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Deep Borehole Disposal Research: Demonstration Site Selection Guidelines, Borehole Seals Design, and RD&D Needs

Fuel Cycle Research & Development

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EXECUTIVE SUMMARY

The U.S. Department of Energy has been investigating deep borehole disposal as one alternative for the disposal of spent nuclear fuel and other radioactive waste forms, along with research and development for mined repositories in salt, granite, and clay, as part of the used fuel disposition (UFD) campaign. The deep borehole disposal concept is straightforward and consists of drilling a borehole on the order of 5,000 m deep, emplacing waste canisters in the lower part of the borehole, and sealing the upper part of the borehole with bentonite and concrete seals. A reference design of the disposal system (Arnold et al. 2011a) includes emplacement of 400 waste canisters in the lower 2,000 m of the borehole, seals and plugs in the uncased borehole for 1,500 m above the disposal zone, and standard borehole plugging in the cased upper 1,500 m of the borehole. Safety of the disposal concept relies primarily on the great depth of burial, the isolation provided by the deep natural geological environment, and the integrity of the borehole seals. The DOE developed a research, development, and demonstration (RD&D) roadmap for deep borehole disposal in FY12 (DOE 2012) that emphasized a full-scale demonstration project around which research and development activities would be organized.

The overarching goal of deep borehole disposal research for FY13 is to advance the deep borehole disposal technical basis needed to site and implement a full-scale demonstration project. Given that identifying a demonstration project site is one of the first steps in a demonstration project, a specific objective of the research is to establish technical and logistical guidelines to be used in the evaluation of potential demonstration sites. An additional objective is planning the experimental research program for investigation of alternative sealing methods, including the time-dependent properties of candidate seal materials under a range of environmental conditions. This objective is motivated by the recognition that the borehole seals constitute the primary component of the engineered barrier system in the deep borehole disposal concept. A final objective is to further establish the preliminary safety framework for this disposal concept and for a deep borehole disposal demonstration project.

Selection of a site for a deep borehole disposal demonstration project would be informed by numerous factors that fall into several categories, including technical factors, logistical/practical factors, and sociopolitical factors. Numerous technical factors are potentially important to drilling and construction of a deep borehole, successful completion of a deep borehole disposal demonstration project, and the post-closure safety of the disposal system. Logistical factors for a deep borehole disposal demonstration project are related to drilling activity in the petroleum industry, geothermal industry, and, to a lesser extent, deep scientific drilling activity. Analysis of social and political factors related to site selection is generally beyond the scope of this report, but early engagement with local and regional stakeholders at any potential location, particularly in the scientific and academic communities, would likely improve the chances of implementing a demonstration project. Overall, the site selection strategy for the demonstration project aims to maximize the probability of successfully completing the borehole, at a site with favorable geological, hydrogeological, and geochemical conditions, within budgetary and schedule constraints.

A number of geological, hydrogeological, and geophysical factors have been evaluated that are potentially relevant to successfully completing a deep borehole demonstration project and demonstrating post-closure safety for a deep borehole disposal system:

- Depth to crystalline basement – (less than 2,000 m favorable)
- Crystalline basement lithology – (felsic intrusive rocks preferred)
- Basement structural complexity – (faults, shear zones, and tectonic complexes unfavorable)
- Horizontal stress – (small differential in horizontal stress favorable)
- Tectonic uplift – (low uplift rate favorable)
- Geothermal heat flux – (low heat flux favorable)
- Topographic relief and hydraulic gradient – (low regional topographic relief favorable)
- Quaternary faults and volcanism – (Quaternary-age faulting and volcanism unfavorable)
- Mineral resources potential – (Higher potential for mineral resources in crystalline basement generally unfavorable)

Regarding logistical considerations for a demonstration project, deep drilling is now common within the petroleum industry, but there are few examples where large-diameter wells (greater than about 12 inches diameter) have been drilled in crystalline bedrock to depths of 4,000 to 5,000 meters (Beswick 2008). Although rigs large enough to drill a reference design borehole are not common, there are at least seven drilling contractors in the US that have this capability. These rigs are located in the western and southwestern US. Drilling support services, such as completion and logging services, are available through companies that work with the petroleum drilling sector. The supply chain within the U.S. is robust and it is expected that services and supplies can be procured by competitive bid for each type of equipment or service.

The details of the legal and regulatory requirements for permitting a deep borehole disposal demonstration project vary among states and for Federal versus private land; however, the National Environmental Policy Act compliance framework provides guidance to inform the decision on site selection. The project scope and duration are not of a magnitude that would generally require an Environmental Impact Statement, so planning should be conducted for an Environmental Assessment, which is considerably less rigorous than an Environmental Impact Statement. Drilling, land, and water use permits are also generally subject to state regulation and are routinely granted for other drilling operations in most states.

Key objectives of the borehole seals effort are to use *ex situ* testing to: 1) demonstrate performance of bentonite seals; 2) measure brine/cement impact on bentonite permeability; 3) build the technical basis for rock-welding of seals, and 4) identify (any) effects of waste package corrosion on seals. Avoiding bentonite shrinkage is one key to assuring low seal permeabilities. Another is demonstrating that cement will not undergo large-scale volume changes over several thousand years. Bentonite volume is reduced by high ionic strength and/or the introduction of divalent cations, such as Ca^{+2}, Mg^{+2}, and Fe^{+2} (produced during the anoxic corrosion of steel casing).

Research on alternative seals has been directed at the main seals emplaced above the waste disposal zone and at the sealing and support matrix that surrounds the waste canisters. Rock welding in the main seals zone by partial melting and recrystallization of crushed rock within the borehole and in the surrounding host rock would produce a robust seal of the borehole and the excavation damage zone. A rock welding seal would be highly durable because, unlike bentonite and cement, it would be in chemical and mineralogical equilibrium with the physical and chemical conditions at depth. Modeling work indicates that a rock melt volume of sufficient size to form such a seal could be generated with an electrical resistance heater, with a modest power requirement (about 11 kW) and in a reasonable time. The shape and size of the rock weld can be controlled by varying the length and diameter of the heater. Materials such as bentonite, cement grout, and low melting temperature metal alloys have been investigated as sealing and support matrices; however, challenges remain concerning the operational emplacement and suitability of these materials. Research is continuing to address these challenges and to evaluate candidate formulations with regard to rheology, setting or thickening time, hardening and mechanical properties, geochemical reactions, and durability.

The technical bases for the safety framework have been updated or reevaluated with regard to thermally driven groundwater flow, nuclear criticality and operational safety. Large-scale thermal hydrologic modeling has been updated to incorporate more realistic geological and hydrogeological conditions, and to provide input to an updated performance assessment (PA) model of the deep borehole disposal system. Thermal-hydrologic simulations indicate vertical upward groundwater flux in the borehole and surrounding disturbed rock zone of the waste disposal zone for an extended period of time. Significant, but lower vertical flux also occurs above the waste disposal zone through potentially degraded seals and/or the surrounding disturbed rock zone. Criticality safety is not a design, operation or permitting issue for conducting the demonstration project, because the use of actual nuclear fuel is not anticipated.

A systematic approach to the prioritization of RD&D activities uses information from several previous PA analyses and from the updated PA model documented in this report. The basis of this prioritization is primarily the post-closure safety of the deep borehole disposal system. A synthesis of existing PA analyses has identified the more important processes with regard to disposal system safety and the characterization activities necessary to help reduce uncertainties associated with these processes.

The updated deep borehole disposal PA model incorporates the simulated vertical flow rates from the updated thermal-hydrologic modeling and includes a significant conceptual improvement relative to previous PA modeling through the implementation of lateral radionuclide diffusion between the borehole and the surrounding rock. The updated PA model for a single borehole is implemented in the GoldSim® software code. Base case simulations with the updated PA model demonstrate lateral diffusion of radionuclides from the borehole into the surrounding bedrock and indicate no releases of radionuclides to the biosphere within 1,000,000 years of deep borehole disposal. Sensitivity analyses for a case in which the vertical groundwater flow rates are increased by a factor of 10 and the waste form degradation rate is increased by a factor of 100 show a negligibly small peak mean annual dose at 1,000,000 years, primarily from releases of I-129.

The primary objective of the safety framework study is to confirm the safety of disposing SNF and/or other forms of radioactive waste in a deep borehole disposal system. The initial safety framework documented as a stand-alone report in Appendix A focuses on a generic safety framework for the deep borehole disposal concept. This safety framework is developed using information collected and analyses conducted prior to and during the course of the deep borehole demonstration.

The Deep Borehole Disposal Consortium was established through the course of two meetings in Albuquerque, New Mexico in 2011 and 2013 and consists of industrial and academic partners that were assembled to enhance efforts to complete a deep borehole demonstration. A Memorandum of Understanding (MOU) was signed to enable collaboration between the parties to "promote the construction and operation of a deep borehole demonstration to evaluate the feasibility of long-term disposal of nuclear waste." Members having signed the MOU include Areva, CH2M-Hill, DOSECC Exploration Services, Massachusetts Institute of Technology, Olympic Research, Sandia National Laboratories, University of Sheffield, and URS.

Important conclusions from this milestone report include the following:

- Evaluation of technical and logistical site selection guidelines indicates that there are large areas within the conterminous U.S. that are favorable for the location of a deep borehole disposal demonstration project, in particular, and long-term deep borehole disposal, in general.
- Specific requirements for experimental evaluations of bentonite and cement as seals materials have been identified.
- Numerical modeling of rock melting and the formation of rock welding seals indicates that this is a potentially viable alternative borehole sealing method.
- Higher priority science and engineering R&D activities for a deep borehole demonstration project have been identified, based on importance to post-closure safety.
- Updated thermal-hydrologic modeling of a multiple-borehole disposal system and updated PA modeling that includes lateral diffusion from the borehole indicate no radionuclide releases to the biosphere within 1,000,000 years for the undisturbed base-case scenario.
- A Deep Borehole Disposal Consortium consisting of Sandia National Laboratories, industrial, and academic partners was established to "promote the construction and operation of a deep borehole demonstration to evaluate the feasibility of long-term disposal of nuclear waste."
- A generic safety case study has been documented and indicates that a defensible safety case can be developed for deep borehole disposal of high-level nuclear waste, assuming that the demonstration project confirms the technical bases underlying the deep borehole disposal concept.

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FIGURES

TABLES

ACRONYMS

BH	Borehole
BOPe	Blow Out Prevention equipment
CAA	Clean Air Act
CFR	Code of Federal Regulations
CSNF	Commercial Spent Nuclear Fuel
CWA	Clean Water Act
DBD	Deep Borehole Disposal
DOE	U.S. Department of Energy
DRZ	Disturbed Rock Zone
DZ	Disposal Zone
EBS	Engineered Barrier System
EGS	Enhanced Geothermal System
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
FEPs	Features, Events, and Processes
GIS	Geographical Information System
HDSM	High-Density Support Matrix
HLW	High-Level Waste
IAEA	International Atomic Energy Agency
ID	Inside Diameter
LEU	Low Enriched Uranium
LGM	Last Glacial Maximum
MIC	Microbially Influenced Corrosion
MIT	Massachusetts Institute of Technology
MOU	Memorandum of Understanding
MWD	Measurement While Drilling
NCA	Noise Control Act
NEA	Nuclear Energy Agency
NEPA	National Environmental Policy Act
NNSA	National Nuclear Security Administration
NPDES	National Pollutant Discharge Elimination System
NRC	U.S. Nuclear Regulatory Commission
NS	Natural System
NWPA	Nuclear Waste Policy Act
NWTRB	U.S. Nuclear Waste Technical Review Board
OD	Outside Diameter
PA	Performance Assessment
PWR	Pressurized Water Reactor
QA	Quality Assurance
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RMEI	Reasonably Maximally Exposed Individual

RW	Reprocessed Waste
SCC	Stress Corrosion Cracking
SMU	Southern Methodist University
SNF	Spent Nuclear Fuel
SSCs	Structures, Systems, and Components
SSM	Sealing and Support Matrix
SZ	Saturated Zone
TH	Thermal-Hydrologic
TRU	Transuranic
UFD	Used Fuel Disposition
UFDC	Used Fuel Disposition Campaign
UNF	Used Nuclear Fuel
USGS	U.S. Geological Survey
UZ	Unsaturated Zone
WIPP	Waste Isolation Pilot Plant

1. INTRODUCTION

1.1 Background

Deep borehole disposal (DBD) of high-level radioactive waste has been given consideration for geological isolation for many years, including original evaluations of nuclear waste disposal options by the U.S. 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 high-level waste (HLW) and spent nuclear fuel (SNF) have primarily focused on mined repositories. Nonetheless, evaluations of deep borehole disposal have periodically continued in several countries (O'Brien et al. 1979; Woodward and Clyde Consultants 1983; Juhlin and Sandstedt 1989; Heiken et al. 1996; Nirex 2004; Anderson 2004; Gibb et al. 2008a). An updated conceptual evaluation of deep borehole disposal of SNF and a preliminary performance assessment have also been completed (Brady et al. 2009). A reference design and operations were developed for deep borehole disposal of SNF using available drilling technology by Arnold et al. (2011a). Site characterization methods were analyzed using basic performance assessment methodology and were described in Vaughn et al. (2012a). These studies have identified no fundamental flaws regarding safety or implementation of the deep borehole disposal concept.

The reference deep borehole disposal concept is straightforward and consists of drilling a borehole on the order of 5,000 m deep, emplacing waste canisters in the lower part of the borehole, and sealing the upper part of the borehole with bentonite and concrete seals. A reference design of the disposal system (Arnold et al. 2011a) includes emplacement of 400 waste canisters in the lower 2,000 m of the borehole, seals and plugs in the uncased borehole for 1,500 m above the disposal zone, and standard borehole plugging in the upper 1,500 m of the borehole. Safety of the disposal concept relies primarily on the great depth of burial, the isolation provided by the deep natural geological environment, 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 systems, such as waste canisters and/or buffer material, to a greater degree.

Factors suggesting that the deep borehole disposal concept is viable and safe have been summarized previously in Brady et al. (2009) and Arnold et al. (2011a). Crystalline basement rocks are relatively common in stable continental regions, either at the surface or within 2,000 m depth. Existing drilling technology should permit the reliable construction of sufficiently large diameter boreholes to a depth of 5,000 m, although this remains to be demonstrated. Total costs for a deep borehole disposal system for SNF, including drilling, casing, borehole completion, waste canister fabrication and loading, emplacement, and borehole sealing have been estimated at about $US 40 million per borehole (Arnold et al., 2011a). For the reference borehole disposal design this cost is equivalent to about $US 158/kg heavy metal. The projected waste inventory from the current fleet of nuclear reactors in the U.S., operating through 2055, could be disposed in about 580 boreholes, based on the reference design, which includes fuel rod consolidation. A non-technical advantage that the deep borehole concept offers over a mined repository concept is that of facilitating incremental construction and loading at multiple, perhaps regional, locations. Low permeability and high salinity in the deep continental crystalline basement at many locations suggest extremely limited interaction with shallow fresh groundwater resources (Park et al. 2009), which is the most likely pathway for human exposure to radionuclides released from a deep borehole disposal system. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the sorption of many radionuclides in the waste, leading to reduced mobility in groundwater. Preliminary disposal system modeling analyses indicate that radiological doses from deep borehole disposal would be significantly less than representative postclosure exposure regulations (Brady et al. 2009, Lee et al. 2012, Swift et al. 2012).

The U.S. Department of Energy (DOE) has been investigating deep borehole disposal as one of the alternative for the disposal of SNF and other radioactive waste forms, along with research and development (R&D) for mined repositories in salt, granite, and clay, as part of the used fuel disposition (UFD) campaign. The DOE developed a research, development, and demonstration (RD&D) roadmap for deep borehole disposal in FY12 (DOE 2012a) that emphasized a full-scale demonstration project around which R&D activities would be organized.

1.2 Objectives and Scope

The overarching goal of deep borehole disposal research for FY13 is to advance the deep borehole disposal technical basis needed to site and implement a full-scale demonstration project. Given that identifying a demonstration project site is one of the first steps in a demonstration project, a specific objective of the research is to establish technical and logistical guidelines to be used in the evaluation of potential demonstration sites. An additional objective is planning the experimental research program for investigation of alternative sealing methods, including the time-dependent properties of candidate seal materials under a range of environmental conditions. This objective is motivated by the recognition that the borehole seals constitute the primary component of the engineered barrier system (EBS) in the deep borehole disposal concept. A final objective is to further establish the preliminary safety framework for this disposal concept and for a deep borehole disposal demonstration project.

The scope of the deep borehole disposal work package consists of three tasks: (1) an evaluation of site selection guidelines for a deep borehole demonstration project, (2) an assessment of deep borehole seals and waste emplacement, and (3) development of a safety framework for deep borehole disposal.

Task 1 establishes site selection guidelines by considering technical guidelines that are potentially related to the drilling and completion of a deep borehole and to post-closure safety of the deep borehole disposal system. A deep borehole demonstration project could be successfully conducted at a wide variety of locations in the U.S. and the site selection guidelines therefore focus on increasing the probability of success by screening sites for characteristics that are potentially unsuitable or inappropriate. Evaluation of a number of technical factors (see Section 2.3) is conducted at a regional scale using existing data. This evaluation activity leverages and is integrated with the UFD campaign work package establishing a Geographical Information System (GIS) database on regional geology for alternative mined repository disposal concepts in salt, granite, and clay (DOE 2012b). Qualitative evaluations of guidelines related to drilling logistical and permitting factors are also being conducted.

Task 2 reviews and develops candidate borehole seal designs, based on bentonite and cement borehole plugs, as well as alternative seals designs, such as rock welding and canister support matrices. The scope includes a literature survey and test planning for testing long-term integrity of candidate seal materials, such as cement and bentonite, under representative down-hole temperature, pressure, and geochemical conditions. Work is also being conducted on numerical simulation of heat transport and operational evaluations for rock melting for the rock welding seals concept.

Task 3 consists of several related activities, all directed toward updating and improving the safety framework for the deep borehole disposal concept. Existing information and analyses have been compiled to identify science and engineering R&D needs important to safety, using a systems engineering approach to prioritization. This R&D prioritization is based in part on an updated performance assessment (PA) model of the deep borehole disposal system that utilizes results from a thermal-hydrologic simulation of multiple disposal boreholes. A preliminary safety case report for deep borehole disposal has been written to document the overall safety framework for the deep borehole disposal concept (see Appendix A).

This report is organized around the three primary tasks described above. Section 2 discusses geological, hydrological, and geophysical guidelines for selecting a site for a deep borehole demonstration project and disposal system, and presents relevant data at a regional scale for the conterminous U.S. Section 2 also discusses logistical factors bearing on site selection for the demonstration project, including associated permitting considerations. These logistical factors are related to the local availability of drilling and support services needed for a demonstration or long-term disposal project. Borehole seals testing strategy and alternative seals research are discussed in Section 3 of the report. Section 4 documents several topics related to the safety framework for deep borehole disposal, including updated thermal-hydrologic modeling, discussions of nuclear criticality and operational safety, a synthesis of PA analyses regarding the importance of physical-chemical processes and related R&D characterization activities, an updated PA model, and a generic safety case study of deep borehole disposal. Section 5 discusses planning for a deep borehole demonstration project and the role of the Deep Borehole Disposal Consortium in this effort. A summary and conclusions are presented in Section 6. Appendix A contains a stand-alone preliminary safety case report on the deep borehole disposal concept.

2. DEMONSTRATION SITE SELECTION GUIDELINES

2.1 Demonstration Site Selection Strategy

Selection of a site for a deep borehole disposal demonstration project should be informed by numerous factors that fall into several categories, including technical factors, logistical/practical factors, and sociopolitical factors. Technical factors include geological and hydrogeological characteristics that are related to the suitability of the site for waste disposal and the long-term safety of the deep borehole disposal system. Technical factors also include geological characteristics of the site that could impact the drilling, borehole construction, and waste emplacement testing activities at the site. Logistical and practical factors include the local or regional availability of drilling equipment, engineering services, materials, and research support for the DBD demonstration project. Social and political factors include the support or opposition of local and state entities to the demonstration project.

Numerous technical factors are potentially important to the post-closure safety of the deep borehole disposal system. Although the demonstration project does not include waste disposal or testing with radioactive materials, it is highly desirable that the deep geological and hydrogeological environment at the demonstration site be consistent with physical and chemical characteristics important to post-closure safety of the disposal system. In particular, disposal zone depths should be in crystalline basement rocks, deep fluids should be highly saline, geochemical conditions should be reducing, deep fluids should exhibit evidence of long-term isolation from shallow groundwater resources, larges-scale structural features should be absent, and deep economically attractive resources should be absent. Technical factors for post-closure safety are identified at a high level by preliminary analysis of features, events, and processes (FEPs) in previous studies (Brady et al., 2009 and DOE, 2012a). A successful demonstration project should demonstrate the ability to characterize the geological system with regard to important components of the safety case for deep borehole disposal.

Many technical factors related to drilling and borehole completion exist, but are more difficult to assess using site-selection guidelines prior to drilling. Borehole stability and borehole deviation control are important to successfully drilling and constructing the borehole. Drilling operations always involve elements of uncertainty; however, some site-selection guidelines may be useful, including information on the anisotropy in horizontal stress and the potential for borehole breakouts, and heterogeneity and foliation of crystalline basement rocks, as they relate to borehole deviation. Previous drilling experience near potential demonstration sites may be useful, although drilling experience to depths of 5,000 m in crystalline rock is limited.

Logistical factors for a deep borehole disposal demonstration project are linked to drilling activity in the petroleum industry, geothermal industry, and, to a lesser extent, deep scientific drilling activity. The availability of drilling equipment, personnel, and support services is greater in regions with significant drilling activity, although drilling services may be acquired at more distant locations at higher costs for mobilization and demobilization. Assuming that drilling and borehole construction is provided by a private drilling contractor, the availability of drilling services may also be a factor of competing drilling projects in other industries.

Analysis of social and political factors related to site selection for a deep borehole disposal demonstration project is beyond the scope of this report. However, early engagement with local and regional stakeholders at any potential location, particularly in the scientific and academic communities, would likely improve the chances of siting a demonstration project and hasten its initiation. Engagement with scientific communities, such as state geological surveys and state university faculty also provides local and regional geoscientific knowledge that is important to evaluating the suitability of potential deep borehole demonstration sites.

Overall, the goal of the site-selection guidelines for the demonstration project is to maximize the probability of successfully completing a borehole in geological, hydrogeological, and geochemical conditions favorable for waste isolation, within budgetary and schedule constraints. These guidelines are based in part on a set of important site characteristics, described in Sections 2.3 and 2.4, that influence the performance of the disposal system or relate to logistical considerations.

2.2 Relationship of Site Selection to the Disposal Safety Framework

The focus of this section is to illustrate the linkages between site selection, concept demonstration, and the development of a deep borehole disposal safety framework. The term *safety framework* rather than *safety case* is used herein because the goal of a demonstration is not to build a *safety case*, but rather to collect and develop the generic information needed to confirm that deep borehole disposal technology can be implemented safely if properly sited and implemented.

2.2.1 Components of Safety Case and Relationship to Site Selection

A *safety case* is an integrated collection of evidence, analyses, and other qualitative and quantitative arguments used to demonstrate the safety of the repository and is a widely accepted approach for documenting the basis for the understanding of the disposal system, which describes key justifications for its safety, and acknowledges unresolved uncertainties and of their safety significance (OECD 2004 and IAEA 2006). A safety framework is similar to a safety case, but is developed for a generic disposal system. A major goal of deep borehole demonstration is to develop and verify a safety framework with information obtained from a deep borehole demonstration using non-nuclear surrogate waste packages.

The safety framework is a living document that evolves throughout the course of the demonstration from site selection and characterization (including facility design), construction, operation, and closure. As the demonstration program evolves from siting to closure, the level of completeness and rigor increases and the associated safety framework becomes more detailed with the addition of more data from site characterization, system design, and safety assessment activities.

The linkages between site selection, demonstration, and the safety framework can best be understood by examining the major elements of the safety framework. In this study, the major elements of the safety framework are patterned after the NEA post-closure safety case (NEA 2004) and also include aspects of pre-closure safety as follows (see Appendix A of this report for additional detail):

Statement of Purpose

This element describes the current stage of the demonstration program and the current completeness of the safety framework. At the site selection step much of the information is qualitative and has a high level of uncertainty. However, there is a significant amount of data that can be used to identify general siting guidelines. This information can then be used to inform preliminary screening of FEPs and to perform preliminary safety assessments for evaluate risks from potential sites that are consistent with the identified guidelines within the current level of uncertainty.

Safety Framework Strategy

This is the high-level approach adopted for demonstrating safety, and includes (a) an overall management strategy for the demonstration, (b) a siting and design strategy, and (c) a demonstration assessment strategy.

Section 2.1 describes the general siting strategy including socio-political aspects, while Section 2.3 describes the technical basis for siting and section 2.4 describes other siting consideration such as availability of services and other infrastructure support.

Site Characterization and Deep Borehole Disposal System Design

This element contains key portions of the demonstration *assessment basis* , and includes a description of (a) the primary characteristics and features of the demonstration site, (b) the location of the deep borehole, (c) a description of the deep borehole engineered barriers, and (d) a discussion of how the deep borehole engineered and natural barriers will function synergistically.

The information collected to develop and evaluate the technical siting guidelines discussed in Section 2.3 include geological and hydrogeological characteristics related to the suitability of the site for successful demonstration. This information also serves as initial site characterization data, which supports the technical baseline, the screening of FEPs, and performance assessment modelling. These factors also influence the disposal system design and operations associated with drilling, borehole construction, and waste emplacement testing, and seal design and emplacement.

Pre-closure and Post-closure Safety Evaluation

This includes a quantitative safety assessment of potential radiological consequences associated with a range of possible evolutions of the system over time, i.e., for a range of scenarios, both before and after closure of a generic deep borehole disposal system. As note previously, the deep borehole demonstration will not involve radioactive waste. For the purposes of demonstrating safety, a hypothetical waste form and inventory will be selected that is representative of the waste form for which the demonstration is being conducted.

Performance assessment is a quantitative evaluation of post-closure safety through a systematic analysis of disposal system performance and a comparison of this performance with quantitative design requirements and performance measures, along with an estimation of how quantifiable uncertainties might affect disposal system performance. Such an assessment requires conceptual and computational models that include the relevant FEPs that could be important to safety. A key objective of the post-closure performance assessment is to indicate which FEPs are most important to safety and are therefore candidates for future R&D if their current state of knowledge includes a significant degree of uncertainty.

Demonstrating confidence in pre-closure safety is also an important element of the safety framework and includes transportation safety and operational safety. The pre-closure safety assessment identifies the potential natural and operational hazards for the pre-closure period; assesses potential initiating events and event sequences and their consequences; and identifies 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.

The information collected during the site selection process helps informs FEPs screening and the conceptual design of the post-closure safety evaluation (performance assessment modeling).

Statement of Confidence and Synthesis of Evidence

A statement of confidence is based on a synthesis of safety arguments and analyses and includes a discussion of completeness to ensure that no important issues have been overlooked in the safety framework. A statement of confidence recognizes the existence of any open issues and residual uncertainties, and perspectives about how they can be addressed in the next phase(s) of demonstration, if they are considered to be important to establishing safety. The strength of the safety confidence statement is dependent on the appropriate selection of the site and its robustness with respect to the technical guidelines developed in section 2.3.

2.2.2 Summary of Technical Site Selection Guidelines Supporting the Safety Framework

Section 2.3 identifies and describes in detail the technical site selections guidelines. In addition to supporting the site selection of a deep borehole demonstration, these guidelines also contribute to the safety framework by providing part of the technical basis for the post-closure safety assessment. Examples of how these guidelines are related to disposal system safety are identified below.

Depth to Crystalline Basement

The depth to crystalline basement could be anything less than 2,000 m. As described earlier, this guideline would be satisfied by either depths of less than 2,000 m to the basement or by locations with surface outcrops of crystalline rock. Areas with outcropping crystalline basement rocks would have the advantage of direct access to the rocks for detailed surface geological mapping and sampling. Major structural features in the basement rocks, such as faults and shear zones, could also be more directly observed. One potential disadvantage from a safety perspective is that major throughgoing vertical structural features could have uninterrupted continuity between the deep borehole disposal zone and the shallow subsurface, potentially providing higher-permeability pathways for radionuclide migration. Regions with the crystalline basement 2,000 m or shallower are generally covered by stratified sedimentary rocks on stable continental platforms or at the margins of sedimentary basins. An advantage of sedimentary rock cover is the low vertical effective permeability created by typical alternating layers of coarse-grained clastic rocks, carbonate rocks, and fine-grained sedimentary rocks, such as shales. Sedimentary rocks in the stable continental interior typically contain saline connate fluids at depths of greater than a few hundred meters, inhibiting vertical flow by density stratification and precluding utilization of deep fluids as a groundwater supply resource. Sedimentary rocks may also function as a "cap" on throughgoing vertical structural features in the underlying crystalline basement, disrupting potential pathways for radionclide migration to the shallow subsurface. A disadvantage of locations with sedimentary cover is that crystalline basement rocks cannot directly be mapped and there would be uncertainty about the lithology and structure of crystalline basement rocks that would be encountered in drilling.

Crystalline Basement Lithology

The deep borehole safety framework may be strongly enhanced for boreholes that penetrate extensive thicknesses of older crystalline rock and, in particular, if the seal and disposal zones (the lower 3 km of the borehole) are within this crystalline basement. However, this is dependent on the particular lithology of the crystalline basement rock. Increased confidence in the stability and robustness of the drill hole results from the advantageous mechanical properties characteristic of older homogenous granitic batholiths. These characteristics lead to more ease in drilling a vertical hole and increase the confidence that waste package strings can be emplaced without incident. Conversely, crystalline rocks of a layered or foliated metamorphic nature can result in deflection of drill bits leading to less directional control. Additionally, because stress conditions are more uniform and differential stress is less in homogenous crystalline rocks than in layered metamorphic rocks, boreholes constructed in homogenous crystalline rock would be expected to result in increased borehole stability and less wall breakout. This increases the confidence in the safety of proper canister emplacement as well as increased confidence in the robustness of borehole sealing and grouting at the interface of the seals and borehole walls.

With respect to long term post-closure safety, plutonic rocks, and large felsic igneous intrusive rocks in particular tend to be more homogeneous and contain fewer preferential pathways than metamorphic rocks or volcanic igneous units. Thus plutonic rocks would be expected to enhance the isolative capability of the natural system, although large features such as fault zones can also be present plutonic rock.

Basement Structural Complexity

Crystalline basement structural complexity, in the form of major faults, shear zones, and tectonic features could impact drilling operations, borehole construction, and post-closure safety characteristics of a deep borehole demonstration site. Although such features are generally poorly understood in the crystalline basement where covered by sedimentary rocks, geophysical data and inferences from Precambrian lithology and geochronology have been used to infer the locations of some of these subsurface complexities. Basement structural complexity is not a disqualifying characteristic of a potential site, but it does increase the probability of drilling difficulties and hydrogeological characteristics that potentially are not favorable to waste isolation.

Horizontal Stress

The degree of horizontal stress differential at depth in the waste emplacement zone can be an important consideration in demonstration site selection. If a large differential in horizontal stress exists at depth, this may be an indicator of potential difficulties in drilling and instability of a drilled borehole. Because the process of setting borehole casing consists of lowering casing strings into holes with tight clearance, it is important that the borehole be smooth and stable.

Collapse of borehole walls could compromise or make more difficult the process of setting casing as well as compromise the integrity of the disturbed rock zone (DRZ) around the borehole or the seal rock contact. The dominant release pathway from waste emplaced in a deep borehole is vertically up either through the DRZ or through the seal system and its contact with the surrounding rock. A smaller differential in horizontal stress at depth would result in reduced uncertainty, provide for a more isolative capability, and provide for smoother safer operations.

Tectonic Uplift

Tectonic uplift is an increase in elevation of the earth surface due to tectonic processes. Tectonic uplift is important to deep borehole disposal, not because it has a direct impact on performance, but because in areas of tectonic activity there is an increased risk of seismicity, volcanism, and active faulting and these process could impact deep borehole performance.

Geothermal Heat Flux

Geothermal heat flux and geothermal gradient are relevant guidelines for siting a deep borehole disposal demonstration project or disposal system in several ways, including 1) temperature conditions at depth as they affect drilling, emplacement operations, EBS materials, and waste forms, 2) potential for future human intrusion by drilling for geothermal resources, and 3) as indicators of ambient vertical groundwater flow in the regional flow system.

Elimination of sites with significant geothermal heat flux results in reduced likelihood of human intrusion. Lower vertical temperature gradients can help reduce vertical flow and instabilities that can develop resulting in increased isolation capacity and reduced vertical transport. Degradation processes and mineral transformation tend to occur at faster rates under higher temperature conditions, so lower temperatures could increase confidence in the isolative capacity of EBS components, although higher temperatures would facilitate the melting of a high-density support matrix, as described in Section 3.3.2.1. Finally, temperatures at depth can impact the strength of downhole equipment and waste canisters and operating ranges for instrumentation, so reduced temperature conditions can help reduce difficulties in drilling and waste emplacement operations, which can increase confidence in the safety of pre-closure operations.

Topographic Relief and Hydraulic Gradient

Groundwater flow is dominantly driven by topographic relief in most flow systems. The rate of topographically driven groundwater flow, both horizontally and vertically, is determined by recharge rates, the pattern of topographic relief, the permeability structure of the subsurface, and depth. Recharge rates vary both geographically and topographically and generally decrease with increasing depth so that the safety of deep borehole disposal would be less sensitive to regional groundwater flow conditions than a mined repository because of the deeper disposal depth.

Because sites with low topographic relief are likely to have extremely low groundwater flow rates at deep borehole disposal depths, such sites would be expected to provide increased confidence in isolation capability because of a decrease in the likelihood of vertical hydraulic gradients, a decrease in communication with upper ground water, and an increase in the likelihood of very old, highly saline fluids at depth. Higher salinity at depth also contributes to an increase in fluid density gradient, which further acts to reduce upper vertical flow and migration of dissolved radionuclides.

