical and chemical attributes)	N/A	Note #13
BP.01.CP.02	Topography and Surface Morphology	-Recharge and discharge areas -Surface topography	N/A	Note #13
BP.01.CP.03	Surface Water Characteristics	-Lakes, rivers, springs -Dams, reservoirs, canals, pipelines -Coastal and marine features -Water management activities	N/A	Note #13
BP.01.TM.01	Erosion	(A) Mechanical or chemical weathering	Excluded (consequence)	
		(B) Aeolian or fluvial erosion	Excluded (consequence)	
		(C) Denudation	Excluded (consequence)	
		(D) Subsidence	Excluded (consequence)	
		(E) Mass wasting (erosion)	Excluded (consequence)	
BP.01.TM.02	Deposition	(A) Mechanical or chemical weathering	Excluded (consequence)	
		(B) Aeolian or fluvial or lacustrine deposition	Excluded (consequence)	
		(C) Mass wasting (landslides)	Excluded (consequence)	
BP.01.TH.01	Precipitation	(A) Spatial and temporal distribution	Included (deferred)	
BP.01.TH.02	Surface Runoff and Evapotranspiration	(A) Runoff, impoundments, flooding, increased recharge	Included (deferred)	Note #13
		(B) Evaporation	Included (deferred)	Note #13
		(C) Condensation	Included (deferred)	Note #13
		(D) Transpiration (root uptake)	Included (deferred)	Note #13
BP.01.TH.03	Infiltration and Recharge	(A) Spatial and temporal distribution	Included (deferred)	Note #13
		(B) Future changes to hydraulic gradients	Included (deferred)	Note #13
		(C) Future changes to water table elevation	Included (deferred)	Note #13

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
BP.01.TC.01	Chemical Evolution of Soil and Surface Water	(A) Altered recharge chemistry (natural)	Excluded (consequence)	
		(B) Altered recharge chemistry (anthropogenic – e.g., acid rain)	Excluded (consequence)	
		(C) Speciation	Excluded (consequence)	
		(D) Solubility of radionuclides and other species	Excluded (consequence)	
BP.01.TT.01	Transport of Radionuclides in Air (as gas, vapor, particulates, aerosols)	(A) Wind	Included (deferred)	Note #13
		(B) Plowing	Included (deferred)	Note #13
		(C) Degassing, precipitation	Included (deferred)	Note #13
BP.01.TT.02	Transport of Radionuclides in Surface Water	(A) River flow	Included (deferred)	Note #13
		(B) Spring discharge	Included (deferred)	Note #13
		(C) Irrigation	Included (deferred)	Note #13
		(D) Overland flow, aeration, sedimentation	Included (deferred)	Note #13
		(E) Dilution by mixing with surface waters (e.g., lake mixing)	Included (deferred)	Note #13
BP.01.TT.03	Transport of Radionuclides in or on Soil and Sediments	(A) Fluvial (runoff, river flow)	Included (deferred)	Note #13
		(B) Eolian (wind)	Included (deferred)	Note #13
		(C) Saltation	Excluded (consequence)	
		(D) Glaciation	Excluded (consequence)	
		(E) Bioturbation (animals)	Excluded (probability)	The depth of waste disposal precludes animal intrusion.
BP.01.TT.04	Radionuclide Accumulation in Soils	(A) Leaching/evaporation from discharge (well, groundwater upwelling)	Included (deferred)	Note #13
		(B) Deposition from atmosphere or water (irrigation, runoff)	Included (deferred)	Note #13
		(C) Recycling of accumulated radionuclides from soils to groundwater	Included (deferred)	Note #13
BP.01.RA.01	Radionuclides in Biosphere Media	(A) Soil	Included (deferred)	Note #13
		(B) Surface Water	Included (deferred)	Note #13
		(C) Air	Included (deferred)	Note #13
		(D) Plant Uptake	Included (deferred)	Note #13
		(E) Animal (Livestock, Fish) Uptake	Included (deferred)	Note #13
		(F) Bioaccumulation	Included (deferred)	Note #13

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
BP.01.RA.02	Radionuclides in Non-Food Products	(A) Dwellings (location, building materials and sources, fuel sources)	Included (deferred)	Note #13
		(B) Household products (clothing and sources, furniture and sources, tobacco, pets)	Included (deferred)	Note #13
		(C) Biosphere media	Included (deferred)	Note #13
BP.01.HP.01	Land and Water Use	(A) Agricultural (irrigation, plowing, fertilization, crop storage, greenhouses, hydroponics)	Included (deferred)	Note #13
		(B) Farms and Fisheries (feed, water, soil)	Included (deferred)	Note #13
		(C) Urban / Industrial (development, energy production, earthworks, population density)	Included (deferred)	Note #13
		(D) Natural / Wild (grasslands, forests, bush, surface water)	Included (deferred)	Note #13
BP.01.HP.02	Evolution of Land and Water Use	(A) New practices (agricultural, farming, fisheries)	Included (deferred)	Note #13
		(B) Technological developments	Included (deferred)	Note #13
		(C) Social developments (new/expanded communities)	Included (deferred)	Note #13
BP.01.OP.01	Inhalation	(A) Gases and vapors	Excluded (probability)	The radionuclides in the waste do not exist in the vapor phase at ambient surface conditions.
		(B) Suspended particulates (dust, smoke, pollen)	Included (deferred)	Note #13
BP.01.OP.02	External Exposure	(A) Non-Food products	Included (deferred)	Note #13
		(B) Soil, surface water	Included (deferred)	Note #13
BP.02.CP.01	Biosphere Flora and Fauna Characteristics	-Flora and fauna -Microbes	N/A	Note #13
BP.02.TM.01	Animal Intrusion into Repository	(A) Impact on surface sediments	Excluded (consequence)	
		(B) Burrowing into borehole	Excluded (probability)	The depth of waste disposal precludes animal intrusion
BP.03.CP.01	Human Characteristics	-Physiology -Metabolism -Adults, children	N/A	Note #13
BP.03.CP.02	Human Evolution	-Changing human characteristics -Sensitization to radiation -Changing lifestyle	N/A	Note #13
BP.03.CP.03	Human Lifestyle	-Diet and fluid intake (food, water, tobacco/drugs, etc.) -Dwellings -Household activities -Leisure activities	N/A	Note #13
BP.03.OP.01	Radiological Toxicity and Effects	(A) Human health effects from radiation doses	Included (deferred)	Note #13