Quaternary Faults and Volcanism

The assessment of Quaternary faults is important to safety confidence. The presence of these faults is strong evidence for tectonic activity in the geologically recent past, which can be extrapolated to potential future activity. A disposal site with limited or no active faults implies low likelihood of future seismic activity and structural disruption. This will determine whether the consequences of seismic activity on radiological release need to be accounted for in the performance assessment. If this can be eliminated on the basis of low probability then uncertainty is reduced, the performance assessment model is simpler, and confidence in safety increased.

A deep borehole placed in a location with minimal faulting or evidence of volcanic activity implies robust isolative capacity because of the low possibility of high permeability pathways connecting the waste emplacement zone with the surface or potential for direct release of waste by a volcanic eruption.

Mineral Resources Potential

Risk from inadvertent human intrusion, related to direct intrusion into the waste disposal zone and disruption of seals or other features, is a large component of the total risk and often the dominant source of risk for geologic repositories, e.g. (DOE 2008 and DOE 2009). While risk from human intrusion is expected to be lower for deep boreholes because of (a) increased depth of waste emplacement relative to a mined repository, (b) small cross-sectional area of the disposal footprint, and (c) high-strength crystalline rock that hosts the borehole, it is prudent to avoid locations that have known natural resource potential. Sites with lower potential for natural resources will result in a lower probability of future drilling activity for these resources and therefore lower risk from this scenario. This increases the confidence in the long-term safety of the deep borehole disposal option compared to those sites that have potential for economically exploitable resources at depth.

2.3 Technical Selection Guidelines

2.3.1 Depth to Crystalline Basement

The reference deep borehole disposal concept uses crystalline basement rock as the preferred host rock because of its long geological history, general association with tectonic stability within the continental crust, and relative homogeneity, particularly in the case of granite batholiths. The depth to the crystalline basement is a significant consideration in selecting a site for a deep borehole disposal demonstration site.

For a borehole disposal zone occupying the bottom 2,000 m of a borehole and allowing for an overlying 1,000 m length seal zone within crystalline rocks, the maximum depth to the crystalline basement would be 2,000 m. The depth to crystalline basement could be anything less than 2,000 m on this basis, including a site with crystalline basement rocks that outcrop at the surface. As with many other site selection guidelines in this section, definitive or quantitative guidelines have not yet been established, but are instead based on qualitative aspects of the deep borehole disposal system. For example, it has not been shown that 1,000 m of borehole length in the crystalline basement is necessary for the borehole seal zone to provide adequate long-term safety for the disposal system. Nonetheless, the 2,000 m maximum depth to crystalline basement provides a useful general guideline for delineating areas that would be potentially favorable for a deep borehole disposal demonstration project.

A regional-scale database for the depth to crystalline basement for most of the continental U.S. has been assembled by the UFD campaign in the form of a GIS data set (Perry, 2013). Figure 2-1 shows a contour plot of depth to crystalline basement and outcrops of crystalline rocks in red. Contour filling with brown to tan to yellow colors indicate depths of less than 2,000 m to the crystalline basement. Light green to blue to purple colors indicate increasing depths to crystalline basement. Major sedimentary basins, such as the Michigan basin in Michigan, the Illinois basin in southern Illinois and Indiana, the Williston basin in North Dakota and Montana, and the Gulf of Mexico basin in southern Texas, Louisiana, and Mississippi stand out as large areas of cool colors and greater depths to crystalline basement in Figure 2-1.

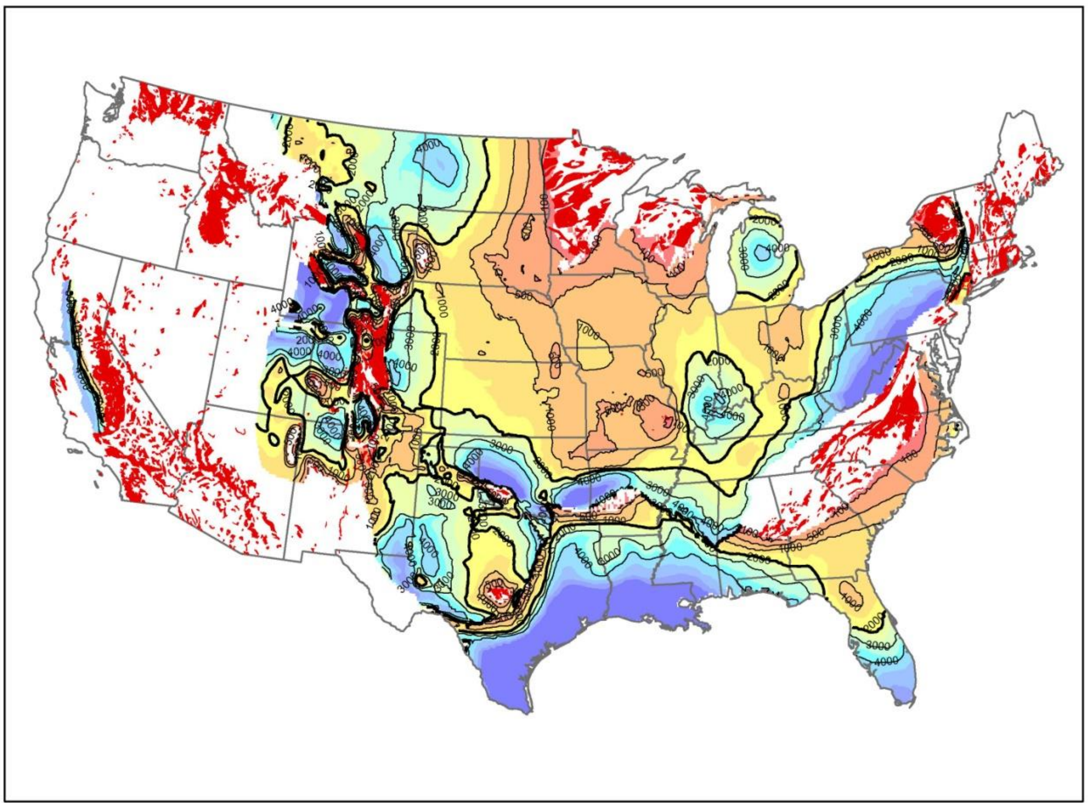


Figure 2-1. Depth to crystalline basement outcrops in the continental U.S. Depth of 2,000 m shown with the bold contour line and crystalline basement outcrops shown in red.

It is important to note several limitations to the dataset and interpretation of depth to crystalline basement shown in Figure 2-1. White areas indicate lack of data and/or areas that have greater geological complexity that make interpretation of the depth to crystalline basement difficult.

Areas immediately adjacent to outcrops of crystalline basement generally have a shallow depth to crystalline rocks, except where major faults have displaced the basement to greater depths near the outcrops. The white areas in northern Minnesota, Wisconsin, Michigan, and the New England states correspond to varying thicknesses of glacial deposits and have relatively shallow depths to crystalline basement. Much of the western U.S., with the exception of the central valley of California, is plotted in white because of lack of data and relatively greater structural complexity. Interpretation of the depth to crystalline basement in the western U.S. would require more intensive, local-scale data analysis or acquisition. White areas in Figure 2-1 should not be interpreted as areas that are necessarily unsuitable for deep borehole disposal or for a deep borehole demonstration project.

Overall, the analysis of depth to crystalline basement rocks indicates large areas of the continental U.S. with depths of less than 2,000 m. Figure 2-2 shows the same interpretation of depth to crystalline basement with the areas of less than 2,000 m depth shown with brown shading for emphasis. Very large areas of the central and northern Midwest meet this guideline. Another large area consists of the Atlantic coastal plain to the east and south of the Appalachian Mountains. In addition, there are many other smaller areas in Texas and the western states with depths of less than 2,000 m to the crystalline basement. As described earlier, much of northern Minnesota, Wisconsin, and Michigan, and the New England states have outcrops of crystalline rock or have relatively thin covers of glacial deposits. Also, as noted before, there are many smaller areas with depths of less than 2,000 m to the crystalline basement that are scattered across the more structurally complex western U.S.

As described earlier, this guideline for depth to crystalline basement rocks would be satisfied by depths of less than 2,000 m to the basement or for locations with surface outcrops of crystalline rock. Areas with outcropping crystalline basement rocks would have the advantage of direct access to the rocks for detailed surface geological mapping and sampling; although the characteristics of the crystalline rocks may be significantly different at the disposal depths. Major structural features in the basement rocks, such as faults and shear zones, could also be more directly observed. One potential disadvantage from a safety perspective is that major throughgoing vertical structural features could have uninterrupted continuity between the deep borehole disposal zone and the shallow subsurface, potentially providing higher-permeability pathways for radionuclide migration. Areas with depths to the crystalline basement of up to 2,000 m are generally covered by stratified sedimentary rocks on stable continental platforms or on the margins of sedimentary basins. An advantage of sedimentary rock cover is the low vertical effective permeability created by typical alternating layers of coarse-grained clastic rocks, carbonate rocks, and fine-grained sedimentary rocks, such as shales. Sedimentary rocks in the stable continental interior typically contain saline connate fluids at depths of greater than a few hundred meters, inhibiting vertical flow by density stratification and precluding utilization of deep fluids as a groundwater supply resource. Sedimentary rocks may also function as a “cap” on throughgoing vertical structural features in the underlying crystalline basement, disrupting potential pathways for radionclide migration to the shallow subsurface. A disadvantage of locations with sedimentary cover is that crystalline basement rocks cannot directly be mapped and there would be uncertainty about the lithology and structure of crystalline basement rocks that would be encountered in drilling.

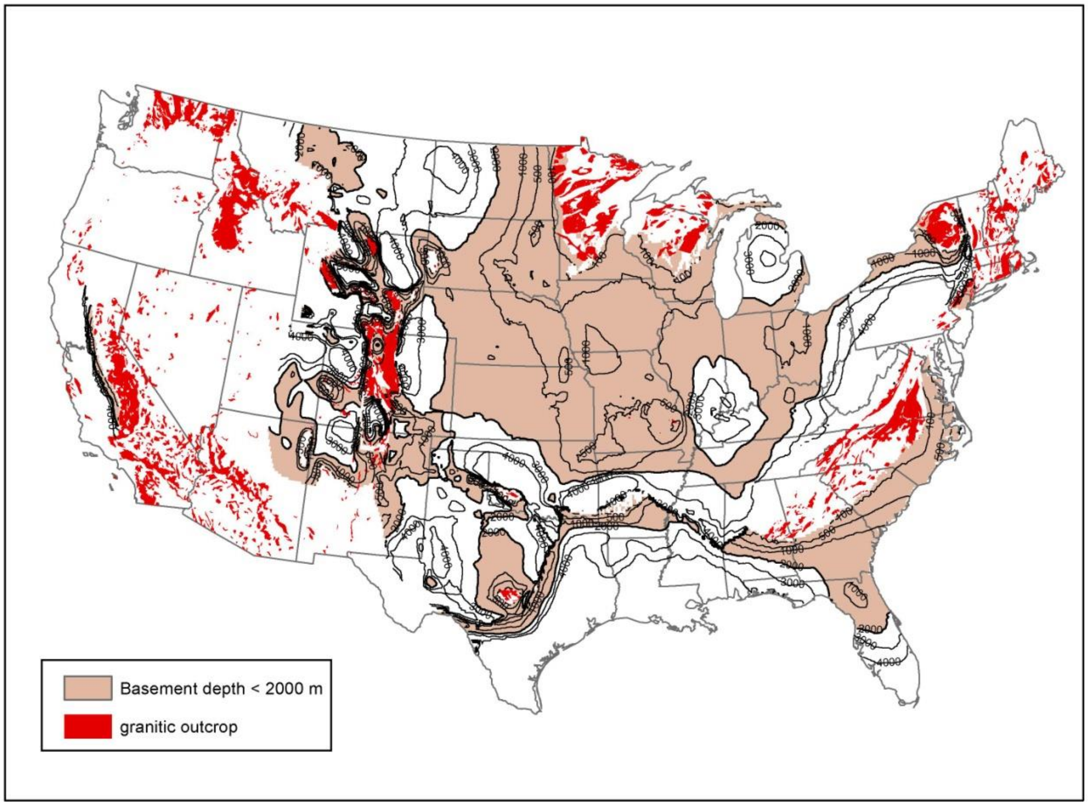


Figure 2-2. Depth to crystalline basement outcrops in the continental U.S. Depth of 2,000 m or less shown with brown shading and crystalline basement outcrops shown in red.

2.3.2 Crystalline Basement Lithology

The preferred host rock for deep borehole disposal is crystalline basement rock, which is a generic term that includes a diversity of rocks of igneous and metamorphic origin. Crystalline basement generally refers to the older, often Precambrian-age, rocks that underlie the sedimentary cover in stable continental interior regions and sedimentary basins. The term crystalline basement may also apply to geologically younger igneous and metamorphic rocks in more recent tectonically active terranes, such as the Mesozoic-age plutonic rocks exposed in the Sierra Nevada and similar rocks underlying the Central Valley in California.

The lithology of the crystalline basement may be important to deep borehole disposal in terms of drilling and borehole completion, and with regard to post-closure safety of the disposal system. Plutonic rocks in general, and granitic batholiths, in particular, tend to be more lithologically, mineralogically, and mechanically homogeneous than volcanic or metamorphic rocks; although variations in fracturing and the presence of fracture zones can make them hydrogeologically heterogeneous. Geological interpretation of crystalline basement lithology in areas with sedimentary or surficial cover tends to be highly simplified due to limited availability of drilling data and the uncertainties associated with the interpretation of geophysical data. However, it should be expected that covered crystalline basement rocks exhibit the same lithologic and structural complexity that is observed in similar outcropping geologic terranes.

Drilling operations may be affected by crystalline basement lithology in several ways. Directional control of drilling is generally easier in homogeneous crystalline rock, such as plutonic rocks. The drill bit can be strongly deflected by layered or foliated metamorphic rocks in which the fabric of the crystalline rock is oriented at an angle to the desired drilling direction (i.e., steeply dipping layers or foliation in a vertical borehole). Inability to control the verticality of a deep borehole can lead to a large deviation in the location of the borehole at depth and to curvature in the borehole that can interfere with drilling and borehole completion operations. Various drilling technologies exist for deviation control, but may add significant cost to drilling the borehole under extreme conditions. Crystalline basement lithology may also impact drilling rate and bit life. Some rock types, such as quartzite, can be particularly problematic in this regard. Changes in drilling methods and bit type can compensate for some variations in crystalline basement lithology; however, avoiding sites with known occurrences of extremely hard rock, such as quartzite would be advisable. Stress conditions in more homogeneous crystalline rocks, such as granite, tend to be more uniform relative to layered or foliated metamorphic rocks in which stress is concentrated in the higher strength rocks. Thus high differential stress conditions and resulting borehole breakouts may be more prevalent in deep boreholes penetrating heterogeneous metamorphic rocks versus plutonic rocks in the crystalline basement. Drilling operations can also be adversely affected by lost circulation of drilling fluids in high-permeability zones and washouts of the host rock. Such drilling problems are more likely associated with structural features such as fracture zones, which can occur in any rock type.

The relationship between crystalline basement lithology and post-closure safety for deep borehole disposal of high-level radioactive waste has not been explicitly evaluated and is a complex topic related to variations in the hydrological, geochemical, mineralogical, and geomechanical characteristics of different crystalline rock types. However, some general statements can be made about this relationship. Plutonic rocks, and large felsic igneous intrusive rocks in particular, tend to be more homogeneous than metamorphic rocks or volcanic igneous units. The relative homogeneity of felsic plutonic rocks may contribute to the isolation of radioactive waste by presenting fewer heterogeneous features that could serve as preferential pathways for contaminant migration. However, it is important to note that throughgoing structural features, such as fault zones that might active as preferential pathways, can occur in plutonic rocks, as well as other crystalline rock lithologies. The analysis and assessment of a more homogeneous host rock for deep borehole disposal system safety would be more straightforward and less uncertain than for a highly heterogeneous crystalline basement lithology. The relationship between crystalline basement lithology and permeability is not well understood. However, data presented by Stober and Bucher (2007) from the crystalline basement of the Black Forest region in Germany indicate that average permeability to depths of 1,000 m in gneiss is lower than in granite. Permeability in both granitic and metamorphic rocks generally decreases with depth, as indicated by data from a number of sources (e.g., Manning and Ingebritsen 1999 and Stober and Bucher 2007).

Information on crystalline basement lithology is available from a number of sources. Detailed geological maps are available for most areas in the U.S. where crystalline basement rocks outcrop at the surface and these provide the most accurate information on lithology for the crystalline basement. Definitive data on covered crystalline basement lithology are available at point locations from borehole drill cuttings and core that have penetrated the basement. Because most deeper boreholes are drilled through the sedimentary cover for hydrocarbon exploration purposes, drilling is usually terminated soon after the crystalline basement is encountered and sampling is limited to the very upper portion of the crystalline basement.

Interpretation of borehole data on Precambrian lithology and age, combined with outcrop data, has been made at the continental scale by Reed (1993). This effort provides some information on crystalline basement lithology at the regional scale, but is primarily aimed at unraveling the tectonic and structural history of North America in the Precambrian, particularly over the broad regions in which basement rocks are obscured by sedimentary cover. Various provinces or terranes identified in the geologic interpretation of Reed (1993) can provide information on the lithologic types and structural nature of the subsurface crystalline basement, although this information lacks the spatial resolution provided by surface outcrops.

In very general terms, the Precambrian basement map of Reed (1993) shows older Archean-age crystalline rocks of the Superior and Wyoming Cratons across much of the north central part of the U.S., and consisting of structurally complex metasedimentary, metavolcanic, and plutonic rocks. Several provinces of Proterozoic-age rocks form the Precambrian basement to the south and southeast of the Superior Craton, representing accretionary growth of the North American continent in the later Precambrian. These provinces also consist of metamorphic and igneous rocks, but some tend to be dominated by felsic volcanic and plutonic rocks. Granitic batholiths in these Proterozoic-age provinces tend to be smaller in size than the large batholiths present in the Archean cratons, such as the Wolf River Batholith in Wisconsin (Reed 1993). Crystalline rocks of late Proterozoic and Cambrian age constitute the Appalachian Orogen in the eastern and southeastern U.S. and dominantly consist of low- to intermediate-grade metasedimentary and metavolcanic rocks, with minor occurrences of granitic and mafic plutonic rocks.

Some states maintain databases of boreholes intersecting the Precambrian basement and these data are brought together for geological interpretation at a more detailed resolution than the work of Reed (1993). Figure 2-3 shows an example plot of these data and interpretation of the Precambrian basement geology for the state of South Dakota, as taken from McCormick (2010). Major bounding faults in the crystalline basement are based on the interpretation of aeromagnetic data and samples of the basement from drilling. Most of the Precambrian basement consists of rocks of the Superior Craton, transitioning into early Proterozoic-age rocks in the southern part of the state. The most commonly encountered crystalline basement lithology from drilling is granite, with quartzite occurring over a relatively large area in the southeastern part of South Dakota. Another example of relatively detailed geological interpretation of the Precambrian basement in Iowa is shown in Figure 2-4, from Anderson (2006). This map of the crystalline basement shows a wide variety of lithology, generally progressing from older Precambrian rocks in the northwest part of Iowa toward younger terranes in eastern and southeastern Iowa, with middle Proterozoic-age clastic sedimentary and mafic volcanic rocks of the mid-continent rift complex (see Section 2.3.3) superimposed across the central part of the state.

Geophysical data may also provide information on the nature and extent of certain rock types on the crystalline basement, particularly when combined with lithologic data from previous drilling.

For example, Figure 2-5 shows the first horizontal derivative of gravity data for South Dakota from McCormick (2010). Two ovoid features in the image that occur in the east-central part of the state and are elongated in the east-northeast to west-southwest direction between the two major thrust faults shown in yellow have been interpreted as potential large granite batholiths. This interpretation is supported by the uniformity of lithologic data from drill holes in the area. Another example is the aeromagnetic data from Kansas shown in Figure 2-6 from Xia et al. (1995). Several magnetic highs shown by the red colors in eastern Kansas in Figure 2-6 are interpreted to be relatively small magnetite-bearing granite intrusions. This interpretation is confirmed by drilling data and is part of a trend of such plutonic rocks extending from southeastern Nebraska (Reed 1993) across eastern Kansas.

Overall, data on crystalline basement lithology are available over large areas on the conterminous U.S., with variations in the resolution of supporting data and the geological interpretation among states. In the absence of site-specific information on crystalline basement lithology (e.g., a previous borehole that has sampled the basement) there would be uncertainty in the rock type encountered at depth by a deep borehole disposal demonstration project, but existing geological interpretations of subsurface geology would significantly improve the probability of correctly predicting the lithology of the basement at many locations. As a general guideline for siting a deep borehole demonstration project, a felsic intrusion, such as granite, would be preferable to layered or highly foliated metamorphic rocks. Smaller granitic plutons may be preferable to larger plutons because of possibly lower fracture density in smaller granite intrusions relative to older, larger Archean-age granitic bodies. However, the geometry of typically smaller granitic plutons in the Precambrian Proterozoic provinces of the central U.S. is not well known, and it is possible that a deep demonstration borehole to a depth of 5 km could fully penetrate a diapiric intrusion and exit the granite into lower metamorphic or volcanic host rocks.

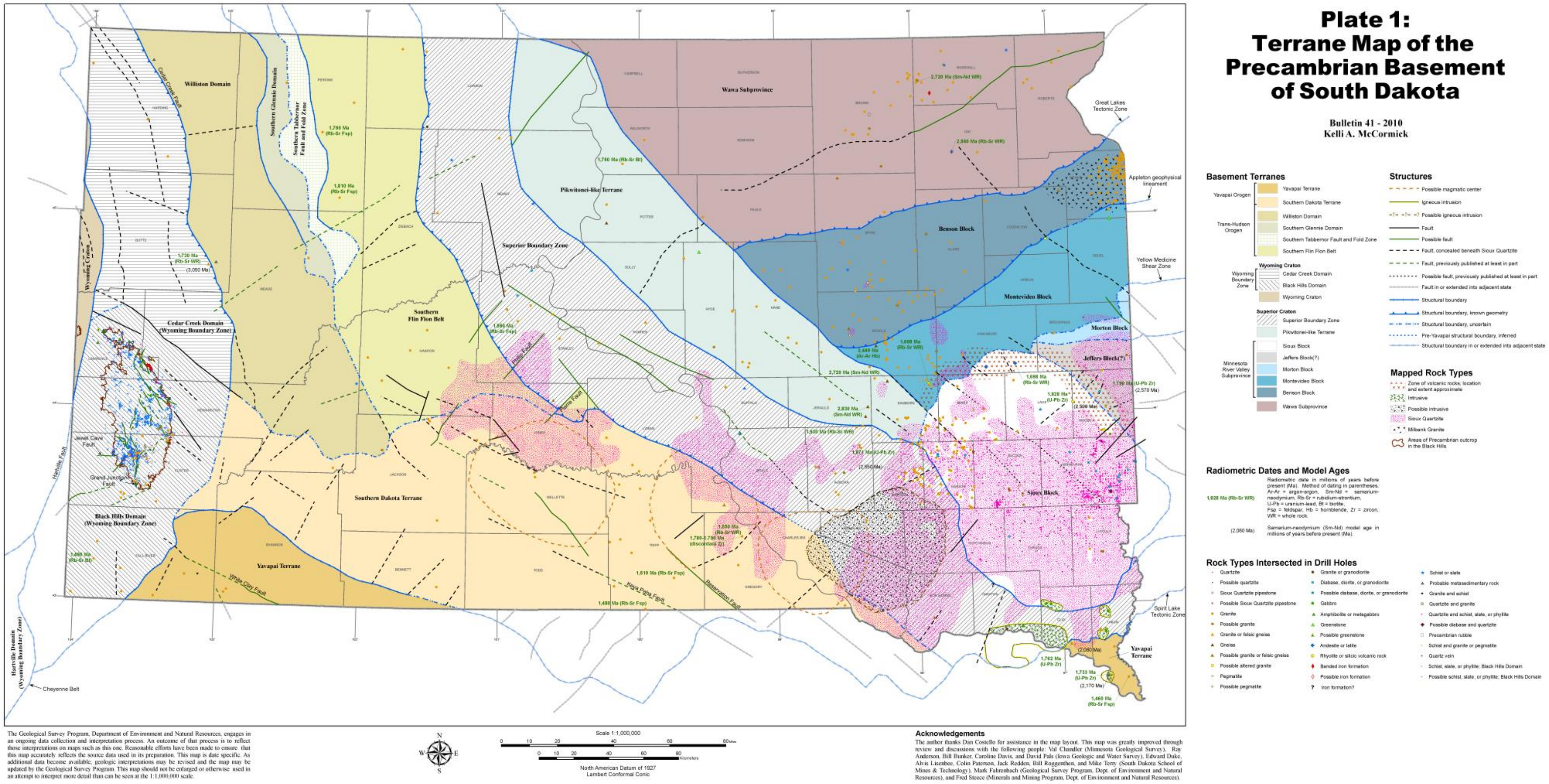


Figure 2-3. Terrane map of the Precambrian basement of South Dakota (from McCormick 2010)

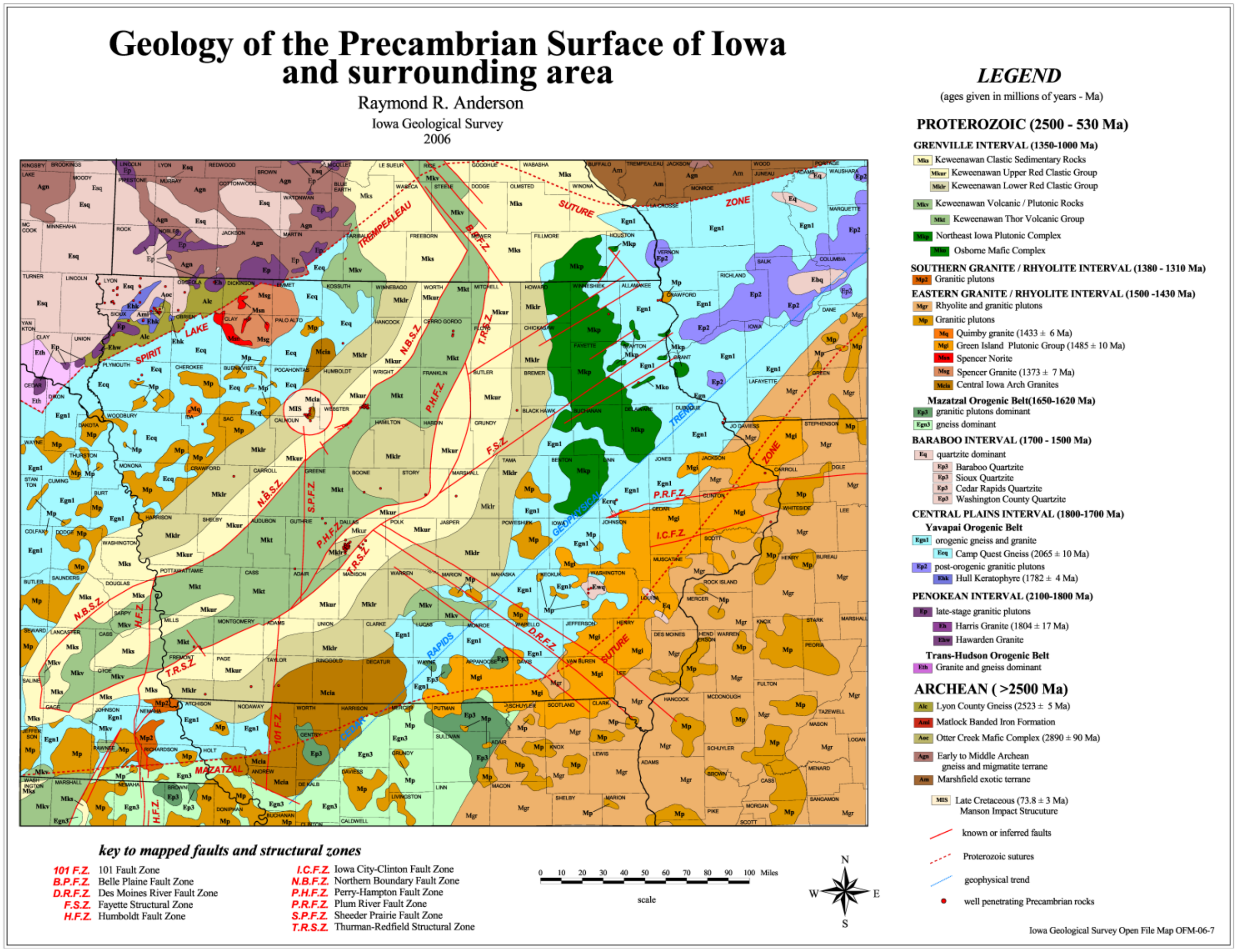
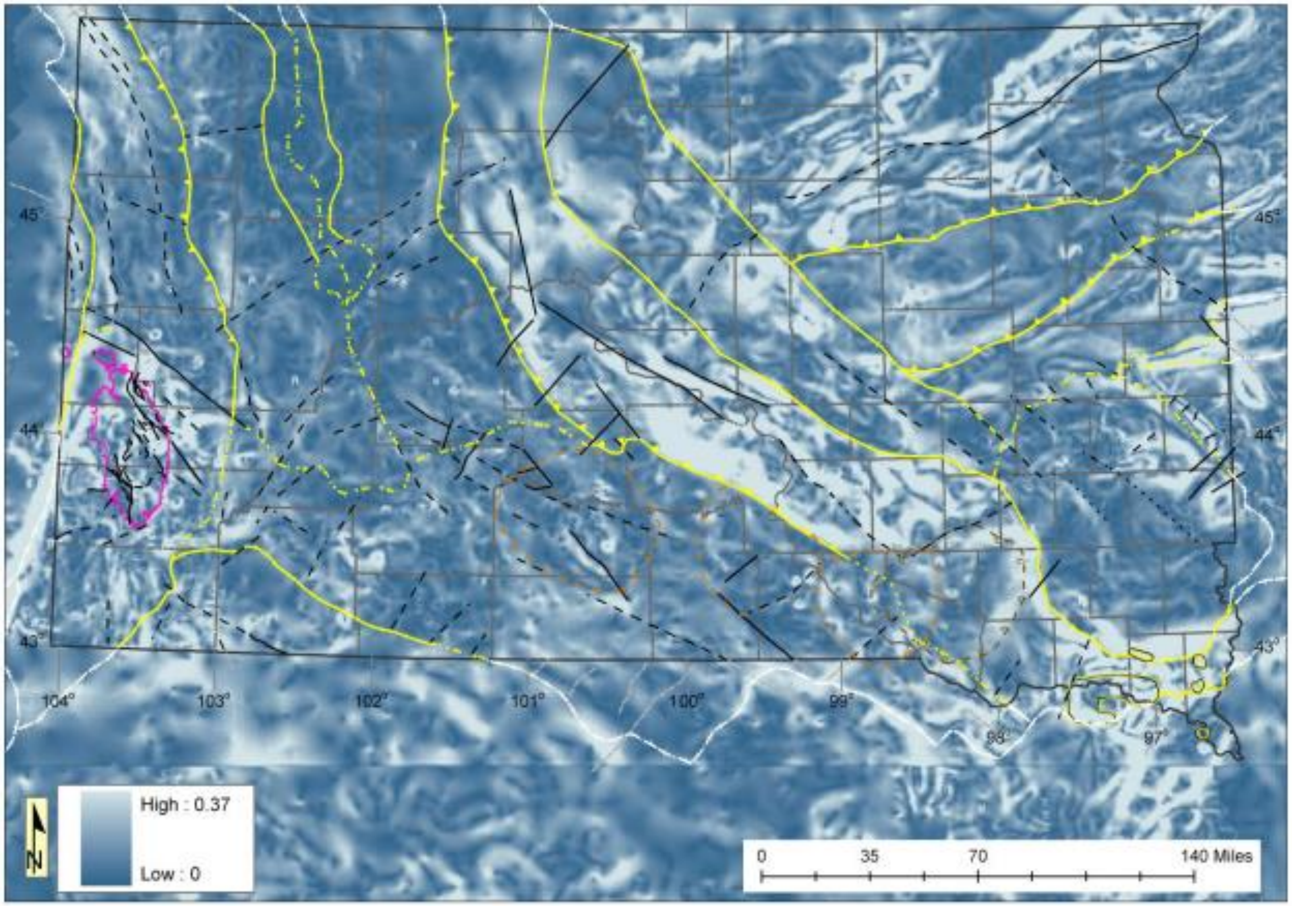


Figure 2-4. Geology of the Precambrian surface of Iowa and surrounding area (from Anderson 2006)



Map shows county boundaries, outline of the Precambrian outcrop area, and basement structures (see pl. 1)
Black lines = faults; lines dashed where uncertain, dotted where inferred
Yellow lines = structural boundaries

Figure 2-5. Map of the first horizontal derivative of the gravity data for South Dakota, with hillshade (from McCormick 2010)

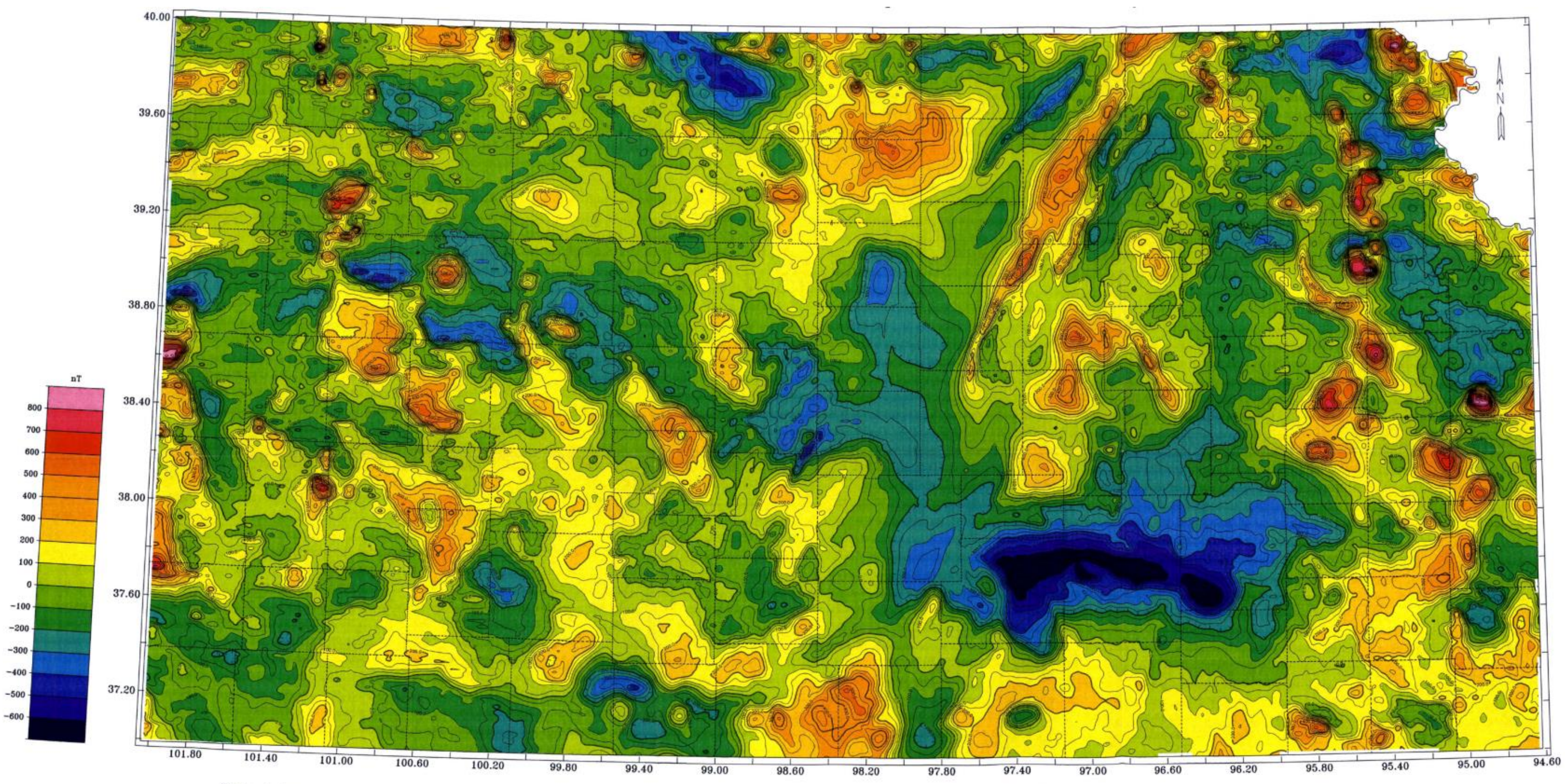


Figure 2-6. Residual aeromagnetic map of Kansas, second order regional trend removed (from Xia et al. 1995)

2.3.3 Basement Structural Complexity

Major structural features such as faults, shear zones, folding, and tectonic complexes in the crystalline basement could have significant, generally negative impacts on drilling, borehole construction, and post-closure safety characteristics of a deep borehole demonstration site. Faults and shear zones in the crystalline basement may be associated with highly fractured rock that could result in washouts or loss of drilling fluid circulation during the drilling process causing delays in drilling or potentially requiring abandonment of the borehole. Major faults may also be throughgoing, high-permeability pathways in the crystalline basement that could be routes of enhanced migration of radionuclides to the shallow subsurface or surface, which has potential negative consequences for post-closure safety of a disposal system. Intense folding of layered or foliated metamorphic rocks is common in older crystalline basement terranes and could make control of borehole deviation during drilling difficult, as described in Section 2.3.2. Some large-scale Precambrian tectonic features, such as the midcontinent rift complex in the north-central U.S., are characterized by faulting and anomalous lithology.

Large-scale structural features in the crystalline basement are often inferred from geophysical data, particularly where outcrops of Precambrian rocks are obscured by sedimentary cover. Figure 2-7 shows aeromagnetic data for the conterminous U.S. and the associated interpretation of large structural features from Sims et al. (2008). In many parts of the country this interpretation is based largely on linear discontinuities in the aeromagnetic values that are assumed to coincide with offsets in the crystalline basement and the juxtaposition of crystalline basement rocks with contrasting magnetic characteristics. Structural features have been projected from surface outcrops into the subsurface in some locations.

The midcontinent rift system in the Precambrian basement is a large tectonic feature in the north-central part of the U.S. that has significance for site selection of a deep borehole disposal demonstration project. As shown in Figure 2-8, this structural system extends from Kansas to Lake Superior in a semi-continuous fashion. This extensional tectonic feature was active in middle to late Proterozoic times and consists of thick clastic sedimentary and mafic volcanic rocks filling an elongated structural basin that is bounded by a complex system of normal faults. The arkosic sandstones and basalts that dominate the midcontinent rift system are not the target lithology for deep borehole disposal and are potentially more permeable than typical crystalline basement rocks at the depths of deep borehole disposal. In addition, the rift faults that bound this structural system could have higher permeability and constitute potential pathways for deep groundwater circulation and radionuclide migration from a deep borehole disposal system.

Overall, zones of structural complexity and faulting in the crystalline basement constitute areas of potential drilling problems and hydrogeological conditions potentially adverse to waste isolation. As a site selection guideline, such areas are not necessarily excluded, but they do increase the risk of an unsuccessful outcome to a deep borehole demonstration project.

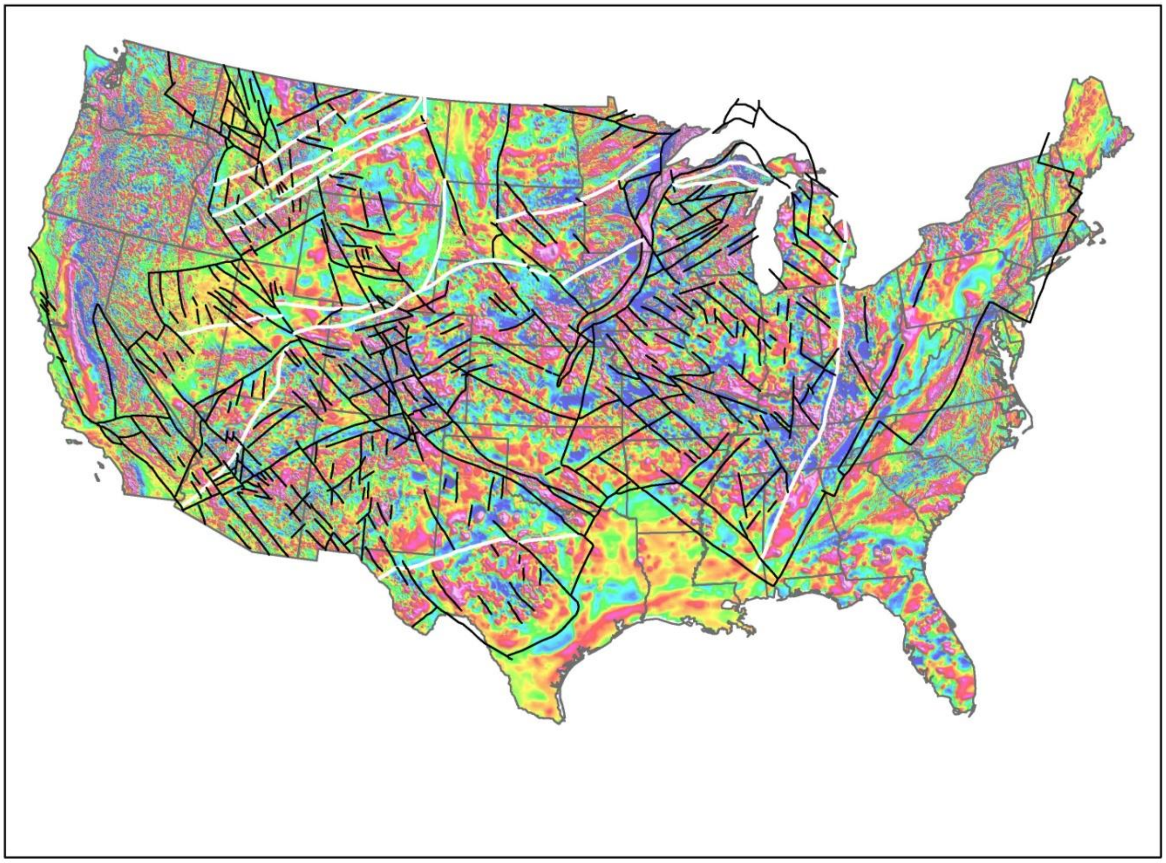


Figure 2-7. Precambrian basement structure map and aeromagnetic data. (Perry, 2013, source: Sims et al. 2008)

2.3.4 Horizontal Stress

It is important to understand regional and localized horizontal stress in order to best ensure borehole integrity and characterize the disturbed rock zone (DRZ) around the borehole. Where the magnitude of the two principle directions of horizontal stress differ (S_h = orientation of least horizontal *in situ* stress and S_H = orientation of greatest *in situ* horizontal stress), the borehole walls may spall and form breakouts along the direction of S_h. Thus, when borehole breakout occurs, the borehole becomes more of an oval with the dimension of the borehole being greater in the direction of the minimum horizontal stress (Figure 2-9).

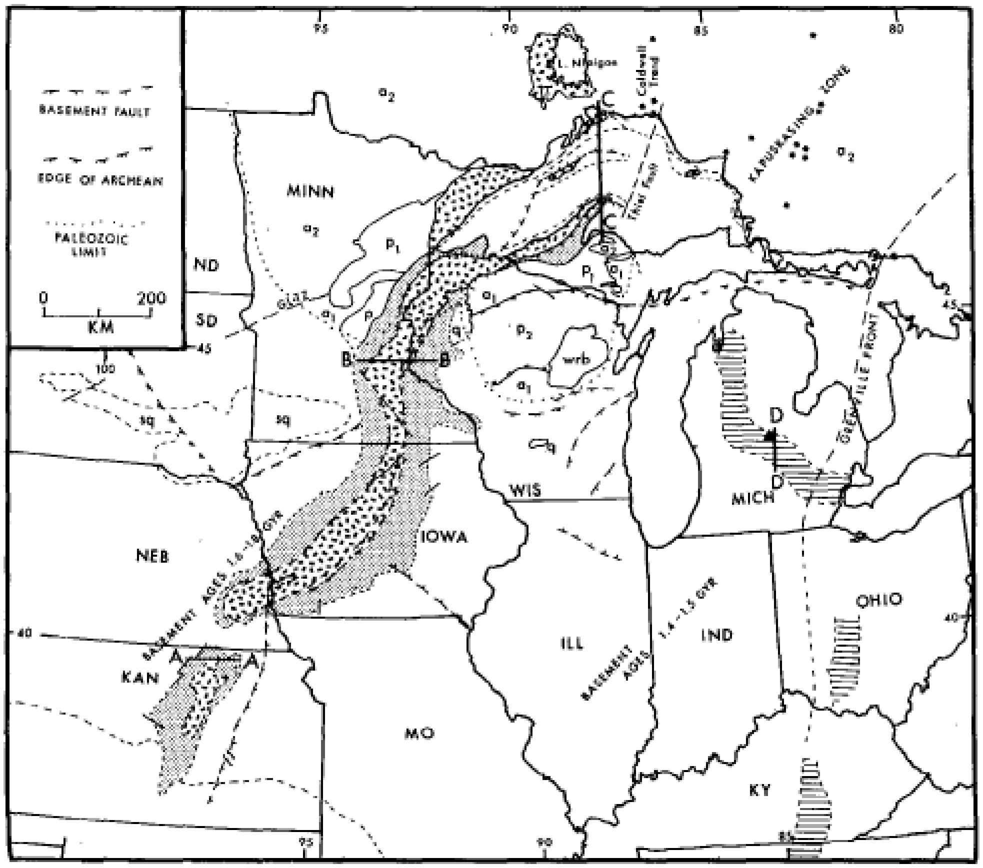


Figure 2-8. Generalized geologic map of the midcontinent rift system. (from Van Schmus and Hinze, 1985)

With borehole breakout, a deeper disturbed rock zone would develop along the sides of the borehole in the direction of minimal horizontal stress, potentially compromising both borehole and seal integrity. This DRZ could exist along the whole length of the borehole, depending on the stress fields. Therefore, in site selection for a deep borehole demonstration it is best to choose a site with minimal differential horizontal stress.

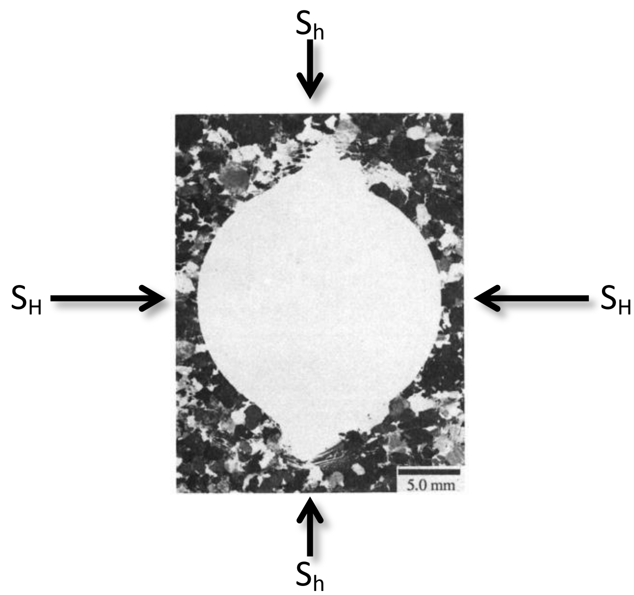


Figure 2-9. Cross section of a borehole wall showing two diametrically opposed breakouts with major and minor horizontal *in situ* stress axis displayed. (source: Lee and Haimson, 1993).

Horizontal stress data have been compiled as part of The World Stress Map Project (http://dc-app3-14.gfz-potsdam.de/pub/introduction/introduction_frame.html). Data for the United States are presented in Figure 2-10. Breakouts (lines with inner-facing arrows) have been measured along the West Coast, in Texas, Oklahoma and Colorado. In the mid-west the majority of borehole breakouts are measured in southern Illinois and Indiana. Borehole breakouts have also been measured in Ohio, Kentucky, Virginia, West Virginia, Ohio, Pennsylvania and New York. North Dakota, South Dakota, Iowa, Michigan, Alabama and North Carolina are void of stress measurements and very few have been made in Kansas, Minnesota, and northern Missouri.

The color of the symbols shown in Figure 2-10 gives an indication of the stress-regimes in the different areas in the country. California appears to be dominated by strike-slip (green) and thrust (blue) faulting. East of the coastal states (Idaho, Nevada, Utah, Arizona, and New Mexico) is dominated by a normal faulting regime. New England and New York appears to be dominated by thrust faulting. Zoback and Zoback (1989) generalize the stress fields on the United States (Figure 2-10)

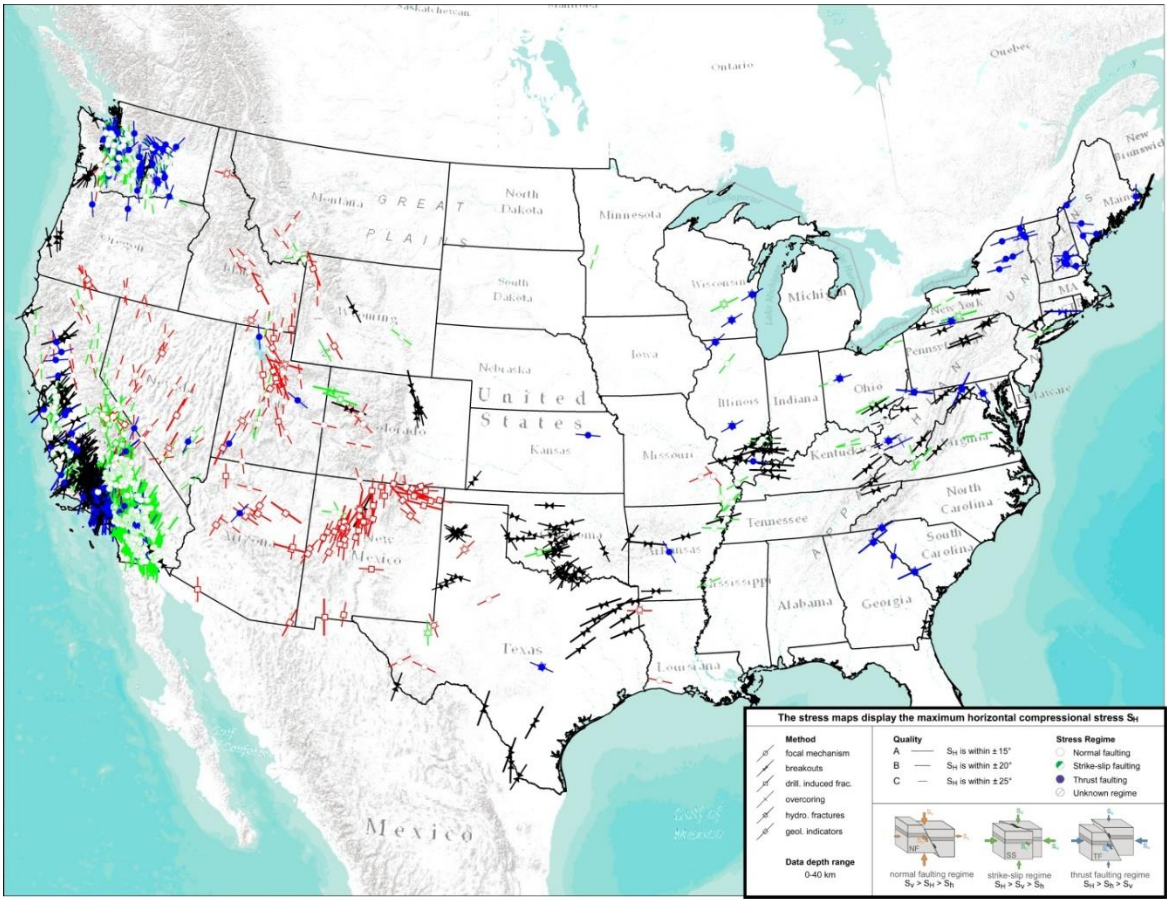


Figure 2-10. Horizontal stress data for the United States compiled by the World Stress Map Project (source: Heidbach et al, 2008).

Regional stress regimes can be defined by the relative magnitudes of vertical stress (S_v) and minimum and maximum horizontal stress as depicted in the legend in Figure 2-10:

Normal faulting stress regime:	$S_v > S_H > S_h$
Strike-slip faulting stress regime:	$S_H > S_v > S_h$
Thrust faulting stress regime:	$S_H > S_h > S_v$

Zoback et al. (1989) and Zoback (1992) also discuss transitional stress regimes, which are a combination of two stress fields. For example, when $S_v \approx S_H > S_h$ a combination of normal and strike-slip faulting will occur. Likewise, $S_H > S_h \approx S_v$ leads to a combination of strike-slip and thrust faulting. Given these definitions of stress-fields and available in the World Stress Map data (Heidbach et al. 2008), Zoback and Zoback (1989) define generalized stress-field regimes for the United States (Figure 2-11).

The premise of Zoback and Zoback's (1989) stress provinces shown in Figure 2-11 is that plate-tectonics is the source for the stress. While this may be true when studying stress fields at a regional scale, there are other factors impacting stress fields at a local scale. Erosion, denudation, over consolidation of sediments, and the sequence of glacial loading, unloading, isostatic movements and postglacial uplift can also impact horizontal stress (Amedei and Stephansson 1997).

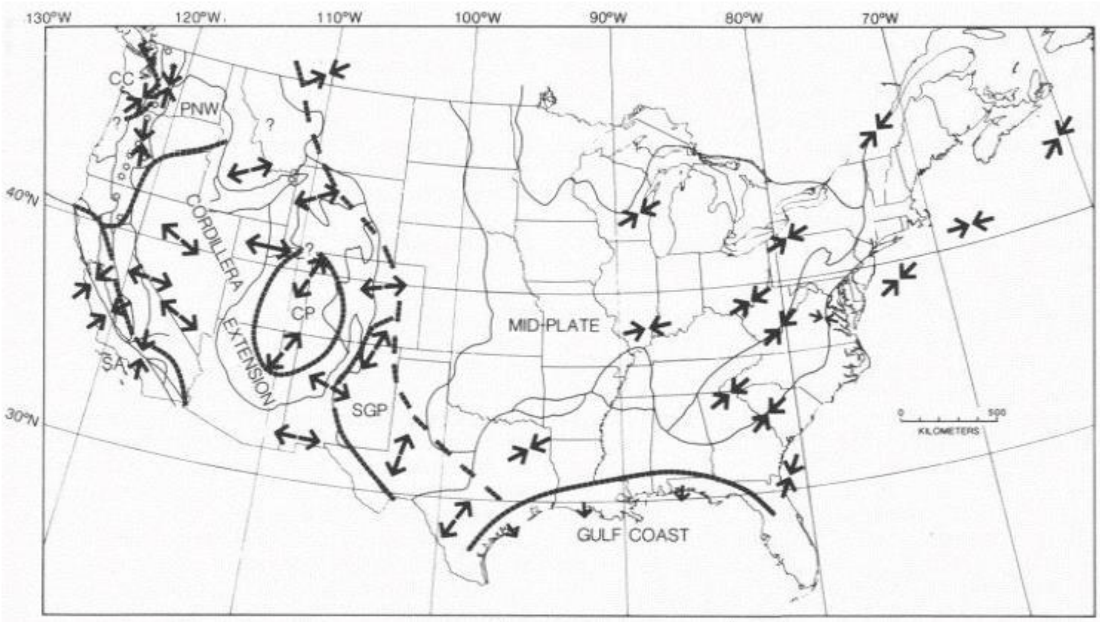


Figure 2-11. Generalized stress provinces for the United States (source: Zoback and Zoback 1989).

Overall, data and interpretations of the stress state in the upper crust provide a general picture of the stress regimes and the stress orientations on a regional scale, but provide little information on the magnitude of the anisotropy in horizontal stress. Observations of borehole breakouts, or lack thereof, in individual existing boreholes at the sub-regional scale would likely provide a reasonable indication of the risk of deep borehole instability. Broad areas of uniform orientation in horizontal stress, such as the northeast-southwest compressive stress state over much of the mid-continental U.S., probably offer a more predictable and homogeneous regime in differential horizontal stress than the tectonically more complex western and southwestern U.S. In this sense, the mid-plate region of the U.S. (see Figure 2-11) may be more favorable for siting a deep borehole demonstration project.

2.3.5 Tectonic Uplift

Tectonic uplift is an increase in elevation of the earth surface due to tectonic or isostatic processes. Two converging plates can cause continental crustal thickening leading to tectonic uplift. The elevation of the earth can also increase due to an isostatic response to unloading, thus the two processes need to be distinguished. Tectonic uplift is important to deep borehole disposal, not because it has a direct impact on performance, but because in areas of tectonic activity there is an increased risk of seismicity, volcanism, and active faulting (see Section 2.3.8). The risk of exhumation of waste from deep borehole disposal within a regulatory time frame is much lower than for a mined repository because of the greater disposal depth.

Isostatic uplift, or post-glacial rebound, is the increase in elevation, or rise of the land surface that was lowered during past glaciations. The isostatic uplift rates in the continental United States are greater in the northern states (closer to the margins of the ice sheet - see Figure 2-12) decreasing to the south.

Rates of isostatic uplift have been estimated (e.g., Paulsen at al. 2005); however, less data are readily available for tectonic uplift rates. Areas where the arrows are pointing towards each other in Figure 2-11 are areas where tectonic uplift is more likely. However, this figure does not give any indication of the rates of uplift and whether or not they are significant.

Quaternary faulting and volcanism, high tectonic uplift rates and horizontal stress are all indicators of tectonic activity. As stated above, tectonic activity is an important process that could negatively impact deep borehole performance due to an increased risk of seismicity, volcanism, and active faulting. After a demonstration study area for deep borehole disposal has been chosen, a more detailed study of the potential of tectonic impacts on the demonstration should be under taken.

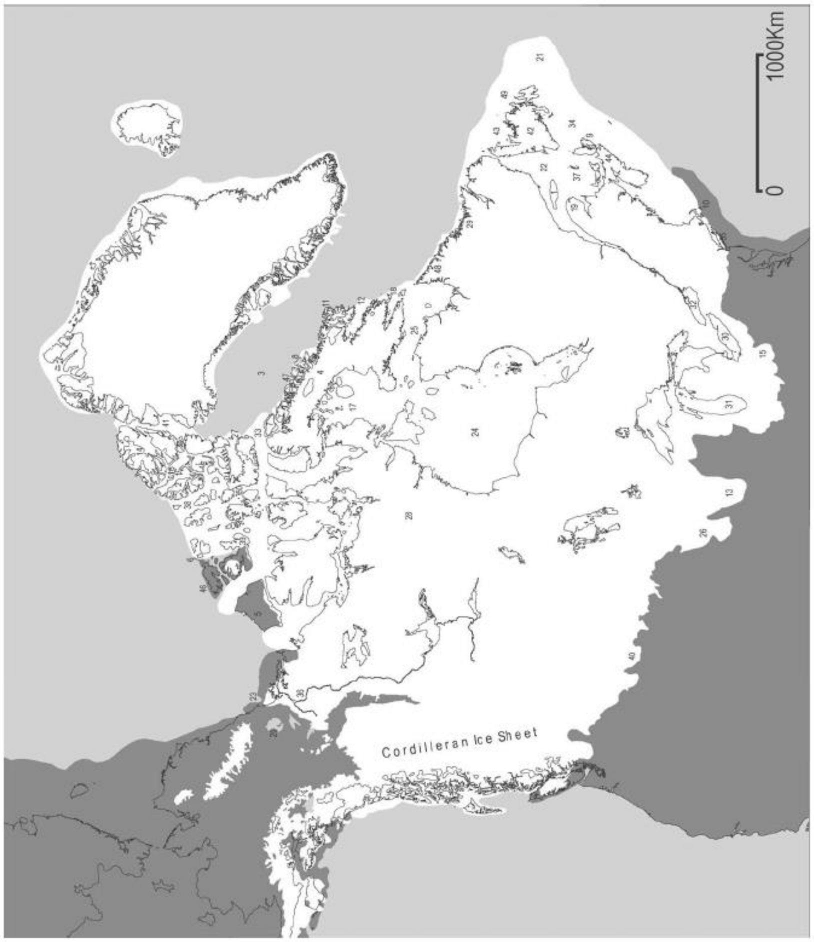


Fig. 1. Ice sheet margins in North America at LGM with major place names and ice lobe names. 1, Anticosti Island; 2, Axel Heiberg Island; 3, Baffin Bay; 4, Baffin Island; 5, Banks Island; 6, Brock Island; 7, Bylot Island; 8, Cape Aston; 9, Cape Breton Island; 10, Cape Cod; 11, Cumberland Peninsula; 12, Cumberland Sound; 13, Des Moines Lobe; 14, Ellesmere Island; 15, Erie Lobe; 16, Eureka Sound; 17, Foxe Basin; 18, Frobisher Bay; 19, Gaspé Peninsula; 20, Glacial Lake Old Crow; 21, Grand Banks; 22, Gulf of St. Lawrence; 23, Herschel Island; 24, Hudson Bay; 25, Hudson Strait; 26, James Lobe; 27, Jones Sound; 28, Keewatin; 29, Labrador; 30, Lake Erie; 31, Lake Michigan; 32, Lake Ontario; 33, Lancaster Sound; 34, Laurentian Channel; 35, Long Island; 36, Mackenzie River and Lobe; 37, Magdalen Islands; 38, Massey Channel; 39, Melville Island; 40, Montana; 41, Nares Strait; 42, Newfoundland; 43, Notre Dame Channel; 44, Nova Scotia; 45, Parry Channel; 46, Prince Patrick Island; 47, Remote Lake; 48, Torngat Mountains; 49, Trinity Trough; 50, Wellington Channel.

Figure 2-12. The extent of the ice sheet margins in North America at the last glacial maximum (LGM) (source: Dyke et al. 2002).

2.3.6 Geothermal Heat Flux

Geothermal heat flux and geothermal gradient are relevant guidelines for siting a deep borehole disposal demonstration project or disposal system in several ways, including 1) temperature conditions at depth as they affect drilling, emplacement operations, EBS materials, and waste forms, 2) potential for future human intrusion by drilling for geothermal resource exploitation, and 3) as indicators of ambient vertical groundwater flow in the regional flow system. The maximum temperatures in the borehole affect drilling operations in numerous ways, including the strength of downhole equipment, operating ranges for instrumentation, and management of heat from drilling fluids. The mechanical strength of waste canisters and their ability to withstand hydrostatic pressures is affected by temperature, with the strength of steel being significantly reduced at higher operating temperatures. Chemical reactions associated with corrosion, mineralogical transformations, and waste form degradation generally occur more rapidly at higher temperatures. A number of technical factors, such as ambient temperature, permeability, and stress state influence the attractiveness of a site for geothermal resource development and potential inadvertent intrusion by future drilling; however, geothermal gradient and temperature at depth are the primary factors in determining future geothermal drilling. Inadvertent human intrusion by drilling for any purpose could result in the release of radionuclides from the deep borehole disposal system to the biosphere in contaminated fluids and/or drill cuttings. Finally, in some cases the geothermal heat flux and temperature gradients may provide information on deep groundwater circulation. Upward or downward groundwater flow, even at moderate flow rates, can significantly alter the geothermal temperature gradient from the value expected from purely conductive vertical heat transport. Upward groundwater flow tends to increase the observed geothermal gradient and would increase the potential for upward transport of radionuclides from the deep borehole disposal system.

Geothermal heat flux is generally calculated from the temperature gradient measured in a borehole and estimated values of thermal conductivity for the rocks penetrated by the borehole. Figures 2-13, 2-14, and 2-15 show maps of the geothermal heat flow, estimated geothermal gradient, and estimated temperature at a depth of 4 km for the continental U.S. The analysis can be complicated by vertical groundwater flow and variations in thermal conductivity and geothermal gradient. The geothermal gradient has been measured in numerous shallow boreholes, but far fewer measurements are available for deep boreholes. Consequently, there can be significant uncertainty in the depth-averaged deep geothermal gradient and the calculated value of temperature at 4 km depth at many locations.

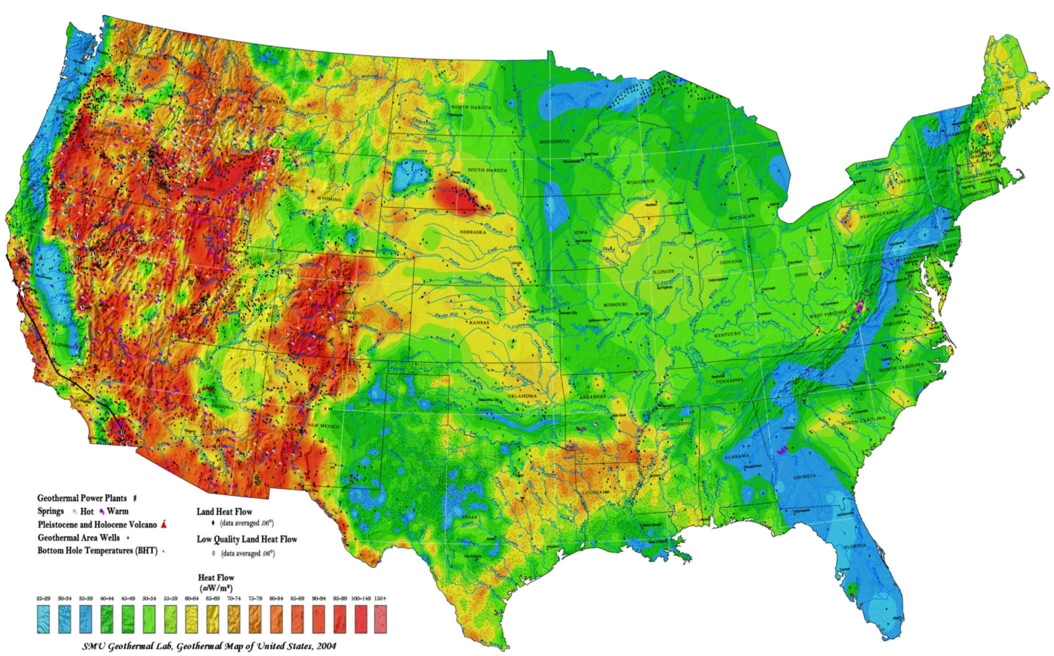


Figure 2-13. Geothermal heat flow in the continental U.S. (source: SMU Geothermal Laboratory 2004).

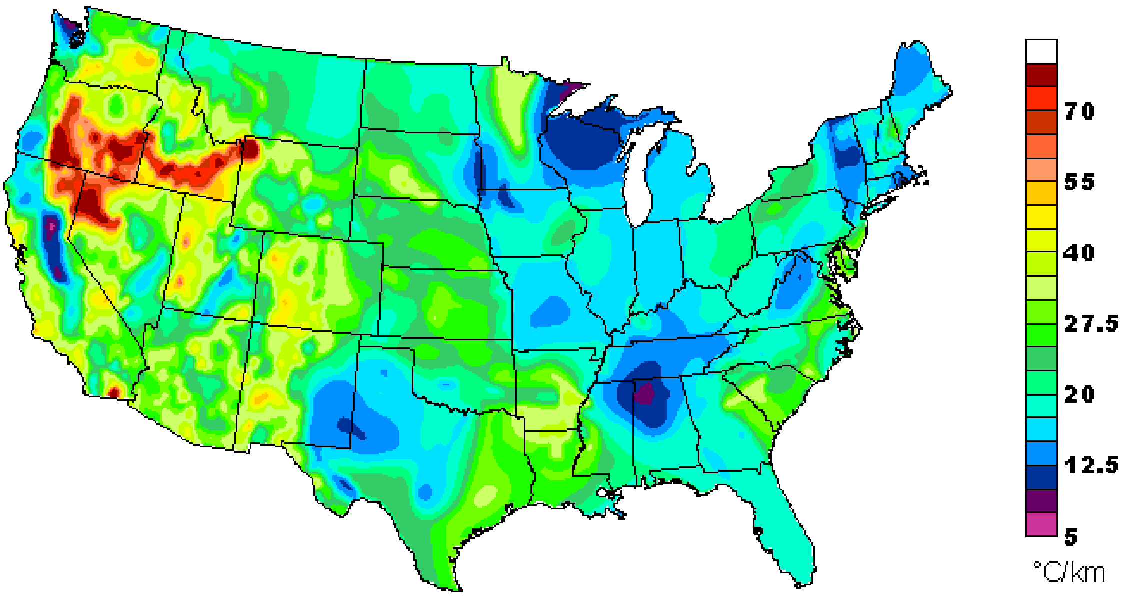


Figure 2-14. Estimated geothermal gradient in the continental U.S. (source: SMU Geothermal Laboratory 2004).