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
BP.03.OP.02	Non-Radiological Toxicity and Effects	(A) Human health effects from non-radiological toxicity	Included (deferred)	Note #13
BP.04.RA.01	Radionuclides in Food Products	(A) Diet and fluid sources (location, degree of contamination, dilution with uncontaminated sources)	Included (deferred)	Note #13
		(B) Foodstuff and fluid processing and preparation (water filtration, cooking techniques)	Included (deferred)	Note #13
BP.04.OP.01	Ingestion	(A) Food products	Included (deferred)	Note #13
		(B) Soil, surface water	Included (deferred)	Note #13
RS.01.CP.01	Repository System Assessment	-Timescales of concern -Spatial domain of concern -Model and data issues	N/A	
RS.01.CP.02	Repository System Regulatory Basis	-Regulatory requirements and exclusions -Retrievability	N/A	
RS.02.CP.01	Repository Design	-Layout of boreholes -Waste package emplacement and heat loading -Backfill/buffer around packages -Borehole seals and plugs	N/A	
RS.02.CP.02	Deviations from Design and Inadequate Quality Control	-Error in waste emplacement (waste forms, waste packages, waste package support materials) -Error in EZ/SP/HR component emplacement (backfill, seals, liner) -Inadequate excavation / construction (planning, schedule, implementation) -Aborted / incomplete closure of borehole -Material and/or component defects	N/A	
RS.02.CP.03	Control of Repository Site	-Active controls (controlled area) -Retention of records -Passive controls (markers)	N/A	
RS.02.TM.01	Mechanical Effects from Preclosure Operations - In emplacement zone - In seals and plugs - In host rock	(A) Creation of DRZ	Included	
		(B) Stress relief	Included	
		(C) Boring and blasting effects	Included	
		(D) Rock reinforcement effects (drill holes)	Excluded (probability)	No rock reinforcement in borehole.
		(E) Accidents and unplanned events	Excluded (consequence)	Effects of significant preclosure accidents would be mitigated.
		(F) Enhanced flow pathways	Included	
RS.02.TH.01	Thermal-Hydrologic Effects from Preclosure Operations - In emplacement zone - In seals and plugs - In host rock	(A) Site flooding	Excluded (consequence)	Effects of significant preclosure flooding would be mitigated.
		(B) Preclosure ventilation	Excluded (probability)	No preclosure ventilation.
		(C) Accidents and unplanned events	Excluded (consequence)	Effects of significant preclosure accidents would be mitigated.

FEP Identifier	Description	Associated Processes	Preliminary Screening	Discussion
RS.02.TH.02	Open Boreholes	(A) Site investigation boreholes (open, improperly sealed)	Excluded (consequence)	The distance to any site investigation boreholes precludes interference with the disposal borehole.
		(B) Preclosure and postclosure monitoring boreholes	Excluded (consequence)	Distance to, and design and depth of, monitoring boreholes precludes interference with the disposal borehole.
RS.02.TC.01	Chemical Effects from Preclosure Operations - In emplacement zone - In seals and plugs - In host rock	(A) Water contaminants (explosives residue, diesel, organics, etc.)	Excluded (consequence)	Significant preclosure effects would be mitigated.
		(B) Water chemistry different than host rock (e.g., oxidizing)	Excluded (consequence)	Significant preclosure effects would be mitigated.
		(C) Undesirable materials left	Excluded (consequence)	Significant preclosure effects would be mitigated.
		(D) Accidents and unplanned events	Excluded (consequence)	Effects of significant preclosure accidents would be mitigated.
RS.03.HE.01	Explosions and Crashes from Human Activities	(A) War	Excluded (consequence)	The depth of waste disposal precludes any significant effects.
		(B) Sabotage	Excluded (by regulation)	Note #7
		(C) Testing	Excluded (by regulation)	Note #7
		(D) Resource exploration / exploitation	Included (deferred)	Note #7
		(E) Aircraft	Excluded (consequence)	The depth of waste disposal precludes any significant effects.
RS.03.OE.01	Meteorite Impact	(A) Cratering, host rock removal	Excluded (consequence)	Most significant effects only at shallower depths.
		(B) Exhumation of waste	Excluded (consequence)	The depth of waste disposal precludes any significant effects.
		(C) Alteration of flow pathways	Excluded (consequence)	Most significant effects only at shallower depths.
RS.03.OE.02	Extraterrestrial Events	(A) Solar systems (supernova)	Excluded (consequence)	Based on arguments made in DOE (2008).
		(B) Celestial activity (sun - solar flares, gamma-ray bursters; moon – earth tides)	Excluded (consequence)	Based on arguments made in DOE (2008).
		(C) Alien life forms	Excluded (consequence)	Based on arguments made in DOE (2008).
RS.03.OE.03	Earth Planetary Changes	(A) Changes in earth's magnetic field	Excluded (consequence)	Based on arguments made in DOE (2008).
		(B) Changes in earth's gravitational field (tides)	Excluded (consequence)	Based on arguments made in DOE (2008).
		(C) Changes in ocean currents	Excluded (consequence)	Based on arguments made in DOE (2008).