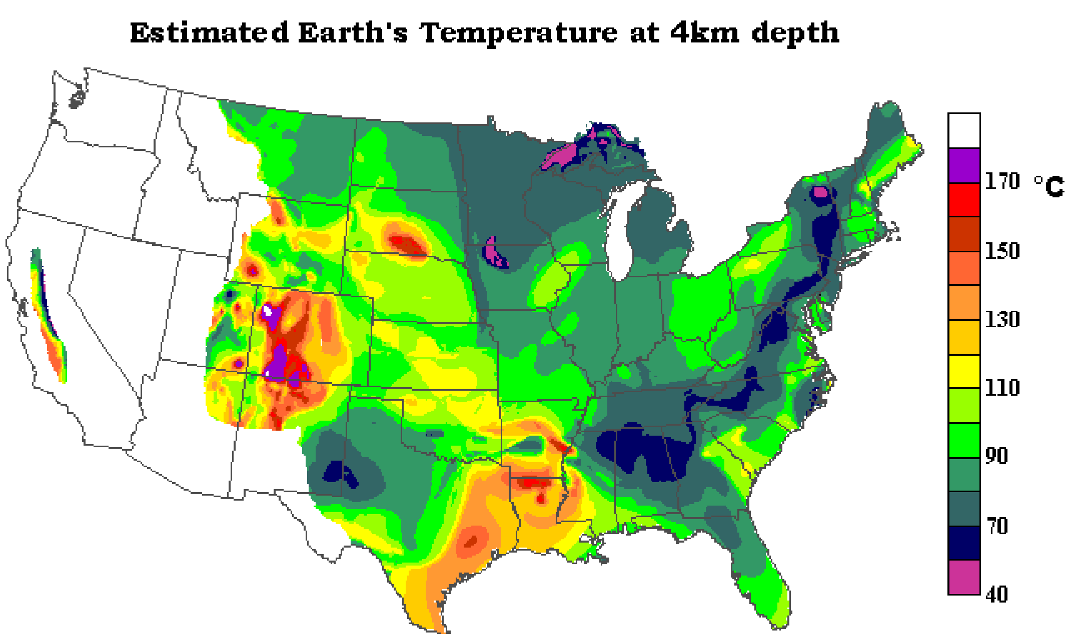


Figure 2-15. Estimated temperature at 4 km depth in the continental U.S. (source: SMU Geothermal Laboratory 2004)

The map of geothermal heat flow in Figure 2-13 shows large variability in heat flux, with generally higher values in the western U.S. and lower values in eastern U.S. Exceptions include relatively low heat flow in the coast ranges of Washington, Oregon, and northern California, and the Central Valley of California. Notably higher heat flow also occurs in south central South Dakota, in a broad area from eastern Texas to western Mississippi, and in isolated areas scattered in the eastern U.S. The area of high heat flow in south central South Dakota is paired with an area of anomalously low heat flow in west central South Dakota, centered on the topographically elevated Black Hills. This feature has been interpreted as the result of a regional-scale groundwater flow system in which downward flow suppresses the heat flux in the Black Hills and emerges as deep upward groundwater flow near the lowlands of the Missouri River in south central South Dakota, enhancing the geothermal heat flow in that area.

The maps of geothermal gradient and estimated temperature at 4 km depth in Figures 2-14 and 2-15 show similar patterns to the heat flux map, but have information that is more directly related to the temperature conditions expected at depths of interest for the deep borehole demonstration project. The geothermal gradient is generally low to moderate in the central and eastern parts of the U.S., with generally higher values of the geothermal gradient in the west. Very high values of the geothermal gradient extend from the Yellowstone volcanic area in northwestern Wyoming, across the Snake River plain and into southeastern Oregon and northwestern Nevada. Note that temperatures at a depth of 4 km have not been projected for most of the western U.S. in Figure 2-15 because of the high variability in temperature gradients and lack of data.

Overall, the analysis of geothermal heat flux and temperature gradient with depth indicates that there are large areas of low to moderate geothermal gradient in the Midwestern and eastern parts of the U.S., with some smaller areas of low to moderate geothermal gradient in the western U.S. There is no definitive basis for setting a threshold value for average geothermal gradient or heat flux to use as a guideline for siting a deep borehole demonstration project. A temperature range of 160 ºC to 180 ºC would correspond to a geothermal gradient of about 30 ºC/km for a 5,000 m deep borehole. In terms of attractiveness for geothermal resource development, current deep drilling for enhanced geothermal systems (EGS), such as that at Soultz, France and the Cooper Basin, Australia, is in locations with geothermal gradients of greater than 30 ºC/km (MIT 2006). Given the abundance of potential locations with geothermal gradients of greater than 30 ºC/km in the U.S., it is unlikely that locations with lower values of geothermal gradient would be at risk for deep drilling for EGS development in the future.

2.3.7 Topographic Relief and Hydraulic Gradient

Groundwater flow is dominantly driven by topographic relief in most flow systems. Such flow occurs in local, intermediate, and regional flow patterns, as identified in the classical analysis of topographically driven flow by Tóth, (1963). The rate of topographically driven groundwater flow, both horizontally and vertically, is determined by recharge rates, the pattern of topographic relief, the permeability structure of the subsurface, and depth. Recharge rates vary both geographically and topographically. Topographic relief varies both locally and regionally, with extensive areas of higher topographic relief occurring in mountainous regions, such as much of the western U.S. and the Appalachian Mountains in the eastern U.S. One measure of topographic relief is the average local slope, as plotted for the continental U.S. in Figure 2-16.

This figure illustrates the regional potential impact of topographic relief as a factor in topographically driven groundwater flow rates. Figure 2-16 shows that areas with steep slopes of greater than 5º are much more common in the western U.S., relative to the rest of the continental U.S. It should also be noted that the absolute differences in topographic elevation, on a regional scale, are significantly greater in the western U.S. The geometric structure of permeability in the subsurface resulting from stratification of aquifers and aquitards, and from structural features can have a profound influence on the pattern, magnitude, and depth of groundwater flow in regional flow systems. Groundwater flow tends to be higher in shallower, regionally continuous aquifers that are separated by horizontally extensive aquitards. However, higher-permeability faults and fracture zones can effectively "short circuit" flow in some stratified sedimentary rocks and may be the dominant flow pathways in fractured crystalline rocks. Topographically driven groundwater flow rates generally decrease significantly with increasing depth according to the Tóth, (1963) model of regional flow, with exceptions occurring for some deep artesian aquifers and some high-permeability structural features.

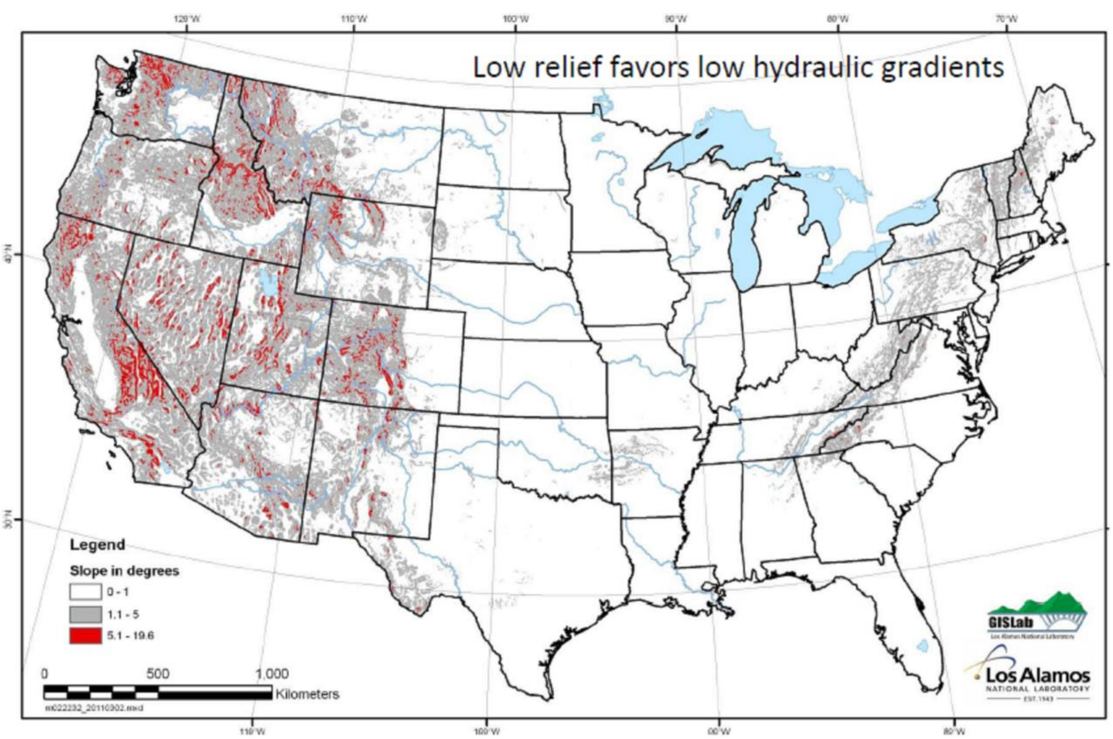


Figure 2-16. Topographic slope in the continental U.S. (Perry 2013)

In general, the safety of deep borehole disposal would be less sensitive to regional groundwater flow conditions than a mined repository because of the deeper disposal depth. Nonetheless, consideration of factors related to topographically driven groundwater flow rates could increase the probability that conditions favorable to waste disposal would be encountered in a demonstration borehole. In particular, lack of topographic driving forces would decrease the likelihood of upward hydraulic gradients in fluid potential and increase the likelihood of very old, highly saline fluids at depth.

Topographic slope, as shown in Figure 2-16, provides a gross measure of the potential for significant deep groundwater circulation that could be important to the deep borehole disposal concept. As described above, groundwater flow rates at depth are affected by several factors in addition to topographic relief. In particular, the variability and structure of permeability can be highly important in determining hydraulic gradients and flow rates at depth. Areas with high topographic slope and relief may have very low groundwater flow rates at depths of several thousand meters, if the low recharge rates and the distribution of permeability within the rocks preclude such flow. Areas with low topographic relief are very likely to have extremely low groundwater flow rates at deep borehole disposal depths, regardless of recharge rates and permeability structure. Low groundwater flow rates at depth would be further reduced from the density stratification of highly saline groundwater (Park et al. 2009) that typically develops over geological time scales in such stagnant deep groundwater systems. It should be noted that topographically driven deep groundwater circulation can be transmitted over horizontal distances of greater than 100 km in some cases, as illustrated by the anomalous geothermal heat flow pattern inferred to be related to the topographically high Black Hills in South Dakota described in Section 2.3.6.

Overall, regional topographic relief is a rough guideline for site selection regarding the potential for deep circulation of groundwater and the potential intrusion of younger, lower-salinity groundwater into the crystalline basement at the depths of deep borehole disposal. In some hydrogeologic settings low-permeability aquitards and the decrease in permeability with depth would preclude deep groundwater circulation regardless of topographic driving forces; however, proximity to high topographic relief increases the probability of deep circulation and upward hydraulic gradients, which are characteristics that are unfavorable for waste isolation.

2.3.8 Quaternary Faults and Volcanism

Deep borehole disposal sites should not be located in the vicinity of active faults or volcanoes. Volcanism could lead to a direct release and dispersal of radionuclides by way of eruption through the disposal zone. Active faults should be avoided because of the increased risk of seismicity and the greater potential of high permeability pathways through the rejuvenated faults.

As a guide, Quaternary faults and volcanism are of importance to deep borehole disposal because of their greater likelihood of being active in comparison to older faults and volcanoes. However, being close to a Quaternary fault or volcano does not disqualify a site for a deep borehole demonstration project. It does means that the area should be studied in greater detail to determine the likelihood of active faulting or volcanism at the site.

Figure 2-17 shows Plio-Quaternary volcanic fields and Quaternary faults in the continental United States. Quaternary faults and Plio-Quaternary volcanic fields are primarily located in western United States. A few Quaternary faults are located in Kansas, Oklahoma, and Texas up the Rio Grande Valley to Colorado. Moving west, the number of faults increase. Large volcanic fields can be seen in Idaho, Oregon, and northern California.

2.3.9 Mineral Resources Potential

The potential for mineral resources in deep crystalline basement rocks is uncertain at any given location that has not been drilled, particularly in areas where the basement is overlain by sedimentary rocks. Geophysical and geochemical exploration methods for mineral resources are generally limited to depths of less than 1,000 m and are rarely undertaken where there is thick overburden above the crystalline basement. However, there are some general associations between geological terrane types and the potential for mineral resources. Petroleum reservoirs very rarely occur in crystalline basement rocks and are not considered in the following discussion. The potential for geothermal resources in the crystalline basement was discussed in Section 2.3.6.

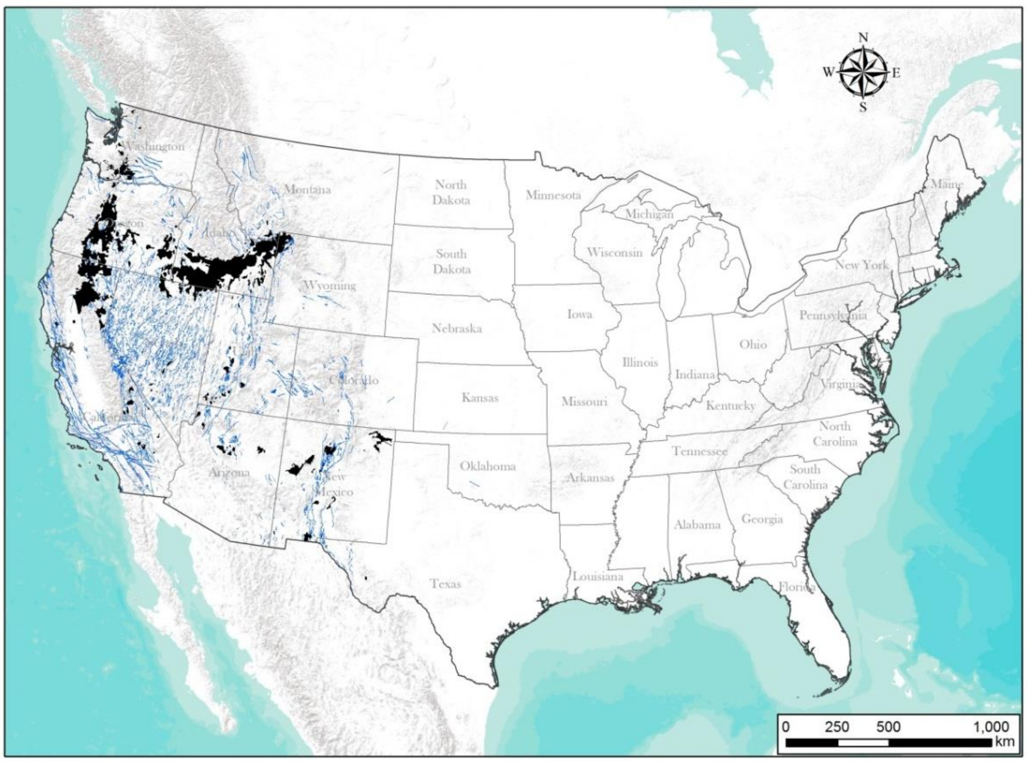


Figure 2-17. Quaternary faults (blue) and Plio-Quaternary volcanic fields (black) in the continental U.S. (source: USGS 2006 and Garrity and Soller 2009).

The presence of mineral or other resources at the depth of deep borehole disposal would potentially impact disposal system performance through direct intrusion by future exploratory drilling and mining activities. Exploratory drilling for mineral resources to the depths of the deep borehole disposal system is unusual under current practice, and generally is undertaken only when shallower mineral resources have been discovered at the location. Intersection of a future exploratory borehole with waste in a vertical deep disposal borehole would be unlikely due to the relatively small target presented by a vertical disposal zone. However, a future mineral exploratory borehole could encounter radionuclide contamination that had migrated laterally from the waste disposal interval. Current mining is conducted at deep borehole disposal depths at a few locations, notably gold mines in South Africa. The size of the ore body must be large and the ore grade must be high to make mining operations at such depths economically viable. In addition, mines to these depths are typically developed by following ore downward from shallower deposits.

A number of ore deposits are associated with felsic intrusive rocks, such as those considered for deep borehole disposal in crystalline basement, including porphyry base metal deposits, iron deposits, cordilleran vein-type base and precious metal deposits, pegmatites, and granitic tin and uranium deposits (Guilbert and Park 1986). Of these deposit types, porphyry base metal deposits and cordilleran vein-type base and precious metal deposits would be the ones that could have sufficiently high ore grade and economic value to warrant underground mining to depths of several kilometers. These magmatic and post-magmatic hydrothermal ore deposits are uncommon occurrences in the total area of the associated intrusive rocks, but are widely distributed in crystalline basement rocks that can potentially host them. They are typically formed within 1 km of the surface at the time of their genesis, so they would be unlikely to occur in crystalline basement terranes that have experienced significant erosion and denudation. Alteration halos for porphyry base metal deposits and cordilleran vein-type base and precious metal deposits may indicate their potential existence at depth, but initial discoveries of such deposits typically occurs in surface outcrops. Prediction of the location of these types of ore deposits in the crystalline basement under significant sedimentary rock cover would be very difficult, although randomly encountering such an ore deposit in a deep disposal borehole would be very unlikely.

Some of the world’s richest gold deposits are related to clastic deposition of gold and sulfide minerals in Precambrian conglomerates, such as those in the Witwatersrand gold deposits in South Africa (Guilbert and Park 1986). These deposits formed under low oxygenated atmospheric conditions about 2.7 to 2.4 billion years ago, which permitted fluvial transport of minerals without oxidation and dissolution. Such geochemical conditions existed in the Archean, but ended in the Proterozoic period, limiting the potential time period under which these deposits could have formed. Most of the crystalline basement Precambrian rocks south of the Superior Craton in the mid-western and southern U.S. are younger than about 2.0 billion years (Reed 1993), implying that Witwatersrand type gold deposits would not be present in the crystalline basement rocks over most of the U.S. In addition, the clastic metamorphic rocks that would host this type of ore deposit are not the target host rock for the deep borehole disposal demonstration project.

Deposits related to subaerial volcanism that might exist in the crystalline basement include epithermal silver-gold deposits, bulk low-grade silver deposits, and basalt-andesite copper deposits (Guilbert and Park 1986). Of these deposit types, epithermal silver-gold deposits could have sufficient economic value to warrant mining at depths of several kilometers, although no such ore deposits have been mined to the depths of deep borehole disposal. Low-grade or disseminated precious metal deposits can be economically mined by open pit methods, but are not amenable to mining by underground methods at the depths of deep borehole disposal. Epithermal gold deposits could be present in the felsic intrusive and volcanic geological environment of the crystalline basement, such as the large Southern and Eastern Granite-Rhyolite Provinces identified in Reed (1993).

Mineral deposits that are related to submarine volcanism include massive sulfide deposits and banded iron formations. Massive sulfide deposits potentially could be of sufficient size and economic value to warrant mining to great depths. Such ore deposits are formed in oceanic crust and are subsequently incorporated into the continental crystalline basement by tectonic accretion of the host terrane. Such geological conditions more commonly occur in Archean age rocks of the older continental craton that exist in the northern mid-western region of the U.S. Very large massive sulfide deposits potentially can be detectable at great depths using geophysical methods.

Another class of large mineral deposits is related to layered mafic intrusions, including the Bushveld igneous complex chromium-platinum deposit and the Sudbury complex copper, nickel-platinum deposit (Guilbert and Park 1986). Such deposits are mined to depths of over 2 km, thus having some potential for human intrusion into a deep borehole disposal system. The layered mafic rocks that host this type of ore deposit are not the target host rock for the deep borehole disposal demonstration project. Very large layered mafic deposits potentially can be detectable at great depths using geophysical methods.

Athabasca-type unconformity-related uranium deposits can occur near the interface between overlying sandstone and underlying crystalline basement rocks containing, in particular, graphitic schists that are hypothesized to have been the source of geochemical reducing agents for precipitation of uranium ore. Such uranium deposits can be quite large and economically exploitable by underground mining; however, mining depths are not as great as deep borehole disposal. Precambrian unconformity-related uranium deposits could occur in the basement rocks of the U.S. in the mid-continent rift structure (see Section 2.3.3), which contains arkosic sandstones overlying the crystalline basement.

Overall, there is a low probability of mineral deposits at a given site that could be economically exploited in crystalline basement rocks of the U.S. at the depths of several kilometers that pose a risk of inadvertent human intrusion to a deep borehole disposal system. The existence of most mineral deposits in the crystalline basement at depths of several kilometers typically could not be determined by existing geophysical or geochemical methods. General guidelines on the potential for mineral deposits are based on the assumption that large gold and base metal deposits are less likely to occur in felsic Proterozoic-age rocks than in heterogeneous Archean crystalline basement.

2.4 Logistical and Other Selection Guidelines

2.4.1 Drilling Contractor Availability

Although deep drilling is now common within the petroleum industry, there are few examples where large diameter wells have been drilled in crystalline bedrock to depths of 5,000 meters. The well most closely resembling the objectives of the deep borehole disposal demonstration project is the KTB Hauptbohrung scientific hole that was drilled in Germany in 1990 to 1994 to a depth of 9,101 m. Casing of 13-5/8 inch diameter was installed to a depth of 6,000 m in a 14-3/4 inch borehole. In reality, the KTB was a technology development hole and provided experience on automated drilling, bit technology, directional control and other issues related to deep drilling in crystalline bedrock.

The drilling industry is highly specialized, with drilling contractors normally providing only the drilling rig, fluid circulation system and drill pipe. Drilling supervision is the responsibility of the client's representative, or "company man". Other support services, equipment and materials are available from other specialized contractors and will be discussed in the next section. Oil field rigs and support services are available throughout the US, but costs will vary depending on distance from supply points and regional offices.

The borehole reference design presented in Arnold et al. (2011a) requires a 2,000 horsepower drilling rig with a minimum hook load of 1,000,000 pounds. Although rigs this large are not common, there are at least seven drilling contractors in the U.S. that have this capability. These rigs are located in the western and southwestern U.S. Their availability and cost are dependent on demand, and utilization rates are presently approaching 80% industry wide. Demand is expected to increase in the short term, based on current trends of expanding petroleum exploration and production.

2.4.2 Drilling Support Services Availability

Drilling support services are available through companies that work with the petroleum drilling sector. The supply chain within the US is robust and it is expected that services and supplies can be procured by competitive bid addressed to a number of different suppliers for each type of equipment or service. A few of the major support items are discussed below. Major support contractors have offerings in a number of these areas and can also provide comprehensive management services.

A significant advance in drilling technology is Measurement While Drilling (MWD) that measures borehole parameters and transmits data to the surface in real time. The DBD demonstration will have strict tolerances for dog legs and deviations from vertical. MWD provides the ability to perform quality control as the borehole is being drilled. Should the borehole start to exceed specifications, corrections can be made using steerable drilling assemblies.

The borehole reference design has called for three casing strings that will be cemented in place, plus a "guidance liner" that will provide the conduit for the emplacement of the waste canisters. The casing strings are of standard oil field size and are available from a number of different suppliers. Cementing the casing also requires a specialized contractor who can provide an analysis of the borehole requirements, cement mixtures to satisfy those requirements and specialized equipment to install the cement. Cement may also be used during the drilling of the well to aid in sealing zones of lost circulation.

Drilling fluid, or "mud", will be required and can become a significant cost in the drilling of the well. Mud is used to lubricate and cool the bit, transport cuttings to the surface and condition the hole to prevent loss of fluids to the formation. The quality of the mud is controlled by mud engineers, and returns of formation chips as well as gasses are monitored by mud loggers. The loggers compile a running lithologic log of the hole and the chemistry of the mud returns gives an indication of permeable zones and the character of formation fluids.

Well-head equipment is used to control any high pressure encountered in the well. Generally this will consist of a master valve and blow out prevention equipment (BOPe). The master valve is connected to the casing that is sealed against the formation. In the case of the DBD demonstration, there will probably be a master valve that will be used during the drilling process. Upon completion, this will be replaced with a second master valve that is specifically designed to permit the passage of the waste canisters. Above the master valve, a blow out prevention stack, consisting of blind and pipe rams, will be used to control potential fluid and gas flow during the drilling of the well.

Down-hole geophysical logging suites have been listed and described in Vaughn et al. (2012a). Logging will take place after each segment of the borehole is drilled and before casing is installed. With the rotary drilling process, only chips from the bedrock are returned to the surface; therefore, geophysical logs are extremely important for documenting lithologic properties of the borehole. The logging industry is very mature and equipment is available in major petroleum centers throughout the U.S.

2.4.3 Permitting Considerations

The details of the legal and regulatory requirements for permitting a DBD demonstration project will be initiated during the planning process for the site selection and continue through the technical planning and drilling of the demonstration borehole. Since the regulatory environment is different in different states and for Federal versus private land, it is important to initiate the process early to allow specific state and local requirements to be considered. At the initial planning level, the permit considerations for the DBD project can be summarized by addressing the major requirements found in the National Environmental Policy Act, the drilling permit, and the land use permit.

Because the demonstration project would not include emplacement of radioactive materials, regulations pertaining to nuclear waste disposal do not apply. Nonetheless, RD&D activities in the DBD demonstration project would be conducted in a manner consistent with their potential future utilization in the regulatory processes associated with licensing a disposal facility.

2.4.3.1 National Environmental Policy Act

The project team will utilize National Environmental Policy Act (NEPA) compliance as guidance to inform the decision on site selection. The legal and regulatory framework for DBD of SNF and HLW will be addressed in subsequent work.

As a Federally funded project, compliance with the NEPA is a requirement. Some uncertainty exists regarding the level of effort required to comply with this requirement. The project scope and duration is not of a magnitude that would generally require an Environmental Impact Statement, so for planning purposes time and money has been included to perform an Environmental Assessment. Initial work has begun to prepare an Environmental Checklist and a meeting is planned with the NNSA Sandia Site Office NEPA Compliance Officer. This discussion will allow finalization of a NEPA compliance strategy.

Generally, an Environmental Assessment will consider and evaluate the potential impact of the following:

Air Quality-The Clean Air Act (CAA) provides for the establishment of national air quality standards to protect public health and the environment from the harmful effects of air pollution. The act requires the establishment of national standards of performance for new stationary sources of emissions, limitations for a new or modified structure that emits or may emit an air pollutant, and standards for emission of hazardous air pollutants. In addition, the CAA requires that specific emission increases be evaluated to prevent a significant deterioration in air quality. For this demonstration project, air quality permits may be required for the drilling operation since the activity represents a point source for emissions. Some states are much more restrictive than others and may require that Tier 3 engines on the drill rig and associated power units meet strict emission guidelines. Also, some local/state regulators require "Fugitive Dust Control" permits that apply when significant soil areas are disturbed, which may be the case for this project.

Noise-The Noise Pollution and Abatement Act of 1970 required the U.S. Environmental Protection Agency (EPA) to establish the Office of Noise and Abatement Control. The Noise Control Act (NCA) was legislated in 1972 to ensure that environments are free from noises that jeopardize the health and welfare of Americans. Congress has not funded the Office of Noise and Abatement Control since 1982 based on the argument that noise pollution is best handled at the state and local level. Many local/state regulators have established guidelines for noise pollution that must be followed.

Clean Water- The Clean Water Act (CWA) establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters. The basis of the CWA was enacted in 1948 and was called the Federal Water Pollution Control Act, but the Act was significantly reorganized and expanded in 1972. Under the CWA, EPA has implemented pollution control programs such as setting wastewater standards for industry.

The CWA made it unlawful to discharge any pollutant from a point source into navigable waters, unless a permit was obtained. EPA's National Pollutant Discharge Elimination System (NPDES) permit program controls discharges. Therefore the DBD demonstration project would require a NPDES Storm-Water Discharge permit prior to the beginning of construction. This permit would likely require that both a Storm-Water Pollution Prevention Plan and Sediment Control Plan be prepared and a Notice of Intent to discharge storm water be filed with EPA. Specific erosion and sedimentation controls, and other best management practices required by the permit would limit the amount of erosion that occurs on site, and restrict potential impacts to the immediate area.

Biological Resource-The NEPA analysis will include an evaluation of potential effects of the DBD demonstration project to vegetation, wildlife, and threatened and endangered species. Certain plants and animal species are protected by the Federal government under the Endangered Species Act or by the state regulating agency under state authority.

Cultural Resources- These include archaeological, traditional and built environmental resources, including districts, sites, buildings, structures, or objects from both the prehistoric and historic eras of human history. Federal, state, and local laws direct the preservation and protection of cultural resources that are historically significant. Preservation and protection of the resources are required by a number or Federal acts, but as part of the NEPA process, the DBD demonstration project, at a minimum, will be required to perform an archaeological survey of the proposed sites.

Waste Management-Since the project will generate nonhazardous wastes and possibly hazardous wastes the activities must be managed in an appropriate manner. If hazardous waste is generated it must be stored and disposed in accordance with the Resource Conservation and Recovery Act.

2.4.3.2 Drilling Permits

A permit to drill a demonstration well will be required from the state agency regulating wells. The request for a drilling permit will generally require that a borehole plan be submitted. Regulators will be interested in seeing a casing program that isolates aquifers and assures effective control of down-hole pressure (Blow-Out Prevention System). They will also be interested in the mud system and containment and disposal of drill cuttings.

2.4.3.3 Land/Water Use Permits

Land use permits will be required on public lands; whereas land owner agreements and leases will be required on private lands. In many instances, the surface and subsurface rights may be separate. The drilling operation will consume large amounts of water; therefore it is likely that a water well will be drilled on location to eliminate the use of water hauls. This water well, if required, will be permitted through the appropriate state agency of water rights.

3. BOREHOLE SEALS AND WASTE EMPLACEMENT

Key objectives of the borehole seals effort are to use ex situ testing to: 1) demonstrate performance of bentonite seals; 2) measure brine/cement impact on bentonite permeability; 3) build the technical basis for rock-welding of seals, and 4) identify (any) effects of waste package corrosion on seals. Although no waste will be emplaced in a demonstration borehole, the demonstration borehole effort will involve detailed planning of waste emplacement steps.

3.1 Seal Materials Testing Strategy

Avoiding bentonite shrinkage is one key to assuring low seal permeabilities. Another is demonstrating that cement will not undergo large-scale volume changes over several thousand years. Laboratory testing will quantify the sensitivity of bentonite volume to: baseline downhole brine composition, alkaline cement leachate, waste form corrosion effluent with a low redox potential, and temperature. A limited number of low- and high-temperature cement-brine equilibration measurements will be used to calibrate a theoretical geochemical model that will be used to assess the long-term stability of borehole cements.

3.2 Review of Bentonite and Cement Seals Stability

Bentonite volume is reduced by high ionic strength and/or the introduction of divalent cations, such as Ca^{+2}, Mg^{+2}, and Fe^{+2} (produced during the anoxic corrosion of steel casing). Brines at the bottom of the borehole are expected to have high ionic strengths and appreciable levels of divalent cations; fluids above the waste emplacement zone will be more dilute; bentonites near cement may be subjected to high Ca^{+2} levels; and bentonites near degrading steel may see high Fe^{+2} and Ni^{+2} concentrations. Temperatures in the upper reaches of the borehole will be 25 – 75^{o}C; they may approach 150^{o}C at depth. Hydrostatic pressures will approach 115 - 340 bar (11.5 - 34.0 MPa) at depth. High temperatures should accelerate reactions, but may also shift the mineral equilibria that influence dissolved concentrations. For example, higher temperatures will favor dissolution of feldspars, thereby increasing dissolved Na^{+}, K^{+}, and SiO_2 levels, and possibly prompting the formation of new clay minerals.

Batch bentonite equilibration experiments will be done at 50 and 150^{o}C as a function of salinity and divalent cation concentration to measure volume and mineralogy changes as a function of temperature. Reactants will be loaded into either a flexible gold or titanium bag and fixed into a 500 mL Gasket Confined Closure reactor (Seyfried et al. 1987) – see Figure 3-1. Experiments will be pressurized to 150 - 160 bar (15.0 – 16.0 MPa) and heated to follow two different temperature profiles: (1) 120°C for 2 weeks, 220°C for 2 weeks, and then 300 °C for 1 week and (2) isothermal at 300 °C for 6 weeks. Reaction liquids extracted during the experiments will be analyzed to investigate the aqueous geochemical evolution in relationship to mineralogical alterations. Geochemical modeling will be used to develop a methodology for predicting limits of bentonite reactivity as a function of depth, time, and proximity to degrading steels and cements.

Figure 3-1. Gold bag (left) and gasket confined closure reactor (right) – Courtesy, Florie Caporuscio, Los Alamos National Laboratory.

Bentonite+cement and cement-only equilibration experiments will be done to quantify the effects of varying water chemistry on cement degradation in borehole brines and what happens when bentonite seals encounter hyperalkaline (pH > 10) cement leachate and (possibly) react to form mixed layer illite-smectites, non-expandable illites and zeolites. Reaction-transport modeling of the cement-bentonite reaction similar to that conducted for the French High Level Waste Repository (e.g. Gaucher and Blanc 2006; Gaucher et al. 2004) will be used to model the batch experimental results, and ultimately used to predict cement duability and chemical evolution at the cement-bentonite interface

3.3 Alternative Seals Research

In the generic DBD concept there are two areas where effective, very long-lived seals are either necessary or highly desirable. First, it is important that the borehole itself does not provide an easier route back to the biosphere for any fluids or gasses containing radionuclides than does the undisturbed host rock. It is thus necessary to completely and permanently seal the borehole above the waste package disposal zone (DZ). This is sometimes referred to as the “main seal(s)”. Second, if the multiple-barrier nature of the DBD concept is to be credibly maintained, particularly from the perspective of the long-term safety case, it is important that the waste packages are surrounded by a barrier – a sealing and support matrix (SSM) – made from an impermeable and durable material with high compressive strength.

The use of bentonite and cements for the main seal(s) has been discussed in Section 3.2, while the use of bentonite, silica, graphite sand and other materials to surround and support the waste packages has been described elsewhere (e.g., Brady et al. 2009; Sapiie & Driscoll 2009). This section considers alternative and potentially better ways of achieving the necessary seals in both contexts.

3.3.1 Borehole Sealing by Rock Welding

Oil, gas and geothermal energy wells are conventionally sealed in various ways for different reasons with materials such as cement, concrete, clay, resin or asphalt/bitumen. Emplacing such seals is not a simple matter and the difficulties of anchoring and sealing the casing to the wall rock with cements in deep hydrocarbon and geothermal energy wells are well known. For DBD the contact between the host rock and sealing material must be as good as it can be and thus would require removal of any casing or liner. Cutting the casing in or above the DZ and withdrawing it, possibly for reuse, has been suggested (e.g., Gibb et al. 2012), but withdrawing such a length and weight of casing is not an easy engineering option. A simpler, quicker and more cost effective alternative would be to cut or grind away the casing over several meters of the borehole to expose the rock where the seals are to be located.

Whatever material is used, the contact surface between the seal material and wall rock is a potential zone of weakness and this could be exacerbated by longitudinal pressures in the borehole, tectonic stresses or geochemical reactions between the seal material(s) and saline groundwaters at elevated temperatures. Over time this could become a path of least resistance for any fluids seeking to flow up or down the borehole.

A further complication arises from the existence of a DRZ around the borehole. In hard rocks like granite this may be limited to tens of centimeters or less but it would be almost impossible to get any sealing material, even where it is in pressurized contact with the wall rock, to penetrate sufficiently far into the micro-fractures of the DRZ to render it impermeable to fluid flow. A permeable DRZ is a potential bypass of the borehole seals for any radionuclide bearing fluids and must be eliminated. Ways of reducing the impact of the DRZ, such as widening of the hole and seal at intervals, have been suggested but are difficult to implement, with no guarantee of success.

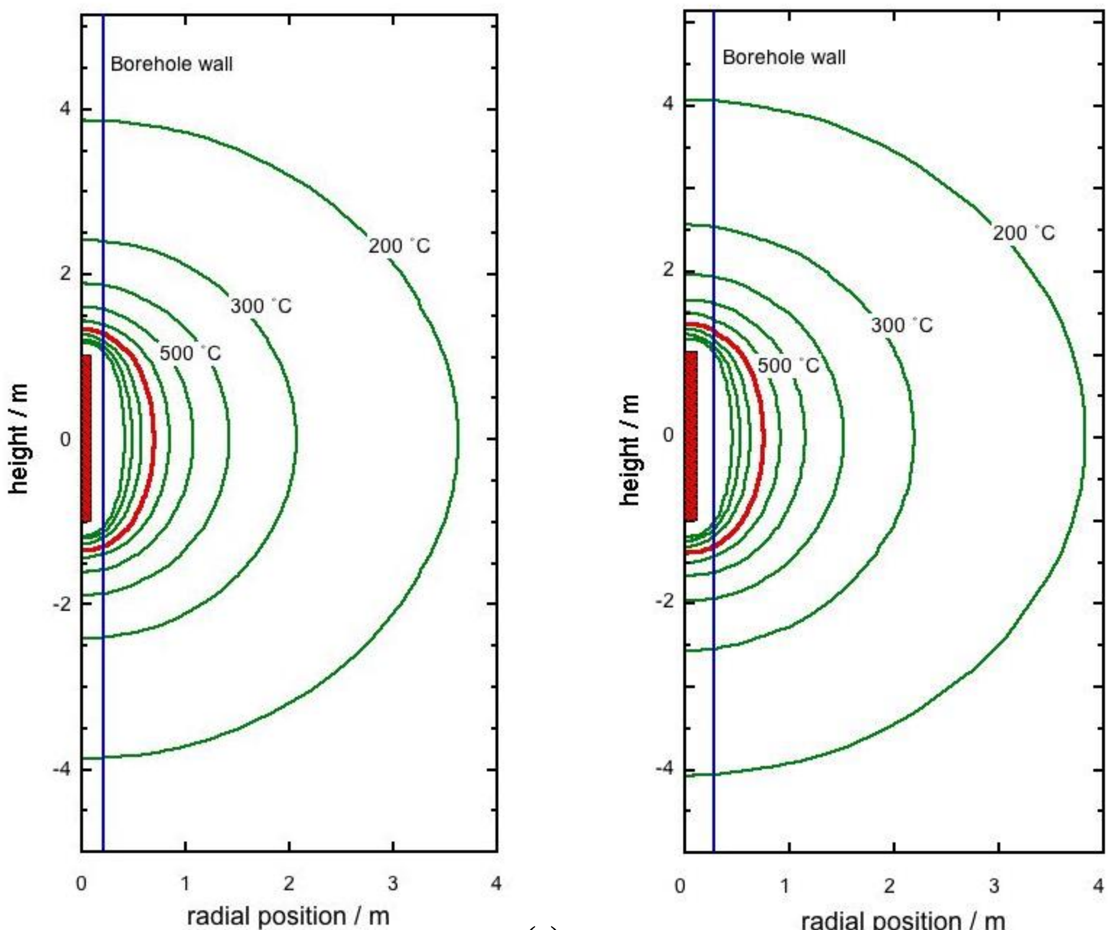
To create a better seal and eliminate the DRZ it has been proposed (Gibb et al. 2008a; 2008b; 2012) that a short length of the borehole, from which the casing has been removed, be backfilled with finely crushed host rock that is then partially melted along with a significant thickness of the wall rock by down-hole electrical heating. On cooling at an appropriate rate the melt recrystallizes to effectively seal the hole and DRZ with material essentially identical to, and continuous with, the host rock – a process that has been referred to as “rock welding”. This could be repeated at intervals, determined by the geology, with the borehole between welds being simply backfilled or, for further “insurance”, sealed with materials such as bentonite or cement. The number, length and positioning of the rock welds can be varied to suit the borehole geology. The ideal location for sealing the borehole is at the top of the DZ a short distance above the uppermost waste package, thus sealing the hole as deep as possible to maximize the geological barrier provided by DBD. Locating the seal(s) above the DZ could entail cutting through concentric layers of casing but doing so in the upper part of the DZ requires removal of only the DZ casing/liner.

Our approach to rock welding R&D began by developing a baseline engineering concept then, using the heat flow software *GRANITE* (Gibb et al. 2008a; 2012), modeling various scenarios to determine the 3-D distributions of temperature with time in and around the borehole. This information is then combined with our knowledge of the melting and recrystallization of granitic rock, refined as necessary, to ascertain the feasibility of creating rock welds of various lengths, shapes and volumes. Data from this process are then used to inform the design of down-hole electrical heaters and their deployment engineering. Beyond this, the concept would proceed to larger scale testing under DBD conditions, including an investigation of properties such as the mechanical strength of the seals, and ultimately to a demonstration in an actual borehole. Given that the weld itself is holocrystalline rock identical in every respect to the host rock (except possibly for minor differences in grain size) there should be no issues about the permeability or longevity of the seal.

The baseline engineering concept involves backfilling the borehole with crushed host rock for a few meters above the topmost waste package then inserting a bridge plug or simple cement plug. Above this plug several meters of the DZ casing/liner is cut or ground away to expose the wall rock and the hole is flushed with fresh water. A concentrated aqueous slurry of finely crushed host rock is emplaced on top of the plug, filling the borehole almost to the top of the exposed wall rock section, and the solids allowed to settle. A sacrificial electrical heating package, which is connected to the surface by an umbilical cord, is then deployed on top of this and allowed to sink a short way into the backfill. More crushed rock is added to fill the borehole for several meters above the heater. A recoverable or sacrificial pressure seal, through which the umbilical cord must pass, is set above the backfill. Power is then supplied to the heater at the required rate to partially melt the enclosing backfill and host rock for an appropriate distance beyond the borehole wall. From what is known about granitic systems (see below) this is likely to require temperatures between 700ºC and 800°C. As melting proceeds, the viscous silicate magma flows into any gaps, reducing the backfilled volume, causing the supercritical fluid phase to migrate upwards and allowing the heater package to settle slightly. During this process the water in the heated part of the borehole is anticipated to remain above its critical point and function as the pressure medium for water-saturated melting. After a prescribed period (days to weeks), the power to the heater is switched off or reduced in a controlled manner so the melt recrystallizes completely by the time it reaches its solidus (~ 550ºC). This should take a matter of months.

It has been demonstrated (Attrill and Gibb 2003a; 2003b) that granite can be partially melted and recrystallized under achievable conditions and on practical timescales in the context of DBD. However, the work of Attrill and Gibb was carried out with a view to high-temperature DBD (Gibb 2000; 2010) under pressures of 150 MPa (1.5 kbar), approximating to the ambient pressure in the continental crust at a depth of 4 km. Until the borehole is sealed and the pressure gradually recovers to ambient values, the pressure at any depth in the hole will be equal only to the weight of the overlying fluid column, which in the case of 3 km of water would be around 29.5 MPa (295 bar). To translate the temperatures generated in rock welding scenarios into meaningful amounts of partial melting it is therefore necessary to repeat some of the experimental work of Attrill and Gibb at lower pressures, the effects of which could raise the solidus by up to 50°C (but probably less). Eventually, when a site and actual host rock have been selected, further experimental work may be needed to refine the data for specific application.

Initial modeling focused on two basic cases – a 0.43 m diameter borehole (Arnold et al. 2011a) and a 0.56 m diameter borehole (Gibb et al. 2012), both with a 2 m long heater having a diameter of 0.4 times that of the borehole. For simplicity in these baseline cases the heater was assumed to be made of homogeneous material with a uniform heat generation, neither of which would actually be the case in practice. The details of the modeling are beyond the scope of this report but the *GRANITE* codes used are being further developed to enable modeling of more sophisticated rock welding scenarios, particularly within the heater itself. However, the initial results (Figures 3-2(a) and 3-2(b)) are enough to confirm that rock welding could be achieved with modest power inputs over realistic times.



(a) (b)

Figure 3-2. Peak temperatures generated in and around a 0.43 m (a) and a 0.56 m (b) diameter borehole by a 2 m long, 0.172 m diameter heater with a power output of 240 kWm^{-3} (a) and 0.224 m diameter with a power output of 150 kWm^{-3} (b) (see text). Isotherms are at 100°C intervals with the 700ºC isotherm (~ granite solidus) in red.

For the cases illustrated, the power densities of the heaters are 240 kWm^{-3} and 150 kWm^{-3}, equivalent to actual inputs of 11.15 kW and 11.82 kW respectively, reflecting the small volume of the heaters. In practice there would be benefits from using larger heaters but there is likely to be an optimum balance between size and cost. The preliminary modeling has highlighted a number of important issues that need to be addressed early in the rock welding R&D program. These include:

- For uniform heat outputs along the length of the heater, temperatures are lower at the top and bottom than in the middle, and the zones of partial melting (the welds) have the shapes indicated by the 700ºC isotherms in Figures 3-1(a) and 3-1(b). It is essential that the melt zone completely encloses the heater, at least around its lower end, but it need only extend far enough out into the backfill and wall rock at the extremities of the heater to ensure the eventual weld has adequate mechanical strength. Provided the weld eliminates the DRZ for a sufficient distance into the wall rock around the middle of the heater, it need not do so along its full length, although the ideal would be for it to do so. It is highly probable that sub-solidus recrystallization (annealing) would re-seal the DRZ for some distance beyond the zone of actual melting but the extent and efficacy of such sealing would have to be determined experimentally.

- The shape and size of the weld can be controlled by varying the length and diameter of the heater, the power input and the distribution of heat output within the heater. A more extensive heat flow modeling study is required to ascertain the effects of such variations and hence to determine how the most appropriate weld may best be generated. The results would then inform the design of a practical heater to achieve such a weld.

- It is clear from the baseline models that there is a possibility that temperatures inside the heater could be unacceptably high from the perspective of the materials available to construct it. To avoid this it will be necessary to consider a range of heater sizes, geometries and differential vertical and radial power distributions within the heater. More sophisticated heat flow modeling will be employed to evaluate the outcomes to feed back into the evolution of heater design and use of the most appropriate materials.

- The isotherms shown in Figures 3-1(a) and 3-1(b) are for the peak temperatures attained in and around the borehole irrespective of the time taken to reach them. The further away from the axis, the longer it takes to reach peak temperature and even at the borehole wall these times can be months or even years (Gibb et al. 2008d). It would not be practical or cost effective to go on supplying power to the heater for the long periods needed to achieve peak temperatures and one objective of the R&D program is to devise heaters that can generate the necessary zones of partial melting in relatively short periods (e.g., a few weeks) before switching off or reducing the power. The next stage of the program would consider such scenarios through the cooling interval to recrystallization.

The design, and eventual construction and testing, of electrical heaters for sealing the borehole by rock welding are key aspects of the research program and the necessary electrical engineering expertise is already involved through collaboration with the Department of Electrical & Electronic Engineering at the University of Sheffield (UK). There is little doubt that suitable heaters can be constructed to operate under the temperatures, pressures and chemical environment of DBD. That the necessary levels of power can be supplied down-hole via an umbilical cord is already known, e.g., by analogy with the electrical power supplied in this way to remotely operated submersible vehicles that function at much greater depths and pressures than in DBD. However, some development work may be required to adapt the technology used for down-hole electrical supplies in the drilling industry to the heavier duty umbilical cords needed and their possible recovery.

Significant progress has been made with the rock welding research program and the essential modeling work continues, as do the investigations of heater designs (with an early focus on resistance heating) and deployment engineering. However, given the importance of sealing the borehole to the viability of the DBD concept, more urgency needs to be attached to the project, particularly the related experimental work on granite melting and the development, construction and practical testing of down-hole heaters. Significant acceleration of these aspects would require increased resources.

3.3.2 Waste Package Sealing and Waste Package Support Matrices

Deep boreholes are potentially suitable for the disposal of a wide variety of high-level wastes, especially SNF, vitrified reprocessing waste and plutonium, and different variants of the DBD concept have been proposed for specific types (e.g., Halsey et al. 1995; Gibb 2000; 2010; Hoag 2006; Gibb et al. 2008a; 2008c; Brady et al. 2009). Common to almost all of these are the use of a cylindrical metal container and the fact that the wastes generate significant, but varying, amounts of heat. For the concept to work the integrity of the containers need survive only until the borehole is sealed above the DZ, but it would be beneficial to the safety case to prolong this far into the future by protecting the containers from the saline groundwater. This could be achieved by inserting an impermeable material – the SSM - into the annulus between the container and the casing and, ideally, the gaps between the casing and borehole wall. Depending on the material used, the SSM could also act as a barrier to the escape of any radionuclides that eventually leak out of the container.

The primary function of the SSM is to prevent (or substantially delay) access of the groundwater to the container, maintain reducing conditions and minimize corrosion, but it also has an important secondary function. It can provide physical support to the waste packages to prevent buckling and load damage to the containers arising from the weight of the overlying stack of, potentially very heavy, waste packages. While it would be possible to design steel containers with sufficient wall thickness to withstand these stresses it would be at a cost and with loss of valuable disposal space. The use of a SSM with high compressive strength would eliminate the need for this or the use of alternative methods of support, such as bridge plugs inserted at intervals up the DZ.

3.3.2.1 High Density Support Matrices

For waste packages that generate high enough temperatures in the annulus between the container and borehole wall the use of a novel high-density support matrix (HDSM) has been proposed (Gibb et al. 2008b). Such packages could contain large numbers of used fuel rods, relatively young used fuel, high burn-up fuel or any combination of these.

The HDSM consists of a Pb-based alloy in the form of a fine shot that is delivered in carefully calculated amounts down the drill pipe (or deployment tube) following the emplacement of each waste package, or batch of packages. The shot will run into all the spaces around and between the packages and, via weight-reducing perforations in the DZ casing, into the gaps between the casing and wall rock. Decay heat from the waste will soon cause the temperature to exceed the solidus of the alloy (~ 185ºC), which will melt to a dense liquid and fill any remaining voids between the container and the borehole wall. Over a period of years to decades, as the heat output of the waste declines, the alloy will re-solidify, effectively "soldering" the packages into the borehole. The use and workings of HDSMs have been discussed at length by Gibb et al (2008b; 2012) and need not be described further here.

For waste packages that do not generate sufficient heat for the use of an alloy HDSM – which could include much of the inventory of older UNF, especially where there is no fuel rod consolidation – an alternative SSM is needed.

3.3.2.2 Cementitious Sealing and Support Matrices

In many mined repository concepts, such as the Swedish KBS-3, the primary barrier around the SNF containers is a layer of bentonite and some DBD concepts have proposed similar material be used to fill the annulus between the waste packages and the casing (e.g., Juhlin and Sandstedt 1989; Arnold et al. 2011a). However, the successful use of a swelling clay like bentonite as a SSM depends on its insertion under pressure into the annulus in a dehydrated state so that subsequent hydration and swelling create a barrier impermeable to water. In a mined repository this is best attempted by using pre-compacted and shaped blocks but the difficulties of doing this are well known and it would be all but impossible to emplace dry bentonite around the waste packages at the bottom of a water-filled borehole. Further, there is a temperature limit (~ 100°C) above which the performance of bentonite as a seal is questionable. Consequently, an alternative material for the SSM in DBD not generating enough heat to use an alloy HDSM would appear to be some form of cementitious grout, as suggested by Woodward & Clyde (1983).

Cements are relatively inexpensive, can be pumped or delivered down-hole in their more fluid forms, remain soft long enough to be emplaced, have good compressive strengths when set and excellent radiation shielding properties. Previously (Gibb et al. 2008a; 2008d; 2012), it was suggested that the cement grout be "pumped down the borehole" via the drill pipe following the deployment of the waste package(s). This assumes the grout would settle into the annulus between the container and casing and, ideally, flow into the gaps between the casing and wall rock before setting. However, the reality is that delivery and emplacement of the SSM are much more complex engineering issues. It is well known that cementing operations are one of the most difficult procedures that the drilling industry has to undertake and success at the depths and pressures of a DBD system will require that a number of specific issues are resolved. Preliminary studies suggest existing, commercially available, cement formulations used by the hydrocarbon & geothermal energy industries (mainly for cementing casing) and their delivery methods are unlikely to be suitable for SSM applications in DBD.

A research program underway at the University of Sheffield (UK) and funded by the Engineering & Physical Sciences Research Council seeks to integrate borehole delivery engineering with a study of cement formulations and their properties. The aim of this program is to come up with a suitable formulation and delivery method such that a cement-based SSM can be successfully implemented in the DBD system for low heat generating wastes. The program began with modeling the dynamic thermal environment of a range of DBD concepts to determine the "conditions of use," i.e., the ranges of pressure, temperature and chemical conditions over which the SSM will have to function. For the initial modeling, a Class G oil well cement with 40% silica flour added was used to simulate the cement SSM.

Figure 3-3 illustrates the evolution of temperatures at the container surface and at the borehole wall for the deep borehole disposal of a single package containing one complete pressurized water reactor (PWR) UO_2 fuel assembly with a burn up of 55 GWd/MT and an out-of-reactor age of 25 years. Figure 3-4 is the corresponding diagram for a batch of five such packages emplaced at one-day intervals. These should be typical of the kind of temperatures likely to be generated in DBD of used UO_2 fuel where no fuel rod consolidation is involved and ambient temperatures in the DZ are relatively low (~ 80°C). The temperatures generated around the waste packages are well below what is required for the use of a Pb alloy HDSM and, unless the ambient temperature is significantly higher, would be appropriate for the use of a cement SSM.

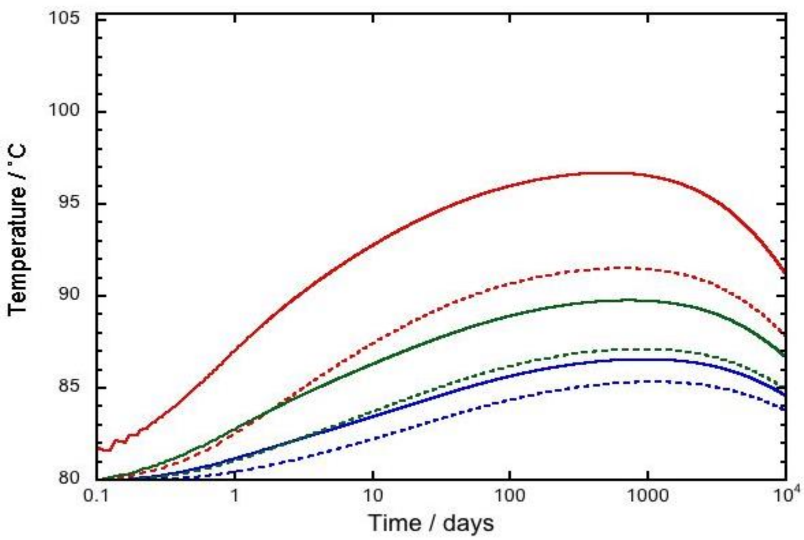


Figure 3-3. Evolution of temperature at 6 points around a single 4.6 m long waste package, 0.36 m in diameter, containing one 25 year old used PWR fuel assembly with a burn up of 55 GWd/MT. Borehole diameter = 0.56 m; ambient temperature = 80°C. Solid lines are for the outer surface of the container; dashed lines are for the borehole wall. Blue = Top of the package; Red = Middle of the package; Green = Bottom of the package.

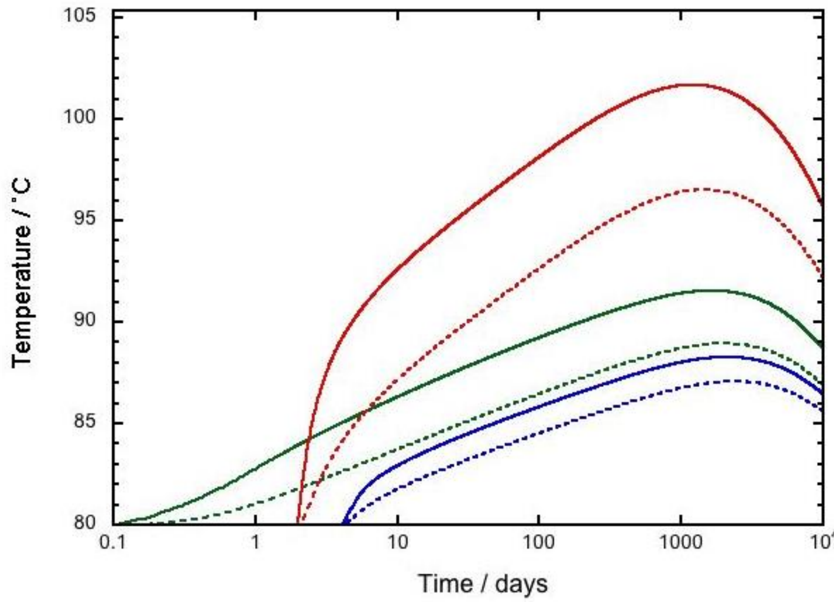


Figure 3-4. Evolution of temperature at 6 points around a batch of 5 waste packages the same as in Figure 3-3 inserted at 1 day intervals. Borehole diameter = 0.56 m; ambient temperature = 80ºC. Solid lines are for the outer surface of the containers; dashed lines are for the borehole wall. Blue = Top of the batch; Red = Middle of the batch; Green = Bottom of the batch.

Two main approaches to the emplacement of the SSM are being investigated. In the first approach the waste package(s) are emplaced, followed by the cement, which then has to find its way into the spaces around the package(s) before setting. In the second, delivery of the cement precedes deployment of the waste package(s), which then has to sink into the cement before it sets. Both approaches would have significant implications for the number of packages that could be emplaced at a time (or in a batch) and for the key properties required of the cement.

For candidate formulations the key properties are being evaluated experimentally using a wide range of physical and chemical tests and measurements and will be compared with the required values of these properties necessary to ensure that the cement can be deployed around the waste packages, fill all the necessary voids, deliver their sealing and support functions and survive on the necessary timescale. The program has identified five such key properties.

- *Rheology.* If the grout is to be delivered after the package(s) via the drill pipe, it must remain sufficiently fluid to be pumped for at least 4 km but dense enough to settle quickly under gravity into the relatively confined spaces around the waste package(s) before setting. Alternatively, if an amount of grout is to be delivered to the bottom of the hole before emplacement of the waste package(s) which then has to sink through the cement, different rheological properties will be required, possibly along with delayed setting. The research program is investigating the rheological properties associated with all options.

- *Setting or Thickening Time.* To provide support for the waste packages the grout must set and develop sufficient compressive strength before too many more packages are emplaced on top. Given that deployments could be less than 24 hours apart (see Section 3.4.2), this could require quite rapid setting. On the other hand, the grout must not set before penetrating and completely filling the annulus around the package (and, ideally, as much of the gap between the casing and wall rock as possible). This might necessitate delaying of a normally rapid set through the use of special formulations or additives, or by developing cement that does not set until a critical temperature is attained. These seemingly conflicting requirements require a thorough understanding and careful control of setting time and other properties.

- *Hardening & Mechanical Properties.* Ensuring the containers can withstand the load stresses in the borehole, especially during filling of the DZ, is a key safety requirement of the concept. Depending on the weights of the packages and the inherent strength of the containers, the grout might be required to have quite high compressive strength when set. Also, if the sealing function is not to be jeopardized, the material used must have a relatively low thermal expansion coefficient, although this is not likely to be a major problem with most cement formulations.

- *Geochemical Reactions.* The grout could react with the container, casing, host rock or groundwater under the high pressure, temperature and chemical conditions encountered. Any such reactions are likely to be minor and of significance only to the long-term containment (sealing) function of the grout but, if they did occur rapidly, they could affect the setting process and mechanical properties of the cement and so must be understood and quantified.

- *Durability.* Once the borehole is sealed above the DZ (by the main seal(s)), it is not essential that the grout continues to support the waste packages, protect them from groundwater and function as a barrier to radionuclide escape. However, from the perspective of the long-term safety case, the longer it continues to fulfill these functions the better. It is therefore important that the durability of the cement and its leaching properties in saline solutions are known and understood.

Evaluation of the candidate cements in the research program against the above guidelines may reveal a suitable material, but it appears likely that improvements will be necessary to develop a formulation that is fit for purpose. Should no such formulation emerge, the project will attempt to develop one that can be taken forward to an experimental testing program and, eventually, to trials in a demonstration borehole, pending additional R&D funding.

3.4 Waste Package Deployment

It is generally assumed that in DBD the waste packages would be deployed singly but it has been suggested that they might be deployed in small batches, separated by time intervals and/or physical spacers (Gibb et al. 2008a) or even in long strings of up to 40 with a total length of nearly 200 m (Arnold et al. 2011a). Emplacement is usually taken to be by lowering on the end of the drill pipe using the drilling rig or a lighter emplacement rig but other, potentially more efficient, mechanisms such as wireline and coiled tubing have been considered (Beswick 2008) and are discussed further below.

For economic, operational and practical reasons, DBD requires that the waste packages can be emplaced at rates of the order of one per day. While the deployment strategy will depend on a number of things, such as the weight of the packages, their heat output, the mechanism employed, the capacity of the emplacement rig, etc., the two main factors controlling the rate at which waste packages can be deployed in DBD are –

- The rate at which the packages can be delivered to the well-head and readied for emplacement, and,
- The time taken to deliver the package down-hole to the DZ and recover the delivery equipment ready for the next emplacement.

3.4.1 Emplacement Rates

For practical reasons related to the emplacement mechanisms, waste packages can only be deployed in DBD by lowering them under tension to the DZ. There can be no question of forcing or pushing them down the borehole, although recoverable additional weight could be added above the package(s) to speed up descent. This places an upper limit on the rate at which they can be lowered equivalent to the rate at which the package(s) would descend in free fall under the influence of gravity alone. This free fall velocity is also an important parameter in the context of accidental release of a waste package during deployment and the operational safety case.

Calculation of the sinking velocity of a cylindrical package in a fluid-filled borehole is not a simple application of Stoke's Law as the "piston effect" or "hydrodynamic damping (or braking)" becomes increasingly important as the diameter of the package approaches that of the borehole or, in the case of DBD, the casing/liner. A series of small-scale experiments have been undertaken to evaluate the effect of the various parameters on the terminal velocity of a metal cylinder sinking in a water-filled tube. By far the most important factor controlling the sinking rate is the clearance between the cylinder (waste package) and the tube (casing) but there is also a relationship between the mass of the cylinder and velocity.

Clearance between the waste package and casing is a crucial parameter for DBD. On the one hand it needs to be as small as possible to minimize the cost of the borehole and maximize the volume of waste that can be put in the container (depending on whether it is the diameter of the container or that of the borehole that is the controlling factor). On the other, it must be kept large enough to eliminate any risk of jamming or damage to the container(s) during descent to the DZ. Suggested values for a suitable clearance tend to be between 2 and 3 cm (Arnold et al. 2011a; Gibb et al. 2012) but the optimum clearance for reliability of emplacement can only be evaluated meaningfully in a full scale demonstration borehole.

Experimental results and calculations reveal that there is a strong linear relationship between clearance and sinking velocity with the velocity tending to zero as the clearance becomes small. Also, as the mass, volume and density of the package increase so too does the sinking velocity for any given clearance but this effect is non-linear and becomes less marked as mass and density increase. Nuclear waste packages for DBD of SNF are likely to have masses between 2,000 kg and 4,700 kg, depending on their construction and contents and it can be estimated that the free fall velocity of such packages in a borehole with a package outside diameter (OD) to casing inside diameter (ID) ratio of 0.85 (Arnold et al. 2011a; Gibb et al. 2012) will lie in the range 0.5 to 1.5 m/sec. For a 4 km deep DBD demonstration this suggests it is likely to prove impossible to deliver packages to the DZ in less than about one hour, although the perforations in the DZ casing/liner would raise the limiting velocity for the last part of the emplacement. The extent of the perforation effect, like the use of any deployment fluid other than water, can only be evaluated properly in a full scale demonstration borehole. In practice, the limiting factor on the deployment rate of waste packages will almost certainly be the mechanism of emplacement, none of which are likely to achieve such rapid descent (see Section 3.4.2).

The rate at which waste packages are emplaced could have implications for the possibility of deploying them in long strings, particularly for high heat generating materials such as relatively young reprocessing wastes and UNF. If it is assumed that the packages are delivered to the DBD site in air-cooled or refrigerated containers, the outside surface of the package should not be significantly above ambient temperature when it is placed into the borehole fluid at the top of the hole. If the package then descends the borehole at a rate of hundreds of m/hr, the flow of fluid past the package should prevent its outer surface temperature from increasing significantly before it reaches a safe depth. If, however, the packages remain immersed in the near-static fluid at the top of the hole for a protracted period while a long deployment string is assembled, there is a risk that the boiling point of the fluid at near-atmospheric pressure could be exceeded with serious consequences. Heat flow modeling (e.g., Gibb et al. 2008d, fig. 5) has shown that for batches/strings of a few containers of relatively young vitrified waste or SNF the temperatures on parts of the package surfaces can increase by over 100ºC in a matter of days when stationary at the bottom of the borehole. The same would be true at the top of the hole where the borehole fluid could boil and create problems. This could place constraints on the time available for assembly of container strings or on the contents of the packages suitable for deployment in this way.

3.4.2 Emplacement Mechanisms

The borehole itself must be constructed and lined such that irregularities or curvature will not affect the emplacement of waste packages either individually or in strings. With the diameter and well construction methods proposed, this should not be an issue but, prior to emplacement, the borehole would be checked by running a caliper and/or a dummy waste package.

Four principle emplacement mechanisms could be considered:

- Free fall
- Wireline
- Use of conventional oilfield drill pipe
- Use of conventional oilfield coiled tubing

3.4.2.1 Free Fall

As reported above, the "free fall" scenario needs to be considered even if only for the remote possibility that a waste package becomes detached from the deployment equipment. This is not an uncommon means of down-hole emplacement in drilling operations and it is the standard method when using wireline corebarrels whereby the inner barrel is replaced by free fall to latch into the outer barrel each sample trip. Rates of decent would depend on a number of factors including the borehole fluid viscosity and the clearance between the waste package and the casing (see Section 3.4.1). However, for deep borehole disposal free fall should not be employed as there is no control on the emplacement.

3.4.2.2 Wireline

The use of a wireline to lower the package has the attraction of simplicity, but its use would limit the weight of the package and it provides less control than the use of drill pipe or coiled tubing. It also carries an increased risk of "hang ups" leading to recovery problems that could be deemed inappropriate for disposal of radioactive wastes. There are two types of line, referred to as "slick line" and "wireline with electrical conductors". Slickline is just a braided wireline in varying sizes. Depth control is maintained at the surface. A wireline with electrical conductors on the other hand allows a waste package release mechanism to be triggered and monitoring data, such as the necessary depth measurements, to be transmitted.

All forms of wireline will stretch much more under load than any metallic tubing and so depth control by reference to casing collar depths previously recorded during installation is essential. The wireline winch system can deliver up to 6000 m/hr but the actual speed of deployment, which will depend on other factors such as the limiting velocity (see above), is likely to be much less. Units are available with combined hydraulic cranes, requiring only a small site set-up area around the borehole.

3.4.2.3 Conventional Oilfield Drill Pipe

This is the traditional means of working within a borehole. It requires a "drilling" or "workover" rig and a relatively large site area. Drill pipe comes in various diameters and steel strengths in 9.45 m or 12 m standard lengths. Deployment with drill pipe is a discontinuous process, in that each length of drill pipe has to be added or removed with each connection being screwed in or out of the next. This is the standard method for drilling and the rigs include various devices for making up, breaking out and torquing the drill pipe to the correct values.

Speed of deployment depends on the height of the rig and whether it is manual or automatic. The traditional "triples" rigs lower or pull three lengths of 9.45 m drill pipe each time (i.e., ~28 m) and rack the pipe stands back in the mast or derrick. There are also a smaller "doubles" variant that pulls two lengths of pipe (~ 19 m) and also "super-singles" rigs that handle one length of 12 m drill pipe.

With conventional rigs this process requires a "derrick hand" working high in the mast to rack the pipe back into finger boards designed to accommodate the size of pipe being used. However, modern rig designs driven by health and safety concerns have eliminated this practice, and hence the need for a person to work in an exposed position, through the use of robotics with various types of pipe handling devices available. Deployment speeds (or "trip speeds") range from 500 m/hr to 600 m/hr for automated systems to typically 1000 m/hr in a cased hole with the best "driller-derrick hand team". The latter requires the team to work efficiently together to enable such fast tripping. For DBD an automatic system would be preferable on safety grounds and modern rigs are becoming more and more sophisticated with the elimination of most of the manual operations.

Using drill pipe, the waste package release mechanism would have to be mechanical, which introduces some uncertainty, but a suitable system could be engineered. Depth control would be through the normal practice of surface monitoring as the drill pipe is run.

3.4.2.4 Conventional Oilfield Coiled Tubing

In recent years the development of coiled tubing systems has been rapid and these systems are now used for drilling, well intervention, logging and well completion operations. A wide range of equipment is available. New systems include electrical conductors through the endless tube allowing commands for release mechanisms and data transmission. The equipment is widely used in different sizes and to depths well in excess of the 4 to 5 km proposed for DBD.

Deployment speeds could be 2000 m/hr to 3000 m/hr with a package release mechanism triggered through some of the conductors in the tubing and data acquisition possible through others. The surface set up would be relatively small and hence more cost effective than maintaining a drilling rig on site at the DBD location. Using this method the risk of radiation exposure to personnel would be kept to a minimum.

The “round trip” for the emplacement of waste packages is not simply a matter of down-hole and return travel times (Schlumberger, 2013). It must also allow for surface operations like attaching the package(s), depth checks and the package release (and any other) procedures that have to be undertaken in the DZ. Conservative estimates of the time required for a single emplacement trip in a 4 km borehole using each of the possible mechanisms are: 8 hours (wireline); 18 hours (drill pipe) and 8 hours (coiled tube). These times for wireline and coiled tube emplacement offer scope for improvement with practice, but at some increased risk, especially for the former where fast running can lead to entanglements. Emplacement of very long and heavy strings of waste packages may require the use of drill pipe but the various advantages of coiled tubing could warrant reconsideration of this long-string strategy towards individual waste package emplacement or smaller strings.

The basic equipment and systems for all of the above options are readily available. There would necessarily have to be some development of nonstandard items, such as the waste package release mechanisms, but development costs would be minimal. Also, consideration would need to be given to the selection of mechanisms and equipment that offer the minimum risk of exposure to people at and around the site.

It is apparent from the study reported above that emplacement of waste packages via the coiled tubing method could emerge as the preferred option and be much more cost effective than the use of a drilling or workover rig. Ideally, the waste disposal organization would own a purpose-designed equipment package so the cost spread over a substantial disposal program would be relatively low. However, for a demonstration borehole or pilot scheme, it would be preferable to utilize the equipment readily available in the drilling industry.

3.5 Seals Demonstration Testing Plan

Ultimately candidate seals and their emplacement must be tested under downhole conditions. In particular, in situ permeability and strength must be measured. This will be done at the demonstration borehole by emplacing constructed seals at depths greater than 2 km and performing standard strength/permeability tests and drilling through the seal after testing. In situ strength will be measured by applying vertical loads via the drill rig itself, or via application of a packer pressure system. In situ permeability testing will be done using a packer system. Seal materials to be tested include traditional materials such as cement and bentonite as well as rock welds.

Verifying emplaceability of seals at > 2 km depth will be central to the seals demonstration effort. Multiple emplacement approaches will be tested for each material, including rock welds, to establish depth effectiveness. For example, bentonite emplacement by containers, plugs, or perforated tubes will be tested. Cement emplacement by balanced plug, cement squeeze, dump bailer, and two plug methods will be tested. Field testing of seals will be done in the final two years of the borehole demonstration.

4. SAFETY FRAMEWORK AND RD&D NEEDS

4.1 Identification of RD&D Needs for Demonstration of Safety

The approach to identifying the science and engineering activities RD&D to support the DBD demonstration first requires identifying a list of potential candidate activities, which are relevant to the DBD demonstration and its objectives and then evaluating this list of potential activities against a set of metrics. This evaluation indicates those activities that best contribute to the success of the DBD demonstration and an understanding of DBD.

The identification step involves three sub-steps: 1) identify objectives of the deep borehole disposal demonstration, 2) identify the relevant features, events, and process associated with deep borehole disposal, and 3) identify potential science and engineering activities needed for the demonstration). These sub-steps are described below.

Deep Borehole Disposal Demonstration Objectives

The DBD demonstration will help resolve key uncertainties about the DBD of nuclear waste and will provide information that permits a comprehensive evaluation of the potential for licensing and deploying DBD for SNF and HLW. This is done in the absence of using nuclear materials. The objectives and tasks of the DBD demonstration have been described previously, (DOE, 2012a), and are briefly summarized below. The four primary objectives are:

1) Demonstrate the feasibility of characterizing and engineering deep boreholes,
2) Demonstrate processes and operations for safe waste emplacement down hole,
3) Confirm geologic controls over waste stability, and
4) Demonstrate safety and practicality of licensing.

The four major tasks that address these goals are:

1) Demonstration Site Selection – This task will locate the demonstration borehole at a site that is representative of the geology and other characteristics that would be encountered if DBD would be implemented in the future. In addition to establishing site selection guidelines, this task also ensures that regulatory permits for borehole construction and demonstration are in place for implementing the DBD demonstration project.
2) Borehole Drilling and Construction – This task will develop a borehole design, establish borehole requirements, implement a contract for construction of the borehole, and ensure that the drilled and completed borehole meets requirements.
3) Science Thrust – This task will identify and resolve data gaps in the deep borehole geological, hydrological, chemical, and geophysical environment that are important to post-closure safety of the system, materials performance at depth, and construction of the disposal system. This task uses a systematic approach to prioritize data gaps and methods for resolving them. This activity will also perform safety analyses demonstrating the safety of the DBD concept for disposal of SNF and HLW.

4) Engineering Demonstration – This task will confirm the capacity and feasibility of the DBD concept and will include canister emplacement operations (in the borehole), canister transference, canister stringing, and operational retrieval. This task will also include design and fabrication of test canisters and other equipment unique to the demonstration. This task will also provide all documentation confirming the safety, capacity, and feasibility of the DBD concept.

FEPs Relevant to Deep Borehole Disposal

A list of potential activities relevant to the DBD demonstration is created by first examining the FEPs that are relevant to the disposal of SNF and HLW in deep boreholes. In Brady et al. (2009) an initial evaluation of FEPs relevant to DBD was conducted. A comprehensive list of 374 FEPs relevant to geologic disposal was examined for relevancy to DBD. In addition to relevancy to DBD, the FEPs were also identified as likely to be excluded from consideration or included in the DBD performance assessment. While this determination is based on scientific judgment, no formal FEPs screening of these FEPs has been conducted and the assessment should be considered as preliminary and requiring supporting justifications. FEPs that are excluded require sufficient justification for their exclusion while FEPs that are included require a sufficient understanding so that they are properly captured and parameterized.

In the FEPs analysis of Brady et al. (2009) excluded FEPs are further qualified according to the level of effort required to make the exclusion argument. Three levels are defined: 1) technical or regulatory basis is readily available, 2) some additional technical work likely is needed, and 3) a significant amount of work is potentially needed. For included FEPs three levels of effort are defined to categorize the level of effort needed to support the inclusion into the PA model: 1) indicates that this is a normal part of modeling, 2) indicates that this is a significant aspect of the modeling, and 3) indicates possible modeling challenges may be encountered.

Identify Science and Engineering Activities Relevant to DBD Demonstration

In the Deep Borehole RD&D Roadmap (DOE 2012a), a preliminary association of potential DBD demonstration activities to the FEPs was presented as an example. This is expanded and re-evaluated in this work. Each of the 374 FEPs identified in Brady et al. (2009) is evaluated for information needs and, if applicable, associated scientific and engineering activities capable of supporting those needs. The result of this association is presented in Table B-1, which associates each proposed science and engineering activity with the FEPs.

Examination of the potential science and engineering activities and the FEPs suggest some commonalities, which help to facilitate the association of science and engineering activities with FEPs. Table B-2 presents commonly occurring groups of science and engineering activities and FEPs that are used in the associations presented in Table B-1. These groupings provide for some consistency in making the associations and also point out the amount of "coverage" the science and engineering activities have in particular technical areas of interest.

As seen in these tables, a total of 45 science and engineering activities are identified. Collectively these activities address 185 of the 374 FEPs. Additionally, it is readily apparent that many of the science and engineering activities address multiple FEPs and multiple science and engineering activities address many of the same FEPs. This apparent redundancy can provide cross-checking of the data collected or can be incorporated as a metric into the prioritization of the activities. The results of the association should still be considered as preliminary because there is a fair amount of subjectivity in assigning of activities to FEPs and more than one opinion should be elicited. This arises because decisions on the degree of relevancy of the association are required.

4.2 Technical Basis for Prioritization in the Safety Framework

The technical bases for the safety framework have been updated or reevaluated relative to previous studies (see Section 4.3) with regard to thermally driven groundwater flow, nuclear criticality and operational safety.

4.2.1 Site-Scale Thermal-Hydrologic Effects

The objectives of the modeling described in this section are to update the thermal-hydrologic model and incorporate more realistic geological and hydrogeological conditions in analyses of thermal-hydrologic effects in deep borehole disposal of used nuclear fuel. Thermal-hydrologic analyses are updated to a reference design for the disposal system (Arnold et al. 2011a) and to examine sensitivities to the number of boreholes in a disposal system array. Additional realism is included with regard to geological layering, variability in model parameters with depth, and coupling of salinity and fluid-density stratification with thermal-hydrologic processes. Simulated thermally driven, vertical groundwater flow rates are important inputs to disposal system model analyses of deep borehole repository safety, which can be updated using the results from these analyses.

Numerous design alternatives exist for a deep borehole disposal system, including borehole depth, diameter, waste canister size, borehole spacing, borehole array size, waste characteristics, and thermal output. In addition, geological and hydrogeological characteristics of the site may vary significantly among potential disposal sites. The analyses for this study were conducted using reasonable disposal system design options and geological conditions that are representative of a stable continental interior and favorable to waste isolation.

The reference deep borehole disposal system design used in this analysis is that developed in a study on feasible design options, general operational procedures, and costs (Arnold et al. 2011a). The reference design consists of a vertical, telescoping borehole design with a 43 cm (17 inch) diameter in the waste disposal zone from 3,000 m to 5,000 m depth. Waste canisters are constructed of carbon steel with a wall thickness capable of withstanding hydrostatic pressures, temperatures, and mechanical stress from overlying canisters during the emplacement and near-term post-closure times. Waste canisters would be emplaced in strings of approximately 200 m length, separated by borehole bridge plugs to support the weight of each canister string. Canisters for the disposal of used nuclear fuel would each contain about 367 PWR fuel rods from the disassembly and consolidation of nuclear fuel assemblies. Used fuel thermal output characteristics are for average PWR fuel (Carter et al. 2011). Following waste canister emplacement, the borehole casing would be removed from the upper 3,000 m of the borehole and a series of seals would be emplaced. Multiple boreholes would be constructed in an orthogonal array with 200 m spacing between the boreholes.

The geological system is assumed to consist of crystalline basement rocks overlain by 1,500 m of sedimentary rocks. The crystalline rocks are assumed to be granite or felsic metamorphic rocks with a similar mineralogical composition. The sedimentary strata consist of horizontal layers of sandstone, shale, limestone, and dolomite. Paleozoic and Mesozoic-age sedimentary units dominated by these rock types cover large areas of the continental interior of North America. Ambient hydrogeological conditions consist of shallow fresh groundwater underlain by stratified conditions of increasingly saline brines with depth. Small-scale, primarily horizontal, groundwater flow may occur in the upper few hundred meters of the sedimentary cover, but no large-scale, regional groundwater flow system exists in the crystalline basement rocks. Furthermore, it is assumed that overpressured conditions resulting from compaction of sediments or from anomalously high heat flow do not exist. Consequently, it is assumed that there is no ambient vertical gradient in fluid potential within the hydrogeological system.

4.2.1.1 Model Setup

The thermal-hydrologic model for the deep borehole disposal system is constructed to provide simulated temperature near the borehole and groundwater flow rates within the borehole and disturbed rock zone, as functions of time. The model domain is large enough to minimize the impacts of lateral boundary conditions on the simulation results near and in the boreholes. As indicated by the results, the grid resolution is sufficiently fine near the boreholes to provide reasonably accurate simulated temperatures near the boreholes and to capture the effects of thermally driven flow near and within the boreholes. However, the grid resolution near the boreholes does not capture the individual components of the engineered disposal system, such as waste canisters, borehole grout, and individual fuel rods. Consequently, the grid resolution is not sufficient to provide accurate estimates of waste canister and fuel temperatures. The thermal-hydrologic model domain uses quarter symmetry, with no-flow boundaries on two sides, to reduce the overall grid size and computational cost of the simulations.

The model grid was constructed using the CUBIT software code (SNL 2012). The 3D model domain is 10 km x 10 km in the horizontal directions and 7 km deep, for a total simulation domain of 20 km x 20 km x 7 km when accounting for the quarter symmetry lateral boundary conditions. The grid is an unstructured hexahedral mesh with progressive grid refinement around the borehole array and individual boreholes. The horizontal grid spacing is less than 1 m at the boreholes and expands to 200 m spacing outward from the borehole array. The vertical grid spacing is uniform 100 m. The grid can accommodate simulation of up to 81 boreholes. This grid consists of 866910 nodes and is illustrated in Figure 4-1.

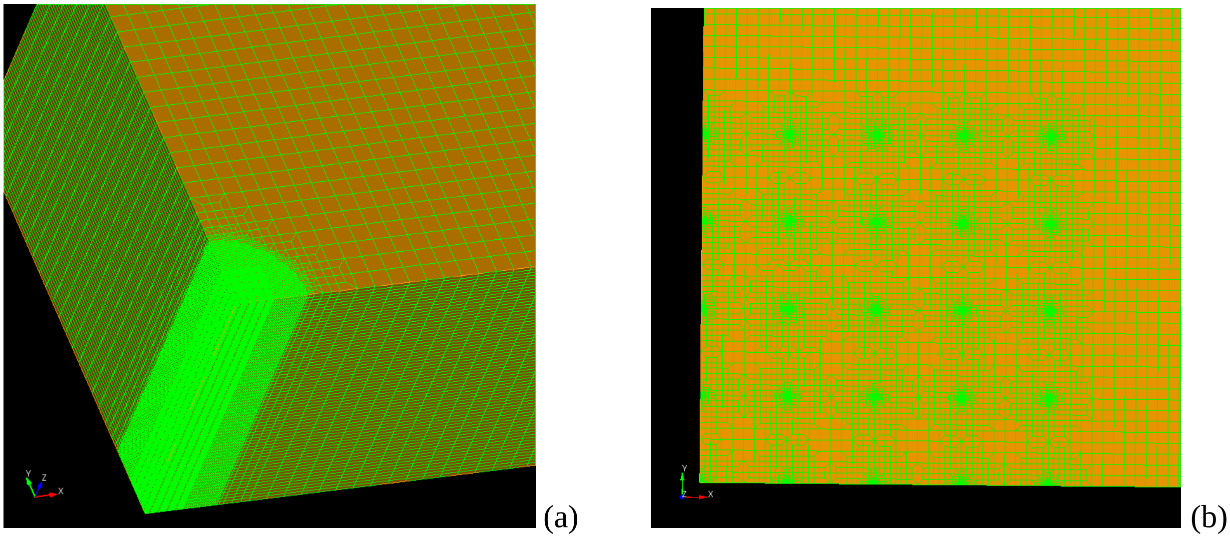


Figure 4-1. Numerical grid for the thermal-hydrologic model from perspective view (a) and expanded top view of the borehole array (b).

The fluid boundary conditions for the thermal-hydrologic model consist of specified atmospheric pressure on the upper surface, no flow at the lower boundary, specified hydrostatic pressure at the far lateral boundaries, and no flow at the reflection, quarter symmetry lateral boundaries. The thermal boundary conditions consist of specified temperature at the upper, lower, and far lateral boundaries, and no heat flow at the reflection boundaries. The upper boundary is set to 10ºC and the lower boundary is set at 185ºC, corresponding to an average geothermal gradient of 25ºC/km. The temperatures at the far lateral boundaries are specified in accordance with the non-uniform equilibrium conduction temperature profile resulting from variations in thermal conductivity (see Figure 4-2). Internal boundary conditions of specified decaying thermal input are set for the waste disposal zones (3,000 m to 5,000 m depth) in the boreholes, according to the waste loading in the reference design (Arnold et al. 2011a) and the characteristics of average used PWR fuel (Carter et al. 2011). The boundary conditions for salinity in the model are specified concentration of 0 weight % at the upper boundary, 30 weight % at the lower boundary, and linear salinity profile at the far lateral boundaries (see Figure 4-3). Initial conditions for the model are hydrostatic fluid pressure, equilibrium temperature profile, and linear salinity gradient.

Parameter values used in the thermal-hydrologic model are generic, but representative of the assumed rock types and are adjusted for depth and ambient temperature in the cases of permeability and thermal conductivity, respectively. The base parameter values for permeability, porosity, thermal conductivity, and heat capacity are shown in Table 4-1. Average permeability of the Earth's continental crust as a function of depth has been estimated on the basis of advective heat transport and advective solute transport in metamorphic reactions (Manning and Ingebritsen, 1999). The resulting relationship of $\log_{10} k = 3.2 \log_{10} z - 14$, where k is intrinsic permeability (m^2) and z is depth (km) is used to calculate adjustments to permeability as a function of depth for granite, as shown in Figure 4-2. Note that the permeability values of the sedimentary rocks at depths of less than 1,000 m are the base parameter values and are not adjusted for depth. The permeability of the nodes at the boreholes was increased by a factor of

10 to account for enhanced permeability in the disturbed rock zone surrounding the borehole and/or for long-term degradation of borehole seals. The central nodes for each borehole are somewhat larger than the borehole diameter and implicitly represent the properties of the sealed borehole and surrounding DRZ, combined.

Table 4-1. Base parameter values used in the thermal-hydrologic model.

Lithology	Permeability (m^2)	Porosity (-)	Thermal K (W/mK)	Heat Capacity (J/kg °K)
granite	1×10^{-14}	0.01	3.0	880.
sandstone	1×10^{-12}	0.30	3.5	840.
shale	1×10^{-15}	0.02	1.8	840.
limestone	1×10^{-13}	0.05	2.7	840.
dolomite	1×10^{-13}	0.05	4.0	840.

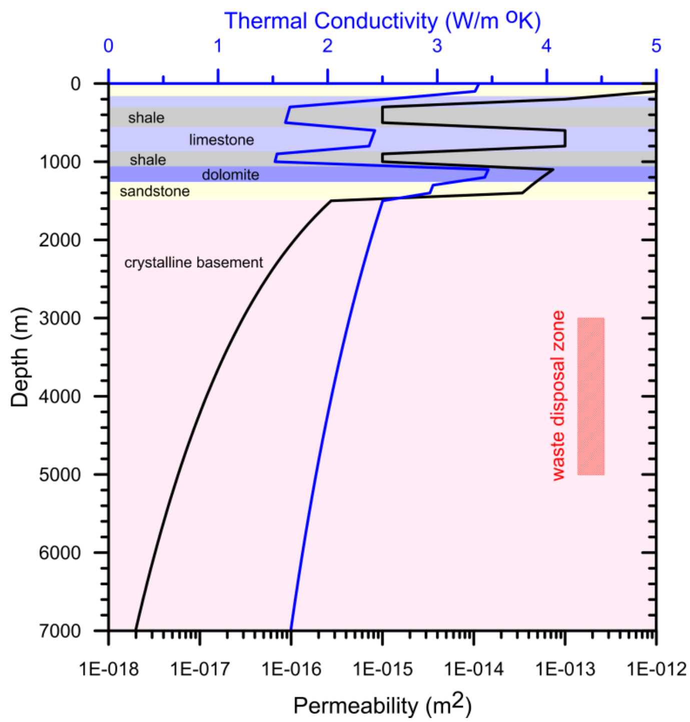


Figure 4-2. Permeability, thermal conductivity, and lithology as functions of depth in the model. Permeability is shown with the black curve and thermal conductivity with the blue curve. The waste disposal zone depth is shown for reference on the middle right of the graph.

Thermal conductivity has been estimated as a function of temperature for crystalline and sedimentary rocks (Vosteen and Schellschmidt 2003). Although the thermal-hydrologic model in this study cannot explicitly implement thermal conductivity as a function of transient temperature, the values of thermal conductivity in the model are specified as functions of ambient temperature, as shown in Figure 4-2 to capture the impacts of variable temperature on thermal conductivity as a function of depth.

Figures 4-2 and 4-3 show the variation in permeability, thermal conductivity, salinity, and simulated ambient temperature as functions of depth in the thermal-hydrologic model domain. These figures also show the stratification in rock type among the sedimentary units in the upper 1,500 m of the model as indicated by coloration and labels and the depth of the waste disposal zone, for comparison. Significant variation in thermal conductivity among the rock types and as a function of ambient temperature result in the non-linear simulated ambient temperature profile shown in Figure 4-3. Note that the permeability varies over many orders of magnitude, in contrast to the thermal conductivity, which varies by only a factor of about two.

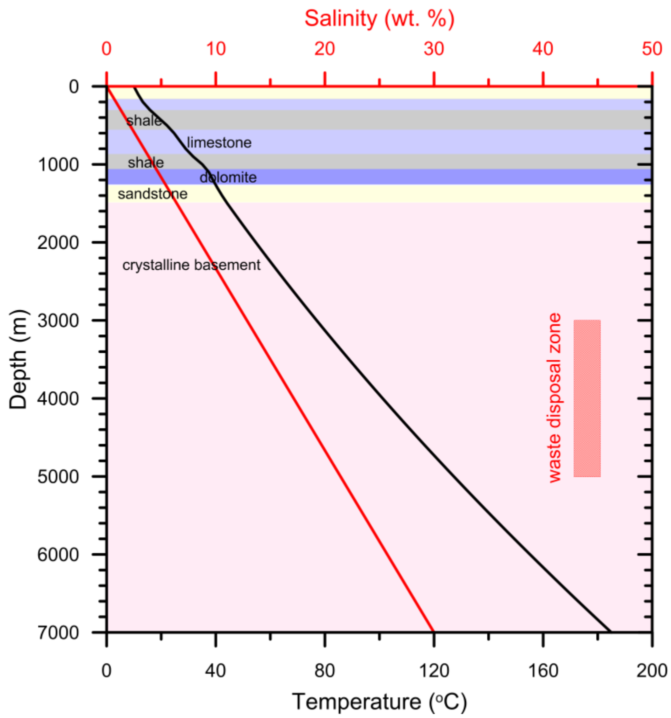


Figure 4-3. Simulated ambient temperature, salinity, and lithology as functions of depth in the model. Simulated ambient temperature is shown with the black curve and salinity with the red curve. The waste disposal zone depth is shown for reference on the middle right of the graph.

Simulations of equilibrium and transient thermal-hydrologic processes were performed using the FEHM software code (Zyvoloski et al. 1997). The full multi-phase (liquid water, steam, and air), non-isothermal solution was implemented in the model with the FEHM code, although single-phase conditions exist throughout the model domain during the simulations. Hydrostatic pressures are high enough at the depths of the waste disposal zone that boiling does not occur from the waste heat. The effects of salinity on groundwater flow are coupled to the thermal-hydrologic solutions through a simple linear relationship between salinity and fluid density. The effects of temperature and salinity on density are additive in their numerical representation in FEHM. The impacts of salinity on thermal-hydrologic flow are further simplified in the simulations by assuming that the overall perturbation to the salinity gradient from convective groundwater flow is small and the salinity concentrations are held constant as a function of depth. This further simplification was required because of numerical instability in the fully coupled solute transport solution.

4.2.1.2 Results and Discussion

Simulated temperatures in the bedrock near the central borehole at 4,000 m depth as functions of time in the thermal-hydrologic model are shown in Figure 4-4. As previous studies have shown (Arnold et al. 2011 and Brady et al. 2009), peak temperatures near the borehole occur within 10 to 20 years of waste emplacement. The change in temperature from ambient conditions to the peak temperature of over 50ºC in this study is significantly higher than the maximum change in temperature of about 30ºC in previous studies, and is primarily attributable to the fuel rod consolidation and increased waste loading in the canisters of the reference design used here. The somewhat lower thermal conductivity of granite at 4,000 m depth in this study also results in higher simulated temperatures, relative to previous studies (Arnold et al. 2011a and Brady et al. 2009). The simulated temperatures for borehole arrays of 1 to 81 boreholes are the same for about the first 100 years following waste emplacement because there is essentially no interaction between the heat from adjacent boreholes at 200 m distance over this time scale.

The simulated temperatures at times of greater than 100 years shown in Figure 4-4 differ significantly among the cases with differing numbers of disposal boreholes in the array. For cases with 25 or greater boreholes, a secondary, lower peak temperature occurs in the time frame of several thousand to 10,000 years, with the temperature and time of the secondary peak increasing with increasing number of disposal boreholes. This secondary peak temperature is consistent with an analytical solution for heat conduction in an infinite array of boreholes (Bates et al. 2012). The secondary temperature peaks result from the interaction of heat from other boreholes in the array. The amount of additional heat introduced to the geological system by the waste is proportional to the number of disposal boreholes. The time scale for interaction of heat among boreholes at several hundred meters distance is much shorter than the time scale for heat to be transported out of the system 2,000 m or greater vertically upward to the ground surface. Consequently, most of the waste heat input remains in the system over the time scale of 1,000 to 100,000 years, as indicated by the secondary temperature peaks.

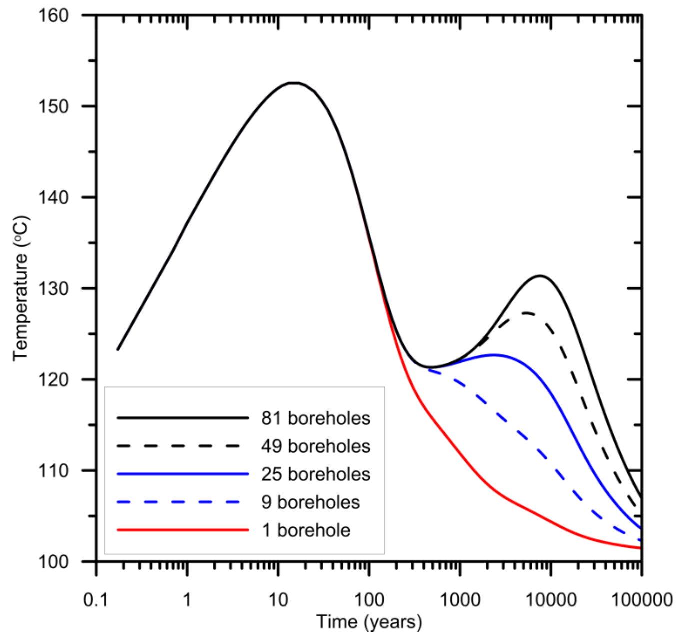


Figure 4-4. Simulated temperature at 4,000 m depth and at 0.8 m radius from the borehole centerline for the central borehole in arrays of varying numbers of boreholes. Results are shown for the disposal of used nuclear fuel rods.

Sensitivity studies are performed to assess the relative contributions of convective versus conductive heat transport in the thermal-hydrologic model and to assess the impacts of the lateral boundary conditions. Comparison of a heat conduction-only model to the thermal-hydrologic model shows very similar simulated temperatures, indicating that heat transport in the thermal-hydrologic model is conduction dominated. This is an expected result, given the low advective groundwater flow rates in the model, as shown in Figures 4-5 and 4-6. The far lateral thermal boundary conditions are changed from specified temperature to no heat flow conditions to evaluate boundary effects. Simulated temperatures in the central borehole are nearly identical for the sensitivity run, indicating that the far lateral boundaries have no impact on the simulation results.

Simulated vertical groundwater flux in the central borehole of an 81-borehole array, as a function of time is shown in Figure 4-5. The different curves show the upward vertical flux for different depths within the borehole nodes. Recall that the permeability in the borehole is increased by one order of magnitude relative to the surrounding bedrock, so these flow rates are higher than in the nearby bedrock. The upward flow rates in the waste disposal zone (-3,000 to -5,000 m) peak within 10 to 20 years following waste emplacement, but show persistent upward flow with a low secondary peak at several thousand years. The earlier peak flow rates are directly caused by the thermal expansion of groundwater and lower flow rates at later times is the result of large-scale buoyant convection. This result is similar to previous modeling results (Arnold et al. 2011b and Swift et al. 2012), but with higher flow rates related to higher values of permeability used in this model and more persistent flow related to the larger number of boreholes in the disposal array. However, long-term upward flow rates are low at about 1 mm/year for depths of 2,000 to 3,000 m (i.e., the 1,000-m borehole zone above the waste). The magnitude and duration of the upward groundwater flow is substantially less at shallower depths, as indicated by the curves for -500 m and -1,000 m in Figure 4-5.

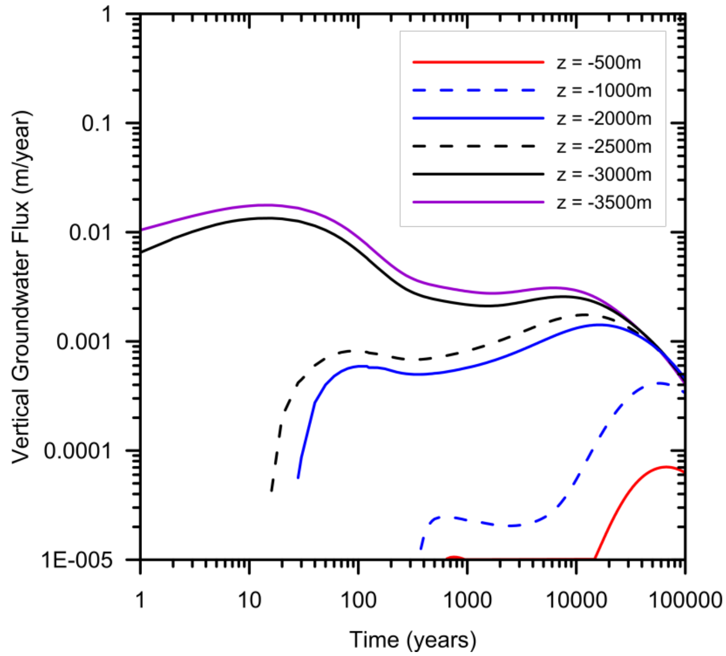


Figure 4-5. Simulated vertical groundwater flux at varying depths in the sealed borehole and disturbed rock zone for the central borehole in an array of 81 boreholes. Results are shown for the disposal of used nuclear fuel rods.

The simulated vertical groundwater flow rates at the top of the waste disposal zone are shown for the central borehole of arrays of varying sizes in Figure 4-6. The highest upward flow rates occur within the first 100 years following waste emplacement for borehole arrays ranging from 1 to 81 boreholes, as directly driven by thermal expansion of groundwater. Small differences in flow rate exist within the first 100 years, with fluxes being higher for greater numbers of disposal boreholes in the array. These differences in flow rate exist in spite of the fact that temperature within the central borehole is not affected by the number of boreholes within the first 100 years (see Figure 4-4). This is because transience in fluid pressure can be transmitted from adjacent boreholes much more rapidly than heat can be transported.

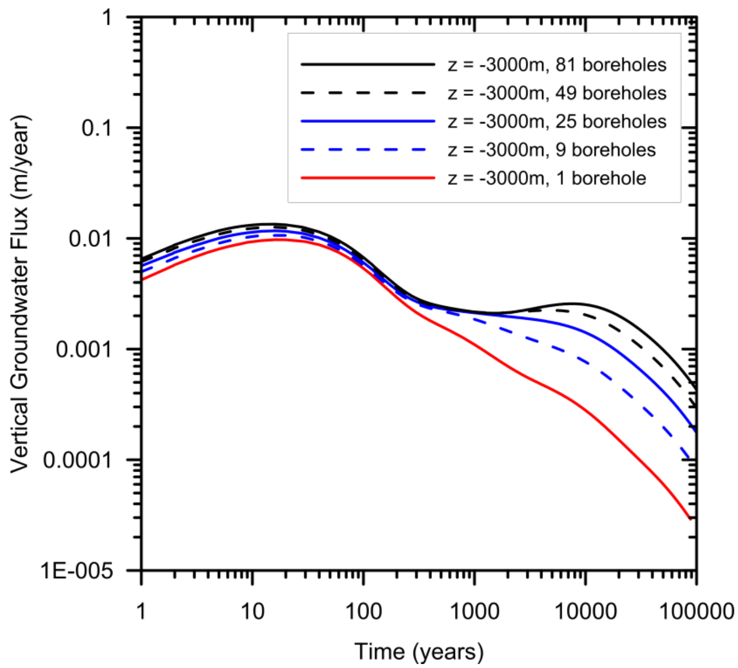


Figure 4-6. Simulated vertical groundwater flux in the sealed borehole and disturbed rock zone at 3,000 m depth for the central borehole in arrays of varying numbers of boreholes. Results are shown for the disposal of used nuclear fuel rods.

At times greater than several hundred years following waste emplacement, the number of disposal boreholes in the array has a significant impact on simulated vertical groundwater flux, as shown in Figure 4-6. Late-time vertical flow rates are greater for greater numbers of boreholes, and cases with more than 25 disposal boreholes exhibit a secondary lower peak vertical flux. Greater numbers of disposal boreholes in the array and the proportionally greater heat input to the system creates more vigorous and sustained buoyant convective flow. Note the log scale on the time axis in Figure 4-6 and the relatively large cumulative impact on total vertical groundwater flow for varying numbers of disposal boreholes for times of 1,000 to 100,000 years.

Results indicate an extended period of elevated temperatures beyond 1,000 years following waste emplacement for arrays with more than 9 disposal boreholes, with a secondary peak temperature occurring at several thousand to 10,000 years. Simulated vertical upward groundwater flux in the borehole and disturbed rock zone occurs in the waste disposal zone for an extended period of time. Significant, but lower vertical flux also occurs above the waste disposal zone through potentially degraded seals and/or the surrounding disturbed rock zone. The persistence of simulated vertical groundwater flow beyond 1,000 years increases with the number of disposal boreholes in the array. It should be noted that the upward vertical flow rates in disposal boreholes on the edges of the borehole array are smaller than the values for the central borehole presented here.

Sensitivity of the model to permeability as a function of depth was examined by constructing a version of the thermal-hydrologic model in which an alternative relationship between permeability and depth was implemented. Stober and Bucher (2007) developed an alternative model of the permeability-depth relationship based on data from well testing in crystalline rocks in the Black Forest region of Germany. This relationship, which is corrected in Ingebritsen and Manning (2010), is $\log_{10} k = -1.38 \log_{10} z - 15.4$, where k is intrinsic permeability (m^2) and z is depth (km) and results in lower values of permeability in the range of 0 to 5 km than the relationship of Manning and Ingebritsen (1999). A comparison of the thermal-hydrologic modeling results from the two permeability-depth relationships is shown in the plot of vertical groundwater flux versus time in Figure 4-7. As shown, the vertical flow rates at a depth of 3,000 m are a factor of two to three times lower for the Stober and Bucher (2007) relationship, which may be more representative of conditions for deep borehole disposal in crystalline rocks than the average crustal relationship of Manning and Ingebritsen (1999).

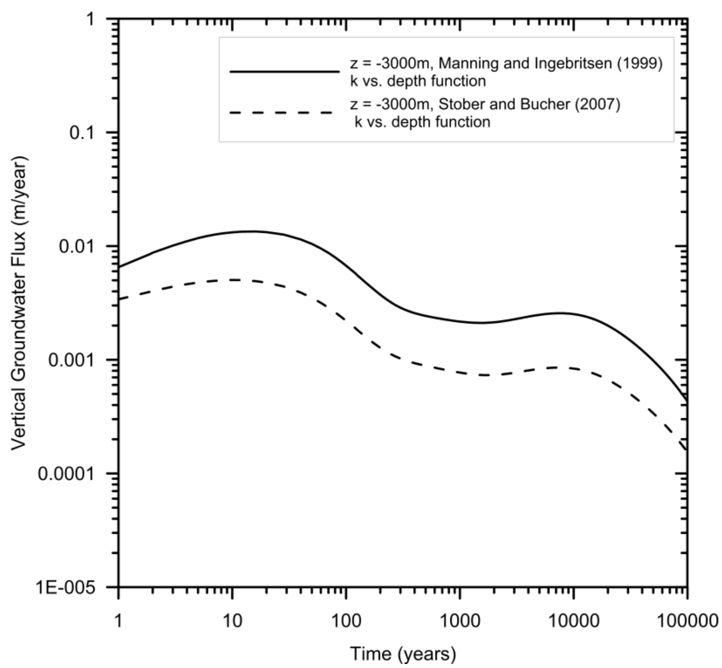


Figure 4-7. Simulated vertical groundwater flux in the sealed borehole and disturbed rock zone at 3,000 m depth for the central borehole an array of 81 boreholes for alternative models of permeability as a function of depth. Results are shown for the disposal of used nuclear fuel rods.

These results may have important implications for the maximum number of disposal boreholes that could be safely emplaced at a single site. Persistence of upward groundwater flow for periods of time on the scale of tens of thousands of years, even at very low rates could impact repository performance. The increased long-term vertical groundwater flux with increasing number of disposal boreholes means that radiological dose would not scale linearly with the number of the boreholes in the array and the total radionuclide inventory at the deep borehole site. Instead, dose would scale by number of boreholes and by the cumulative groundwater flow associated with greater vertical groundwater flux. The thermal-hydrologic modeling results in this study can be the basis for additional disposal system modeling to analyze these effects.

4.2.2 Borehole-Scale Thermal-Hydrologic Effects

Borehole-scale thermal-hydrologic effects interact with the site-scale thermal-hydrology discussed above, but are more specific to the borehole design, engineering and operational practice. Borehole-scale effects focus on the regions between the emplaced waste, including the waste package, the borehole liner (if any), the borehole wall, and the region of rock near the borehole potentially altered by drilling and emplacement operations, grouting, and the post-emplacement thermal transient from the waste decay heat (i.e., the EBS, DRZ, and surrounding thermally impacted host rock).

An example issue is to understand the conditions that could enable significant vertical migration of radionuclides. Such conditions may include vertical crevices or gaps between the waste and the host rock that provide a vertical flow pathway, and the potential for inflow of water from the nearby host rock that could feed vertical flow driven either by thermal buoyancy or thermal expansion of crevice/gap water. As example would be lamellar corrosion of the waste package wall or a liner (if present) that creates crevices oriented along the borehole axis. Other examples could include incomplete grouting between the waste package and borehole wall or spallation of the borehole wall. The potential for such small-scale crevice transport can be addressed through a combination of modeling, laboratory testing, material selection and field test verification.

Questions include how the engineered materials or thermal effects may (1) create preferential flow pathways within the DRZ and disposal boreholes and (2) augment thermal-hydrologic (TH) flow and radionuclide migration within those pathways, as well as within the intact rock. Representing the engineered system in its disturbed state is important, including formation of corrosion products, such as lamellar structures on waste packages. A high-fidelity ‘near-field scale’ TH modeling approach is required to improve understanding of physical processes and conditions most strongly affecting heat-augmented radionuclide migration. The large number of parameters and conceptual-model issues to be addressed necessitates this approach being computationally efficient. In addition to parameters considered in past TH model sensitivity analyses, it is important to address those that characterize preferential pathways. These parameters include the geometries (radial extent) of the DRZ, borehole and waste packages, and those of other engineered materials in the borehole, as well as the range of possible effective porosity and permeability anisotropy. Spatially, the grid should be refined enough to resolve TH conditions within the DRZ, boreholes, and waste packages. The grid should account for the telescoping borehole geometry, individual waste packages, wellbore casing and liners, grout, and seals. Because of the importance of the thermal expansion of brine, variability in fluid and rock compressibility should be addressed. Full coupling of the influence of salinity and temperature on water density is needed, as is the ability to address water density profiles that do not necessarily monotonically vary with depth.

In effect, understanding and avoiding the potential for borehole-scale effects assures that the long-term isolation addressed by the site-scale modeling is not “short circuited” by small-scale processes in or near the borehole. A reasonable approach is to represent TH processes using a 2-D radially-symmetric (RZ) model geometry that can be “embedded” in the site-scale modeling, rather than use a full 3-D model, such as the simulation methods used in Section 3.3.1 and Gibb et al. (2008a). This dramatically reduces computational expense, while allowing for fine grid resolution in the radial and vertical directions, within the borehole and the DRZ, which enables representing waste packages of different heat output. To explore the boundaries of crevice effects, this model should able to use grids in the sub-millimeter scale where needed. The model would also be able to represent degraded or failed waste packages and their potential influence on local transport processes. The model can also represent locally the details of the zones between waste packages or strings of waste packages, as well as near seals and the interface with the isolation zone above the uppermost packages. This efficiency makes it possible to address computationally challenging physical interactions, such as the influence of temperature and salinity on brine density. Such 2-D RZ models have been validated for regular well patterns used in geologic CO_2 sequestration and in geothermal systems. The borehole-scale model must interface with the site-scale model discussed in the previous section. It can spatially resolve the geometry of the engineered system, both in its original and disturbed states, and address questions about the importance of respective EBS components to radionuclide isolation, which will provide useful guidance in identifying and prioritizing laboratory- and field-scale testing activities. This model can also address detailed thermal management questions, such as how waste packages of differing heat output can be arranged to assure isolation performance.

It is expected that the primary information on borehole-scale effects and the evolution of emplaces materials can be demonstrated in laboratory testing, with eventual field verification focused on assuring the validity of the modeling assumption and testing conditions. Field-testing will also demonstrate the reliability of operational processes for emplacing (and removing) the engineered materials that dominate these borehole-scale performance issues.

4.2.3 Nuclear Criticality

Deployment of DBD will require assurance that nuclear criticality can be precluded at all times, including surface operations as well as under long-term post-emplacement conditions when the container and fuel become degraded. It has been proposed (Brady et al. 2009, Section 4.3) that criticality may be excluded at the stage of FEPs screening for DBD. The demonstration project RD&D program should include analysis to confirm such exclusion, along with definition of any design, operation or site parameters that are needed to assure such exclusion.

Criticality safety is not a design, operation or permitting issue for conducting the demonstration project, because the use of actual nuclear fuel is not anticipated. Thus, criticality safety during RD&D is limited to conducting any analyses required to inform a transition from demonstration to deployment, and to define any information needed from the demonstration testing.

Analysis will be performed during the RD&D program to provide a basis for criticality safety assurance for DBD deployment. Because anticipated DBD waste canisters contain a single fuel assembly, criticality safety assurance during normal handling operations and plausible abnormal conditions can be demonstrated using standard analysis similar to those used for handling fresh low enriched uranium (LEU) reactor fuel.

The primary criticality concern for DBD is to preclude any plausible scenarios for criticality in the long-term post-emplacement period. A single fuel assembly remains subcritical even when flooded with moderating water. Thus, any potential criticality scenario would require re-distribution of fissile material within a container, and potentially between multiple containers in an emplacement string. If criticality exclusion relies on one or more DBD design or site feature, then those features should be demonstrated in either laboratory or field testing or demonstration.

These features could include a container design that limits achievable uranium-water concentrations or restricts material re-distribution, or a groundwater composition that limits criticality (either natural or as modified by the borehole and contents).

Analysis during the DBD demonstration project will define the parameter space of possible criticality, and identify design and site features that can assure that DBD operates beyond any plausible criticality scenario. Most or all of the information needed will be obtained by lab and field testing. Any additional design, operational, or site characteristic data needs that are identified specifically for criticality control will be added to the demonstration and testing program.

4.2.4 Operational Safety Assessment

Operational safety for DBD operations can be divided into two categories. First is the conventional industrial safety for site operations, primarily the drilling operations and the handling of drilling materials. Second is the nuclear operation safety of handling and emplacing highly radioactive used nuclear fuel or high-level radioactive waste.

The conventional industrial safety requirements for a field demonstration will be very similar to the conventional operational safety requirements for actual disposal operations. The drilling and material handling for a full-scale field demonstration borehole is comparable to an operating disposal borehole. These conventional operations will be subject to existing drilling safety institutional controls: laws, regulations, standards and practices – at Federal, state and local levels. Other than demonstrating compliance with these controls and demonstrating safe operations at the field demonstration, there are little or no additional data needs for this aspect of operational safety.

The nuclear operational safety issue is similar to the criticality issue discussed above. As there will not be radioactive material emplaced in the field demonstration, there will not be actual nuclear operational safety issues. However, the demonstration should begin to address the questions of how nuclear operations would be conducted in an actual disposal operation, where the nuclear safety issues are significant. In current design concepts, the waste packages are not self-shielded, and thus have very high external radiation levels. This requires the waste package handling equipment and the emplacement operating area to have heavy shielding, and forces remote operation at the borehole surface facility. Contrary to common drilling practice, the emplacement string of waste packages will have to be remote assembled and the wellhead operations would be "hands-off". A significant challenge will be to assure that the range of potential 'off-normal' operating conditions can be managed without having to expose workers to the emplacement string, as even short exposures are not likely to be acceptable. In common industrial practice, even where routine operations have become highly automated, hands-on troubleshooting for off normal conditions is typically assumed, and this will not be possible where an exposed waste package is present. Placing as much equipment as possible in shielded areas, as well as mobile temporary shielding for specific operating conditions, may be required in the DBD design.

The field demonstration does not need any shielding, but could endeavor to incorporate and demonstrate aspects of remote handling and emplacement. It is not necessary for all of the demonstration operations to be conducted in this manner, just a demonstration that remote handling is conceptually possible. This capability will add cost to the demonstration facility, implying that the extent of remote operation used in the demonstration project will be part of the cost-benefit trade-off to be determined during detailed planning for the field demonstration. It is also likely that some (or even all) of this remote handling can be demonstrated in a 'near-surface' industrial facility that could be less expensive than demonstration at the DBD field test itself. The information obtained from such field or industrial-site demonstrations will be useful in DBD design and planning, and it is possible that the need for high-confidence remote operations will constrain the design of the waste packages and the 'concept of operations' for an operating DBD site.

4.3 Analysis of Performance Assessment Results

A systematic approach to identify and prioritize science and engineering needs during the demonstration phase of the DBD concept was described in the Research, Development, and Demonstration Roadmap for Deep Borehole Disposal (DOE 2012a). This section presents a synthesis of previous PA studies that supports the importance metric in the prioritization methodology. These analyses have been limited to undisturbed (in the absence of external events) post-closure performance.

4.3.1 Deep Borehole Disposal of High-Level Radioactive Waste Study

A preliminary safety assessment using an analytical solution of the advection-diffusion equation was conducted in Brady et al. (2009) conditioned on thermal-hydrologic calculations, which indicated that vertical transport was limited to a short thermal period. These DB-PA results are based on several bounding and conservative assumptions, such as: (1) all waste is assumed to instantly degrade and dissolve inside the waste canisters; (2) all waste is assumed to be PWR assemblies; and (3) no credit is taken for sorption or decay along the saturated zone transport pathway from the sealed borehole to the withdrawal well calculated to take 8,000 years.

Sealed borehole properties representative of bentonite in conjunction with the thermally driven driving pressure produced an upward fluid pore velocity of 0.502 m/yr and a corresponding 1000 m borehole travel time of 1990 years for an unretarded radionuclide.

Radionuclide transport up the borehole from the source (waste disposal zone) occurred for approximately 200 years, corresponding to the duration of the thermally driven flow. Subsequent to the thermal period, ambient conditions were not expected to provide any upward gradient, and upward radionuclide transport was assumed to cease. The only radionuclide with a non-zero concentration 1000 m above the waste disposal zone in the sealed borehole was ^{129}I, which is the only radionuclide that had no retardation in the analysis. The non-zero ^{129}I concentration (5.3×10^{-8} mg/L) represented the leading edge of the dispersive transport front. However, the center of mass never reaches the top of the 1000 m sealed section of the borehole because there was no further movement after 200 years. The total dose to the reasonably maximally exposed individual (RMEI) at 8,200 years was 1.4×10^{-10} mrem/yr.

Some high-level conclusions from Brady et al. (2009), relevant to the deep borehole demonstration activities are:

1) The coupled thermal-hydrologic-chemical-mechanical behavior of the borehole and disturbed region during the thermal pulse, and in the presence of density-stratified waters, should be modeled more accurately.
    a. **High** PA metric rating for Science Activities: Temperature Log, Waste Canister Mockup Electrical Heater Test, Fluid Samples from Packer Testing, Drill Cuttings, Intermittent Coring, Chemical Equilibrium Modeling, TH Modeling, Conceptual Model Design, Numerical Model Implementation of Sub-Models, Construction of System Model.
    b. **Moderate** PA metric rating for Science Activities: Chemical Kinetics Modeling
2) Additional consideration should be focused on the design and long-term performance of deep seals.
    a. **High** PA metric rating for Science Activities: Fluid Samples from Packer Testing, Seals Integrity Testing and Cement Degradation Testing and Engineering Activities: Demonstration of Casing Emplacement, Demonstration of Liner Emplacement, Bentonite Seal Emplacement, Cement Seal Emplacement.
3) Modeling of the full-system performance of multi-borehole arrays should be undertaken, consistent with an assumption that a regional borehole disposal facility could entail an array of 10 to 100 individual boreholes.
    a. **Moderate** PA metric rating for Science Activities: Multi-Well Hydraulic Testing, Cross-Hole Tomography, Multi-Borehole Modeling.

4.3.2 Deep Borehole Seals Study

A preliminary performance assessment model for the deep borehole disposal system was used to analyze the relationship between the effectiveness of the borehole seals and risk to human health using Monte Carlo sampling for propagating uncertainty (Herrick et al., 2011). The objective of this analysis was to determine the maximum effective permeability of the borehole seals and the surrounding DRZ that would result in an acceptable level of risk, as estimated by radiological dose.

In the disposal system model, the waste-disposal zone contained 400 waste canisters in the lower 2,000 m of the 5,000 m long borehole. The upper 3000 m consisted of a 1000 m seal zone of bentonite directly above the waste zone and a 2000m upper zone extending to the surface consisting of backfill. Waste canisters were surrounded by bentonite grout and strings of canisters were separated by bridge plugs and compressed bentonite plugs. Flow and radionuclide transport occurred in the waste-disposal and seal zones with an effective 1 m^2 cross-section that included the borehole, canisters, grout, seals, and the surrounding DRZ. Twenty FEHM simulation runs were carried out with different rock and disturbed zone permeability values for the SNF assembly waste.

Results from a detailed the thermal-hydrologic model were coupled to the generic deep borehole disposal system model. The thermal hydrologic simulations assumed 9 boreholes with borehole spacing of 200 m. For the sensitivity study, 20 different host rock and effective seal/disturbed rock zone permeability combinations were investigated. Thermal-hydrologic simulations were conducted for three major types of waste, as summarized below.

Commercial Spent Nuclear Fuel (CSNF): Flow at the top of the waste disposal zone generally decreases throughout time. Some permeability combinations decrease continuously, while others have a peak around 10 years and then decrease continuously. The only exceptions to these trends are those cases with a host rock permeability of 10^{-19} m^2. In each of these exceptions, upward flow decreases continuously and turns downward between 2,000 and 10,000 years after which upward flow resumes at a lower velocity and then decreases continuously to 1,000,000 years. Initial upward flow varies between 10^{-4} m/yr and 10 m/yr and either turns downward or declines approximately 4 orders of magnitude by 1,000,000 years. Each order of magnitude decrease in permeability of the intact rock or DRZ results in approximately an order of magnitude drop in upward velocity.

The temperature profiles at the top of the disposal zone associated with all of the 20 permeability combinations are nearly identical beginning at an ambient temperature of 85°C and peaking about 50°C higher and then declining asymptotically back to ambient after about 100,000 years. The similarity in temperature profiles for all permeability combinations indicates that the heat flow is conduction dominated. This may be due to the fact that convection occurs mainly around the narrow borehole and excavated rock zone region, while conduction could occur in the larger intact rock. Additionally, temperature and vertical groundwater flux in the host rock decreases rapidly with increasing horizontal distance from the borehole. Vertical groundwater flow rates in the borehole also decrease rapidly with vertical distance above the waste disposal zone.

High Level Waste: Simulations were also carried out for DOE defense HLW. For this waste type simulations were conducted for the base case and upper bounding permeability values only. Compared to CSNF, upward vertical flow rates at the top of the disposal zone for HLW are about two orders of magnitude lower, and significant vertical upwards flows do not extend beyond several hundred years. This can be attributed to the lower heat output of the HLW, as evidenced by the lower temperature rise only a few degrees higher than the initial condition, in contrast to the 50 °C rise for the SNF assembly waste.

Reprocessed Waste: Simulations were also carried out for reprocessed waste (RW). The groundwater fluxes for the reprocessed waste are slightly higher than those for the SNF assembly waste. The peak temperature is about 90 °C higher than the initial condition. As with CSNF and HLW, the reprocessed waste shows little temperature changes as a result of permeability changes.

Table 4-2 summarizes the results from the six cases reported, which considered two inventory cases: CSNF and DOE HLW and two disposal system cases: a Base Case and a Seal Degraded Case, and cases with or without the sorption of iodine.

Table 4-2. Summary of Results from Herrick et al. (2011)

Case	Iodine Sorption	Waste Type	Peak Dose Rate: mrem/yr	Time of Peak: yr	Notes
Base	No	CSNF	10^{-14}	1,000,000	
Base	Yes	CSNF	No release	NA	
Base	Yes	HLW	No release	NA	
Degraded	No	CSNF	3×10^{-2}	10,000	
Degraded	Yes	CSNF	2×10^{-3}	1,000,000	^{36}Cl dominates between 1,000 and 100,000 yrs. ^{99}Tc, and ^{79}Se also contribute.
Degraded	Yes	HLW	3×10^{-8}	1,000,000	

Some high-level conclusions from Herrick et al. (2011) relevant to the deep borehole demonstration activities are:

1) Heat load is a driver for upward flow of fluids and thermal conduction into surrounding host rock greatly dominates heat transfer mechanisms.
    a. **High** PA metric rating for Science activities: Source Term Modeling, TH Modeling, Construction of System Model, Waste Canister Mockup Electrical Heater Test, Temperature Log, Drill Cuttings, Intermittent Coring
2) Upward flow rapidly diminishes with distance above the disposal zone
    a. **High** PA metric rating for Science activity: TH Modeling
3) Seal permeabilites on the order of 10^{-16} m^2 are sufficient to limit releases and seal integrity is a dominant driver for releases to the biosphere.
    a. **High** PA metric rating for Science activities: Fluid Samples from Packer Testing, Seal Integrity Testing, Cement Degradation Testing and Engineering Activities: Demonstration of Casing Emplacement, Demonstration of Liner Emplacement, Bentonite Seal Emplacement, Cement Seal Emplacement
4) ^{129}I dominates radioactive releases and sorption of ^{129}I greatly reduces or eliminates release.
    a. **High** PA metric rating for Science activities: Source Term Modeling, Chemical Equilibrium Modeling, Fluid Samples from Packer Testing, Radionuclide Characterization, Seal Zone Sorbent Testing

4.3.3 Generic Disposal System Modeling Fiscal Year 2011 Progress Report

A preliminary safety assessment and some supporting system and sub-system sensitivity analyses of deep borehole disposal were conducted by Clayton et al. (2011). In these analyses, uncertainties in parameters were characterized and propagated through system and sub-system models using Monte Carlo sampling of the uncertain parameter distributions. The flow rate histories were obtained from detailed thermal hydrologic model results and coupled to the system model.

A total of six sensitivity analyses were conducted considering two inventory cases, CSNF and DOE HLW, and three disposal system cases, a Base Case, a Seal Degraded Case, and a Seal Degraded Case with iodine sorbent. Table 4-3 summarizes the results of the analysis.

Table 4-3. Summary of Results from Clayton et al. (2011)

Case	Waste	Rock k (m^2)	DRZ k(m2)	Max Flux[1] (m^3/yr)	Max Flux[2] (m^3/yr)	Mean Mass Flux[1] ^{129}I (g/yr)	Mean Mass Flux[2] ^{129}I (g/yr)	^{129}I Dose the biosphere (mrem/yr)
Base	CSNF	$1\ e^{-19}$	$1\ e^{-16}$	$5e^{-2}$	$2e^{-4}$	$2e^{-4}$	$8e^{-10}$	$5e^{-9}$
Degraded	CSNF	$1\ e^{-16}$	$1\ e^{-12}$	$6e^{+1}$	$2.5e^{+1}$	$8e^{-3}$	$8e^{-3}$	$7e^{-2}$
Degraded/ I Sorbent	CSNF	$1\ e^{-16}$	$1\ e^{-12}$	$6e^{+1}$	$2.5e^{+1}$	$8e^{-3}$	$2e^{-6}$	$1e^{-5}$
Base	HLW	$1\ e^{-19}$	$1\ e^{-16}$	$1e^{-3}$	0	$4e^{-5}$	$1e^{-9}$	$9e^{-9}$
Degraded	HLW	$1\ e^{-16}$	$1\ e^{-12}$	$1.5e^{0}$	$4e^{-3}$	$1.5e^{0}$	$8e^{-1}$	$1.5e^{0}$
Degraded/ I Sorbent	HLW	$1\ e^{-16}$	$1\ e^{-12}$	$1.5e^{0}$	$4e^{-3}$	$1.5e^{0}$	$<1e^{-12}$	$<1e^{-12}$

[1] At top of Disposal zone

[2] At top of Seal zone

Base Cases:

CSNF: Upward advective water flow rates are very small, and diffusion is the dominant mechanism to transport dissolved radionuclides in the disposal and seal zones. ^{129}I is the dominant dose contributor, but the calculated radionuclide mean doses are negligibly small.

DOE HLW: The flow rate histories are different from those for the commercial SNF inventory for the same values of permeability because of the different decay heat output characteristics between the two waste types. For the disposal zone, no upward water flows exist anywhere after about 20,000 years, and upward water flows stop at about 300 years near the upper portion of the zone (at depths of 3,000 and 3,100 m). In the seal zone no upward flows exist after about 2,000 years. The lack of upward water flow has significant impact on the radionuclide transport, implying that slow diffusion processes will be the dominant transport mechanism to move dissolved radionuclides toward the biosphere located at the surface. ^{129}I is the only dose-contributing radionuclide, and the calculated mean doses are negligibly small.

Seal Degraded Cases:

CSNF: Sensitivity analyses were conducted to evaluate an assumed condition with a much higher permeability for the system components than the base case permeability. The high permeability case represents a conservative condition, for which the system components (e.g., host rock, disturbed rock zone, seals, etc.) have grossly failed, resulting in a much higher permeability than the expected design permeability values.

Water flows upward at considerably higher rates than the base permeability case for both zones over the entire simulation time. At the top of the disposal zone the mean advective release rates are much higher than the mean diffusive release rates for the entire simulation time. Other radionuclides such as ^{237}Np, ^{107}Pd and ^{93}Nb have higher mean release rates than ^{129}I. ^{237}Np and ^{135}Cs are two dominant radionuclides in terms of the diffusive release rate.

At the top of the seal zone ^{129}I has the highest mean release rate by both diffusion and advection, and the mean advective release rate is much higher than the mean diffusive release rate. Sorbing radionuclides are effectively retarded during transport in the seal zone. Compared to the base permeability case, many other radionuclides (notably ^{99}Tc, ^{36}Cl, ^{79}Se, etc.) are released at considerably high rates.

The mean dose in the biosphere is dominated by ^{129}I, with contributions from ^{99}Tc and ^{36}Cl.

<u>DOE HLW</u>: The upward flow rates are generally lower than the commercial SNF inventory case because of the lower heat loading. Some sections of the disposal zone (at depths between 3,500 and 3,300 m) have no upward flow after about 5,000 to 12,000 years. As in the commercial SNF inventory case, advection dominants transport.

At the top of the disposal zone, ^{129}I dominates release prior to 5,000 years, after which the release from ^{79}Se, ^{135}Cs are comparable and ^{93}Nb is an additional important contributor. At the top of the seal zone ^{129}I and ^{99}Tc are the only radionuclides that are released, mainly because of sorption on the bentonite seal material. It is interesting to note that the ^{129}I peak mean mass release rate is higher than that of the commercial SNF inventory case. This is a result of the higher degradation rate of the borosilicate glass waste form the DOE HLW, which releases ^{129}I from the waste form at a faster rate. Both waste types have a comparable ^{129}I inventory. The ^{129}I mean mass release rate reaches a peak at about 12,000 years and then decreases by about two orders of magnitude before it levels off.

The magnitude of the ^{129}I peak mean dose is higher than that of the commercial SNF inventory case, reaching about 2 mrem/yr at 12,000 years.

Degraded Seal Case with Iodine Sorbent:

All analyses to date show that ^{129}I is the dominant dose contributor for releases from a deep borehole disposal system. This is an expected outcome considering the key characteristics of ^{129}I relevant to geologic disposal of radioactive waste: unlimited solubility, no sorption or very weak sorption on typical geologic material, and extremely long half-life (about 17 million years). One approach to mitigate the potential release of ^{129}I is to load the seal materials with an effective sorbent for iodine.

Sensitivity analyses were conducted to evaluate potential impacts of iodine sorbent (getter) in the seal zone on the generic disposal system performance. The sensitive analyses were performed for the degraded seal case.

<u>CSNF</u>: The mean mass release rates at the top of the seal zone are no longer dominated by ^{129}I. ^{99}Tc and ^{36}Cl have higher mean mass release rates than ^{129}I. The peak mean dose in the biosphere is dominated mostly by ^{99}Tc and ^{36}Cl. The total peak mean dose is reduced by about two orders of magnitude from the case where there is no sorption of iodine.

DOE HLW: The ^{129}I mean release rate from the seal zone is completely suppressed. ^{99}Tc is the only radionuclide that is released at a noticeable mean rate, and is the single dose contributor at the hypothetical AE. The total peak mean dose is reduced by about six orders of magnitude from the non-sorption case.

Conclusions learned from the Clayton et al. (2011) analyses relevant to prioritization of deep borehole demonstration activities are:

1) Diffusion dominates transports in the base case while advection dominates when seals performance degrades.
    a. **High** PA metric rating for Science activities: Drill Cuttings, Intermittent Coring
2) Proper emplacement of seal components and their long term behavior are important even under failed seal conditions; potential doses are well below current regulatory standards.
    a. **High** PA metric rating for Science activities: Fluid Samples from Packer Testing, Seal Integrity Testing, Cement Degradation Testing and Engineering Activities: Demonstration of Casing Emplacement, Demonstration of Liner Emplacement, Bentonite Seal Emplacement, Cement Seal Emplacement
3) The use of iodine sorbent in the seal zone is quite effective at reducing dose.
    a. **High** PA metric rating for Science activities: Source Term Modeling, Chemical Equilibrium Modeling, Fluid Samples from Packer Testing, Radionuclide Characterization, Seal Zone Sorbent Testing
4) Eliminating or reducing causes of upward flow is important in the event of seal failure.
    a. **High** PA metric rating for Science activities: Fluid Samples from Packer Testing, Seal Integrity Testing, Cement Degradation Testing and Engineering Activities: Demonstration of Casing Emplacement, Demonstration of Liner Emplacement, Bentonite Seal Emplacement, Cement Seal Emplacement, Source Term Modeling, TH Modeling, Construction of System Model, Waste Canister Mockup Electrical Heater Test, Temperature Log, Drill Cuttings, Intermittent Coring.

4.3.4 Generic Deep Geologic Disposal Safety Case (Freeze et al. 2013)

A preliminary safety assessment and some supporting system and sub-system sensitivity analyses of deep borehole disposal were conducted in Freeze et al. (2013). In these analyses, a set of “one-off,” *ceirtus paribus*, simulations were performed where individual parameter values were varied while holding all other parameters at baseline values.

The effect of waste form degradation rates, sorption of ^{129}I in the waste disposal region, sorption of ^{129}I in the seal zone, and molecular diffusion were evaluated. Table 4-4 presents the 13 cases that were evaluated. Table 4-5 presents a summary of the results.

Table 4-4. Cases Evaluated in Freeze et al. (2013).

Parameter	Baseline	Variant 1	Variant 2	Variant 3
Waste Form Degradation	2×10^{-5} yr^{-1} 50% in 35,000 yrs 95% in 150,000 yrs 99.9% in 350,000 yrs	2×10^{-7} yr^{-1} (Slow) 50% in 4,8m yrs 76% in 10.0m yrs 99.9% in 350,000 yrs	0.1 yr^{-1} (Fast) 100% in 250 yrs.	NA
Sorption Disposal Zone	K_d = 0.00 $ml \cdot g^{-1}$	K_d = 0.01 $ml \cdot g^{-1}$ Higher	K_d = 0.10 $ml \cdot g^{-1}$ Higher	K_d = 1.0 $ml \cdot g^{-1}$ Highest
Sorption Seal Zone	K_d = 0.00 $ml \cdot g^{-1}$	K_d = 0.01 $ml \cdot g^{-1}$ Higher	K_d = 0.10 $ml \cdot g^{-1}$ Higher	K_d = 1.0 $ml \cdot g^{-1}$ Highest
Molecular Diffusion	D_e= 2.30×10^{-9} $m^2 \cdot s^{-1}$	D_e= 1.15×10^{-8} $m^2 \cdot s^{-1}$ Higher	NA	NA

Table 4-5. Results of Analyses in Freeze et al (2013).

Modeling Case	Parameter Change from Base	Dose Rate[1] (mrem/yr)
Waste Form Degradation Rate	**Degradation Rate (yr^{-1})**	
Base	2×10^{-5}	$7e^{-7}$
Variant 1	1×10^{-7}	$1e^{-8}$
Variant 2	0.1	$4e^{-5}$
Disposal Zone Sorption	**Linear retardation coefficient, K_d ($ml \cdot g^{-1}$)**	
Base	0.00	$7e^{-7}$
Variant 1	0.01	$3e^{-7}$
Variant 2	0.1	$7e^{-8}$
Variant 3	1.0	$8e^{-9}$
Seal Zone Sorption	**Linear retardation coefficient, K_d ($ml \cdot g^{-1}$)**	
Base	0.00	$7e^{-7}$
Variant 1	0.01	$2e^{-10}$
Variant 2	0.1	$<1e^{-12}$
Variant 3	1.0	$<<1e^{-12}$

Molecular Diffusion	Diffusion coefficient, D_e ($m^2 \cdot s^{-1}$)	
Base	2.30×10^{-9}	$7e^{-7}$
Variant 1	1.15×10^{-8}	$7e^{-3}$

[1]: At 1,000,000 yr. Dose has not peaked by 10,000,000 years in all cases.

Waste Form Degradation:

The relative contributions of advective and diffusive transport vary with time and distance up the borehole (flow rates decrease with time and with distance up the borehole). In the fast degradation rate case, 23% of the initial ^{129}I mass reaches the seal zone by 100,000 years, whereas in the baseline case, only 11% of the initial mass reaches the seal zone by 100,000 years, and 22% of the mass is still contained in the undegraded waste form.

Despite the greater early transport of ^{129}I mass away from the repository in the fast degradation rate case, the effect on annual dose is only moderate. This is because diffusion in the upper part of the seal zone attenuates the release. For the slow fractional degradation rate a smaller fraction of the released mass is available for transport during early time when advective transport is more predominant. As a result, the annual dose is lower than for the baseline case.

Sorption in Disposal and Seal Zones:

Sorption in the seal zone is more important to overall system performance than in the disposal zone. For sorption in the disposal zone (variant 3 case), the peak dose shifts to later time by a factor of 2 and the dose at 1,000,000 years decreases about 2 orders of magnitude compared to the base case. For sorption in the seal zone (variant 3), the dose rate curve shifts to a later time by a factor of about 70 and the dose rate at 1,000,000 years drops from $8e^{-7}$ to < $1e^{-12}$mrem/yr.

Molecular Diffusion:

Diffusion dominates advection at all times in most of the seal zone, which is the lowest permeability component in the deep borehole disposal system. The time of peak dose varies approximately linearly with the value of the diffusion coefficient. Variant 1 thus shifts the peak dose by a factor of 5. The dose rate at 1,000,000 years is reduced about 4 orders of magnitude compared to the base case, from $7e^{-3}$ to $8e^{-7}$.

The following observations from the Freeze et al. (2013) analyses can be made regarding the performance of a generic deep borehole disposal system:

1) Waste form degradation impacts dose rate to a receptor in the biosphere.
    a. **High** PA metric rating for Science activities: Source Term Modeling, Fluid Samples from Packer Testing, Waste Form Degradation Testing
2) Processes and parameters affecting radionuclide transport through the seal zone can have a significant effect on annual dose. These include sorption, K_d, seal zone integrity, and molecular diffusivity.
    a. **High** PA metric rating for Science activities: Source Term Modeling, Chemical Equilibrium Modeling, Fluid Samples from Packer Testing, Radionuclide Characterization, Seal Zone Sorbent Testing, Seal Integrity Testing, Cement

Degradation Testing and Engineering Activities: Demonstration of Casing Emplacement, Demonstration of Liner Emplacement, Bentonite Seal Emplacement, Cement Seal Emplacement, Drill Cuttings, Intermittent Coring

3) Diffusion dominates the transport, although if seals degrade, advection can become important. Advective flow is influenced by thermal considerations.

   a. **High** PA metric rating for Science activities: Source Term Modeling, TH Modeling, Construction of System Model, Waste Canister Mockup Electrical Heater Test, Temperature Log, Drill Cuttings, Intermittent Coring

4.3.5 Updated Performance Assessment Model

Revisions were made to the deep borehole disposal system model and to the thermal-hydrologic model, which provides the thermally modified flow fields. Details of the updated thermal hydrologic modeling are presented in section 4.2.1; while a description of updated DBD system modeling is presented in Section 4.4. A summary of the updated modeling is presented in this section. Results of the updated thermal hydrologic modeling relevant to the DBD safety case and the “Importance” metric of the science and engineering activity prioritization reinforce the importance of formation and disturbed rock zone permeabilites. Lower permeabilites result in significantly lower vertical flow rates.

Table 4-6. Permeability Variation with Depth Comparisons.

Permeability Relationship	Log_{10} Permeability at 2000m	Log_{10} Permeability at 3000m	Log_{10} Permeability at 5000m
Manning and Ingebritsen (1999)	-14.96	-15.53	-16.24
Ingebritsen and Manning (2010)	-15.82	-16.06	-16.36

The updated DBD system model utilizes the flow fields from the thermal hydrology calculations of Section 4.2.1. Flow rates from the thermal-hydrologic modeling are for the central borehole in an array of 81 boreholes, resulting in higher upward flow rates for much longer periods of time (see Figure 4-5) than in previous modeling, which only considered a maximum of 9 boreholes. Additional realism compared to previous DBD system models was also added by accounting for the lateral diffusion of radionuclides into the surrounding host rock. This permits diffusive migration of radionuclides both vertically within the near field as well as horizontally toward the far field.

<u>Importance of Lateral Diffusion</u>

While the sensitivity analysis to parameters that influence lateral diffusion has not been conducted, the results from Section 4.4 support the importance of lateral diffusion to the performance of deep borehole disposal. In the presence of lateral diffusion radionuclides become more dispersed and their concentrations are attenuated because of access to large volumes of host rock, which surround the borehole and where many radionuclide species become sorbed. In the disposal zone the lateral diffusive flux of radionuclides exceeds vertical advective flux in the borehole. In the seal zone and upper zones the lateral diffusive flux is the same order of magnitude as their vertical advective flux. Up to 100,000 years mean total release at the top of the disposal zone is dominated by advection in the borehole region, after which vertical diffusion in the surrounding host dominates. In the seal zone vertical diffusion in the host rock dominates vertical borehole advection for all time. It should be noted that advection in the host rock is not currently considered in these or earlier simulations. The relatively strong vertical diffusion is a result of a relatively large vertical radionuclide concentration gradient that is established in the host rock.

Updated Sensitivity Analyses

In Section 4.4, disposal system modeling results of sensitivities to the SNF waste form degradation rate, vertical advective flux in the borehole, and to permeabilities are presented.

Sensitivity to SNF Degradation Rate

In the analysis described in Section 4.4.2.2 the degradation rate of the SNF waste form is increased by a factor of 100. This results in an increase in the peak mean mass flux at the top of the disposal zone from 2×10^{-4} g/yr to 6×10^{-3} g/yr (a factor of 30) and at the top of the seal zone from 2×10^{-13} g/yr to 2×10^{-11} g/yr (a factor of 100).

Sensitivity to Borehole Flux

The vertical flux in the borehole was increased by a factor of 10 across all time and locations. This could be a surrogate for the consequences of a poorly placed seal system (poor contact between seal components and borehole wall) or deterioration of seal material or DRZ. This order of magnitude increase in vertical flux up the borehole results in a modest increase in release at the top of the disposal zone from 5×10^{-4} g/yr to 2×10^{-4} g/yr (a factor of 2.5). The increase in release midway in the seal zone is from 5×10^{-6} g/yr to 3×10^{-7} g/yr; a factor of 17) while the increase at the top of the seal zone is from 8×10^{-9} g/yr to 2×10^{-13} g/yr (a factor of 40,000), although the magnitude is quite small, regardless.

Past simulations that did not include lateral diffusion also examined the sensitivity to vertical flux through large changes in seal permeability. While direct comparisons between previous analyses and the analysis of Section 4.4 are limited because of differences in many of the process representations and implementations, such comparisons are suggestive of the assertion that accounting for lateral diffusion reduces the sensitivities of mass flux and dose to other processes. For example, in Clayton et al. (2011) a degraded seal zone permeability case resulted in an increase in the maximum vertical flux at the top of the disposal zone from 0.8 to 20 m/yr (a factor of 25) and at the top of the seal zone from 10^{-3} to 0.2 m/yr (a factor of 200). This resulted in corresponding increase in mean mass flux of ^{129}I (the dominant radionuclide released) from 2×10^{-4} g/yr to 3×10^{-2} g/yr (a factor of 150) at the top of the disposal zone and from 8×10^{-8} g/yr to 8×10^{-3} g/yr (a factor of 10^7) at the top of the seal zone. In Herrick et al. (2011), the same changes in maximum vertical borehole flux translated to an increase in the dose rate to the biosphere from 1×10^{-14} g/yr to 6×10^{-2} g/yr (a factor of 10^{10}). The magnitude of these changes, which do not include the effect of lateral diffusion, is much greater than in the updated disposal system model, described in Section 4.4.

Sensitivity to Permeability

The values of permeability at various depths for the base case (Manning and Ingebritsen, 1999) and the alternate case (Ingebritsen and Manning, 2010) are shown in Table 4-6). Comparison of these cases show very limited differences in mean total mass flux at the top of the disposal zone and seal zone, respectively. This is because of the differences in permeability (see Table 4-6) and because of the lateral diffusion, which attenuates vertical release reduces the importance of uncertainty in other processes.

Conclusions

Some high-level conclusions from the updated thermal hydrology and DBD system modeling relevant to the prioritization of science and engineering activities are:

1. Science and engineering activities that support the determination of diffusive properties in the host rock are very important and ranked high.
2. Science and engineering activities, that help quantify the magnitude of vertical flow up the borehole are very important and ranked high.
3. Science and engineering activities that support the determination of SNF degradation are somewhat important and ranked moderate.
4. Because of the limited differences in the host rock and DRZ permeabilities used in this analysis, it is difficult to draw many conclusions with respect to the importance of these parameters on deep borehole disposal performance. Earlier analyses indicated these parameters are very important. Additional sensitivity analyses that include lateral diffusion are required to examine whether accounting for lateral diffusion reduces the overall sensitivity of host rock and DRZ permeability to disposal system performance.

4.3.6 Demonstration of Deep Borehole Disposal Post-Closure Safety

The analyses conducted to date not only identify deep borehole disposal system sensitivities but also demonstrate disposal safety, with the caveat that the assessments conducted to date are preliminary, simplified and require additional pedigree. Table 4-7 presents the baseline dose rates from the assessments.

Table 4-7. Summary of Performance Assessment Results.

Assessment	Peak Dose Rate (mrem/yr)	Time of Peak (yr)	Dominate Radionuclides	Note
Brady et al (2009)	1.4e–10	8,200	^{129}I, only	Assumed 8,000 travel time to the biosphere, instant release, no sorption in natural system
Herrick et al. (2011)	<1e–14	1,000,000	^{129}I, only	
Clayton et al. (2011)	5e–9	1,000,000	^{129}I and 36Cl, only	

Freeze et al. (2013)	7e–7	1,000,000	Only considered ^{129}I	
This report, Section 4.4	0.	N/A	NA	

The results of all preliminary system analyses confirm that the deep borehole disposal system is very effective in containing and confining nuclear wastes, with predicted peak dose rates between zero to 7×10^{-7} mrem/yr under undisturbed conditions.

4.4 Updated Performance Assessment Model

The PA model for the deep borehole disposal concept has improved over the past few years (Brady et al. 1999; Wang and Lee 2010; Clayton et al. 2011; Lee et al. 2011; Swift et al. 2011 and 2012; Vaughn et al. 2012b; Lee et al. 2012). These previous PA analyses assumed all mobilized radionuclides remain within the borehole along the length of borehole (5 km), which is an overly conservative approach that does not reflect radionuclide transport into and within the large volume of surrounding bedrock.

The updated PA model has implemented lateral diffusion of radionuclides from the borehole into surrounding bedrock along the entire length of the borehole and also diffusional transport within the bedrock. This better represents the radionuclide transport processes that are expected in the deep borehole repository environment.

4.4.1 Performance Assessment Model Setup

This section describes the model setup for the updated PA model for the DBD concept. Figure 4-8 shows a schematic for the conceptual model of the DBD PA model. The 5000-m deep borehole is divided into three zones: the bottom 2,000 m for waste disposal (referred to as the “disposal zone”), the next 1,000 m sealed with compacted bentonite clay (referred to as the “seal zone”), and the top 2,000 m plugged and backfilled with sedimentary rock materials (referred to as the “upper zone”). For simplification, a uniform cross sectional area of 1 m^2 (or 0.564 m radius), representing the borehole, its contents, and the surrounding DRZ, is assumed for the entire length of borehole. It is conservatively assumed that waste canisters fail at the beginning of the simulation, which is consistent with the reference design (Arnold et al. 2011a) based on carbon steel canisters with little resistance to corrosion.

The PA model assumes the bedrock surrounding the borehole is granite for the entire length of all three borehole zones (i.e., disposal, seal and upper zones). Input parameter data for the granite bedrock (density, porosity and radionuclide sorption) were obtained from the granite generic disposal system analysis of Clayton et al. (2011).

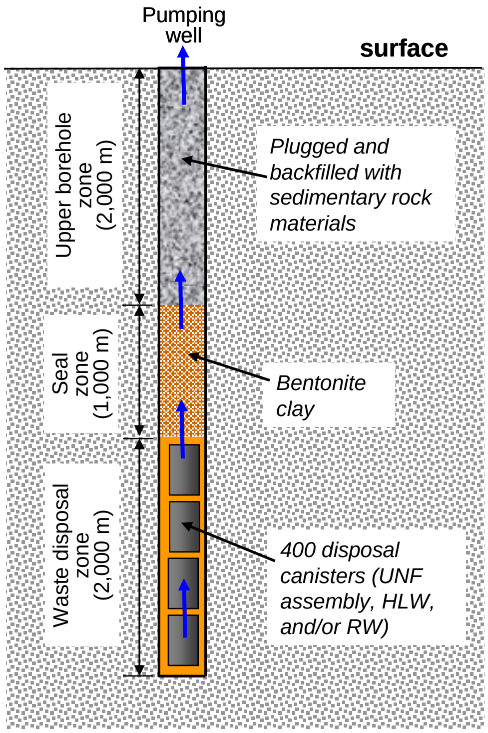


Figure 4-8. A Schematic illustrating the conceptual model for performance assessment of deep borehole disposal (not to scale).

Figure 4-9 shows a schematic illustrating the PA model setup for a 100-m section of deep borehole. A total of 6 concentric cylindrical shells are used to represent radionuclide diffusive transport into and in the surrounding bedrock, with the inner cylindrical shell representing the borehole (R1=0.564 m radius) and the second shell (R2=1.0 m radius and 0.436 m thick layer) for the DRZ. The borehole diameter (1.128 m) and its cross-sectional area (1 m^2) implemented in the PA model is larger than the actual diameter of the disposal zone, and the borehole cross-section represents the borehole and surrounding disturbed rock zone, combined (Arnold and Hadgu 2013). The rest (remaining 4 cylindrical shells) are for granite bedrock layers with increasing thickness in the radial direction: R3= 3 m (2 m annular thickness), R4= 9 m (6 m annular thickness), R5= 34 m (25 m annular thickness), and R6 = 100 m (66 m annular thickness). The radius of the last shell corresponds to the mid-point between two neighboring boreholes. Table 4-8 summarizes the cylindrical shell regions and related geometry and properties that have been implemented in the PA model.

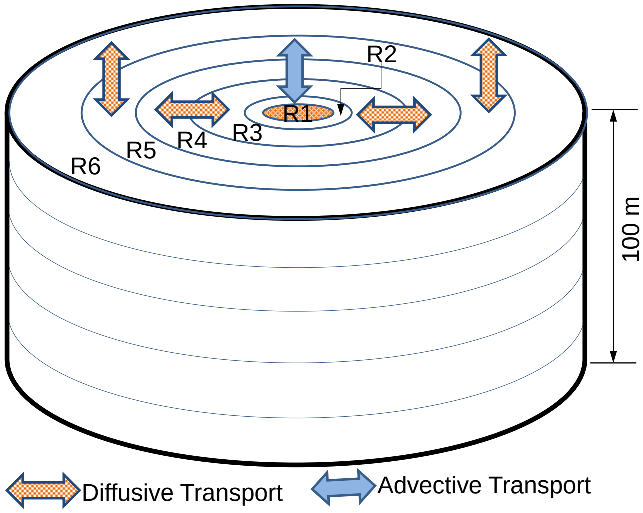


Figure 4-9. A schematic illustrating the PA model setup for a 100-m section of deep borehole (not to scale).

Table 4-8. Properties of cylindrical shell regions implemented in the PA model for deep borehole disposal.

Shell Region	Description	Medium	Shell Radius (m)	Shell Layer Thickness (m)	Porosity
R1	Borehole Disposal zone	Compacted clay and WP & WF degradation products	0.564 (whole cylinder)	0.564 (whole cylinder)	0.034
	Borehole Seal zone	Compacted bentonite clay			0.034
	Borehole Upper zone	Sedimentary rock backfill and seals			0.01
R2	Disturbed rock zone	Granite	1.0	0.436	0.01 – 0.05
R3	Bedrock	Granite	3.0	2.0	0.01
R4	Bedrock	Granite	9.0	6.0	0.01
R5	Bedrock	Granite	34.0	25.0	0.01
R6	Bedrock	Granite	100.0	66.0	0.01

4.4.2 Performance Assessment Analysis Results

This section discusses the updated PA analysis results to evaluate the DBD concept. The current PA analysis was conducted for disposal of commercial SNF in the central borehole of an array of 81 boreholes described in the site-scale thermal-hydrologic model analysis (Section 4.2.1). The PA analysis results are presented in terms of (1) the mean RN mass flux from the disposal subsystems (i.e., disposal zone, seal zone and upper zone) of the central borehole as the intermediate metrics of the system performance and (2) the mean annual dose (mrem/yr) for individual radionuclides at a "hypothetical" biosphere above the disposal system. The model analysis was performed probabilistically, with 100 realizations, over a time period of 1,000,000 yr.

The PA model assumes a hypothetical biosphere at the groundwater pumping location above the repository, and uses the International Atomic Energy Agency's (IAEA) BIOMASS Example Reference Biosphere 1B (ERB 1B) dose model (IAEA 2003) to convert the dissolved radionuclide concentrations in the groundwater to an estimate of annual dose to a receptor. The model assumes that radionuclides are contained in groundwater extracted at a rate of 1×10^4 m^3/year from the aquifer overlying the disposal system, and a receptor in the affected biosphere community consumes the "contaminated" water at a rate of 1.2 m^3/year (IAEA 2003).

4.4.2.1 Reference Case Analysis

The reference case uses the vertical groundwater flux in the borehole arising from the thermal-hydrologic model results for base-case physical properties (Section 4.2.1, Figures 4-2 and 4-3). The water flux in the central borehole of an 81-borehole array at varying depths as a function of time are shown in Figure 4-10 to Figure 4-12 for the disposal zone, seal zone, and upper zone respectively. The missing water flux values for the seal and upper zones at early time periods are due to the negative water flux (i.e., downward water flux). (Note the water flux is on a log-scale, and negative values are not shown.) The vertical water flux time-histories (both upward and downward fluxes) in Figures 4-10 to 4-12 were input to the PA model and the water flux values at 10^5 years are used for the time period from 10^5 year to 10^6 years.

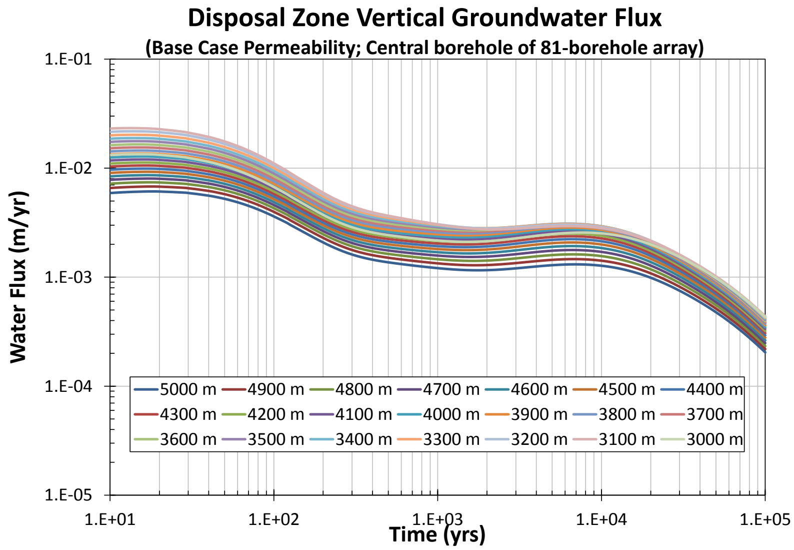


Figure 4-10. Vertical groundwater flux at varying depths in the disposal zone of the central borehole of an 81-borehole array for disposal of commercial SNF calculated with the base case permeability in the borehole and surrounding bedrock.

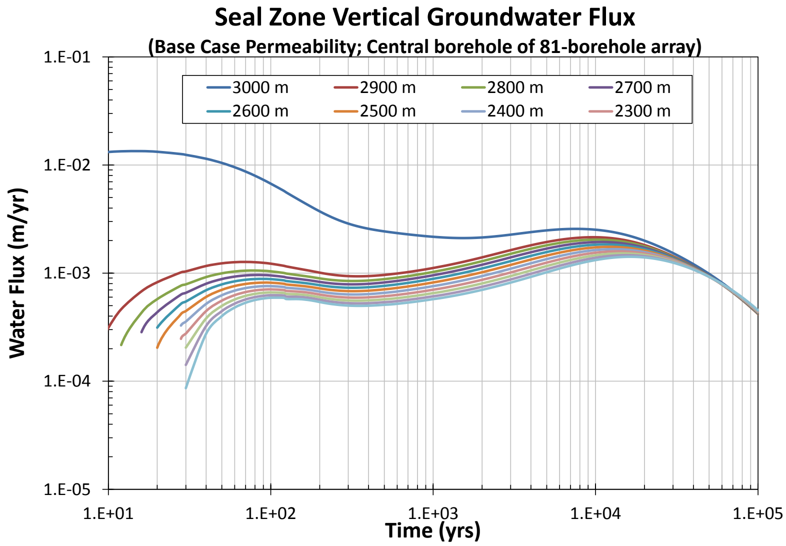


Figure 4-11. Vertical groundwater flux at varying depths in the seal zone of the central borehole of an 81-borehole array for disposal of commercial SNF calculated with the base case permeability in the borehole and surrounding bedrock.

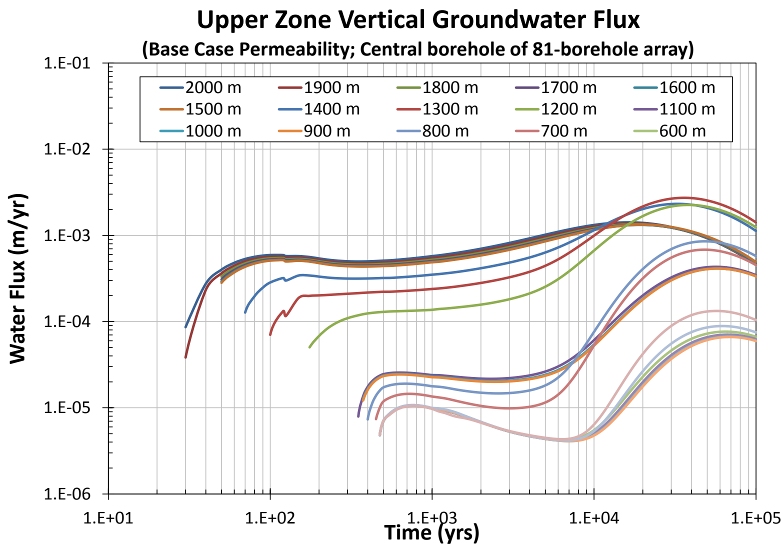


Figure 4-12. Vertical groundwater flux at varying depths in the upper zone of the central borehole of an 81-borehole array for disposal of commercial SNF calculated with the base case permeability in the borehole and surrounding bedrock.

<u>Mass Fluxes at the top of Disposal Zone (3,000 m depth)</u>

Figure 4-13 to Figure 4-15 show the model results of the reference case at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF. Figure 4-13 shows the mean total radionuclide mass fluxes from advection and diffusion combined, indicating that the peak mean total upward mass flux is ~2×10^{-4} g/yr and dominated by the I-129 releases. These mean total upward fluxes are dominated by advective mass flux in the borehole for up to ~10^5 years (Figure 4-14, upper), then by upward diffusive flux from surrounding bedrock (Figure 4-14, lower).

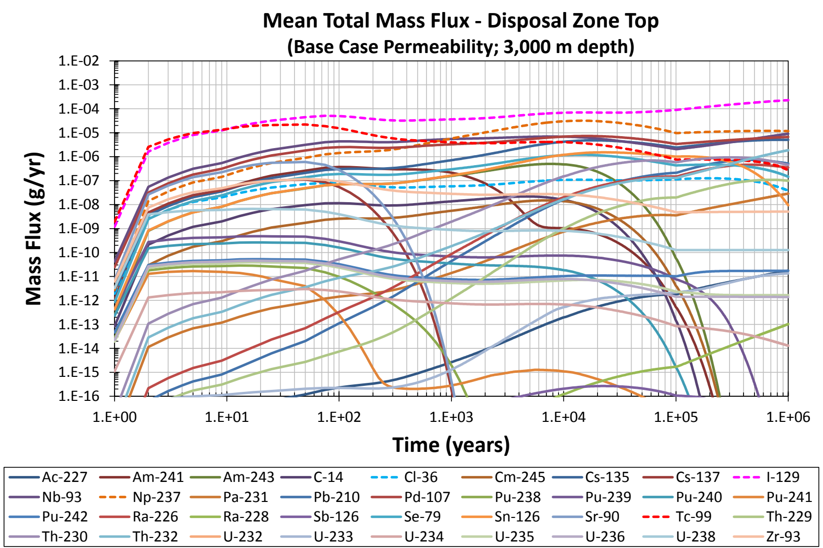
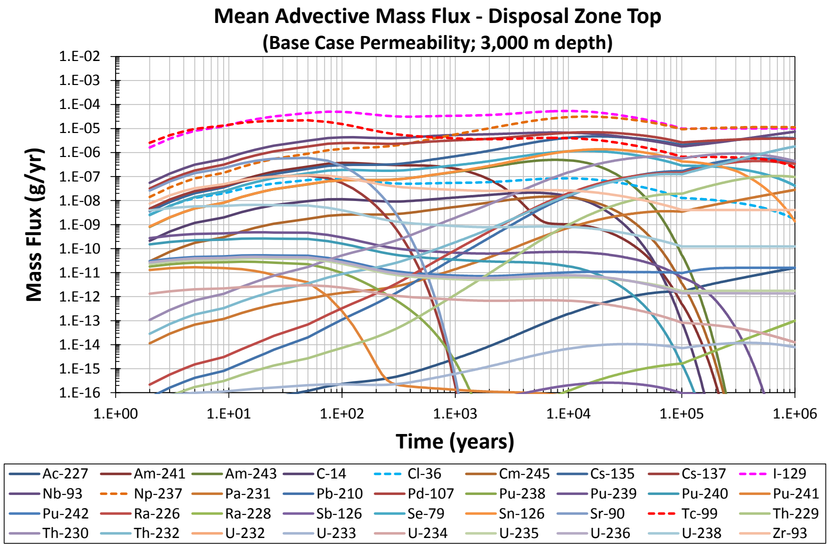


Figure 4-13. Model result of the reference case for mean total mass flux at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

The peak mean lateral diffusive flux from the borehole into the bedrock (~5×10^{-4} g/yr) (upper plot of Figure 4-15) is greater than the total upward flux (Figure 4-13) and is dominated by the Np-237 mass flux. Note that the discontinuous curves (upper plot of Figure 4-15) are due to the back-diffusive mass flux (i.e., negative diffusive flux), which is not shown in the figure with the mass flux (*y*-axis) on a log scale. The mean lateral diffusive flux in outer bedrock shells are dominated by I-129, since other radionuclides are retarded by sorption on the bedrock materials. The lower plot of Figure 4-15 shows the mean diffusive mass flux from Shell Region R5 (second to the last shell; see Table 4-13), and I-129 mean mass flux has reached a steady state at ~5×10^{-5} g/yr after ~10^5 years.



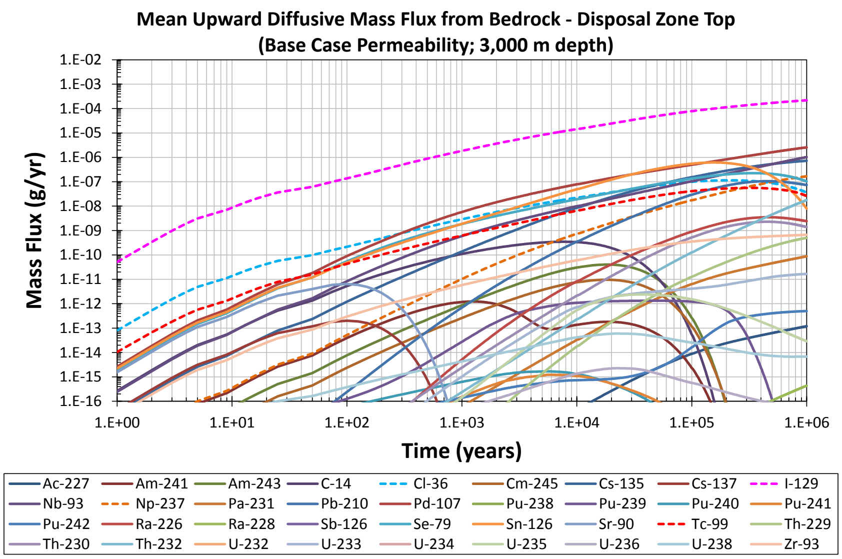
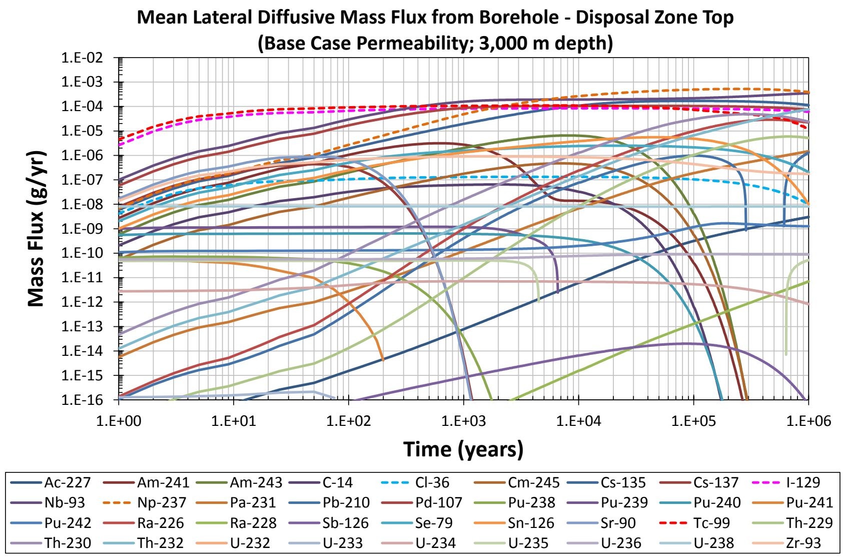


Figure 4-14. Model result of the reference case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.



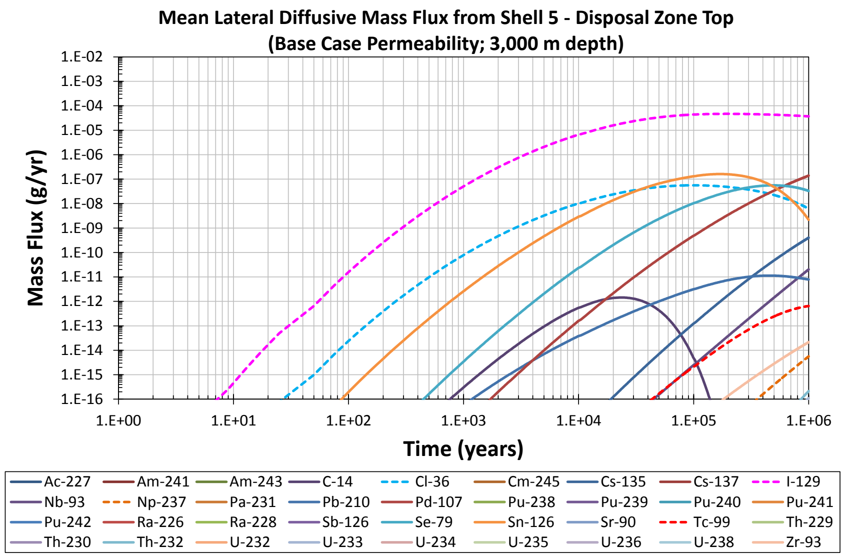


Figure 4-15. Model result of the reference case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (upper) and from Shell Region R5 to R6 (lower) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

Mass fluxes from the mid-section of Seal Zone (2,500 m depth)

Figure 4-16 to Figure 4-18 show the model results of the reference case at the mid-section of the seal zone (2,500 m depth) of the central borehole of an 81-borehole array. The mean total mass fluxes of radionuclides at the mid-section of the seal zone (2,500 m depth) are significantly reduced relative to the fluxes at the top of the disposal zone, as shown in Figure 4-16. Only I-129, Cl-36 and Sn-126 have calculated mass fluxes; the Sn-126 mass flux is not shown in the figure because of its very small mass flux. I-129 and Cl-36 mass fluxes continue to rise until the end of simulation. The mean total flux is dominated by the I-129 upward diffusive flux in the surrounding bedrock (Figure 4-17), and the peak mean flux is ~3×10^{-7} g/yr at one million years. The mean lateral diffusive mass flux from the borehole into the bedrock is about two orders of magnitude lower than the mean total upward mass flux, and the peak mean flux is ~9.3×10^{-10} g/yr at one million years (Figure 4-18). The mean lateral diffusive mass fluxes in the surrounding bedrock shells are about the same, indicating a steady-state has reached.

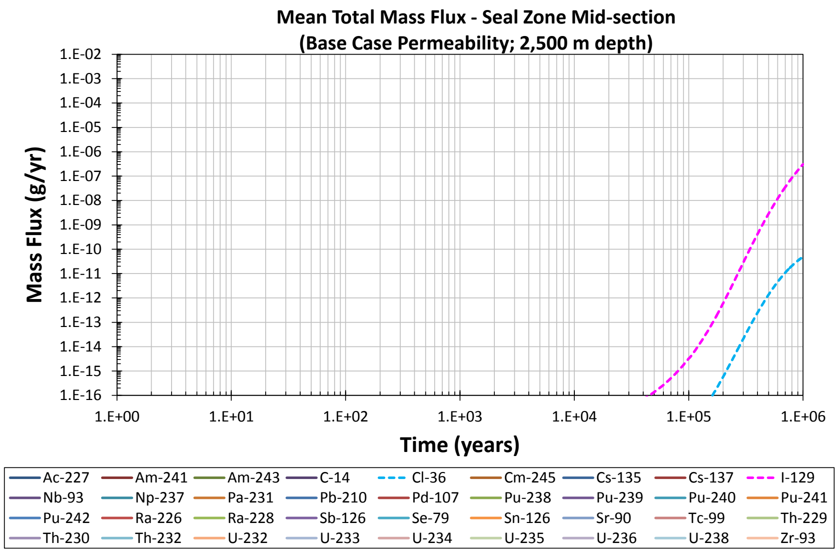
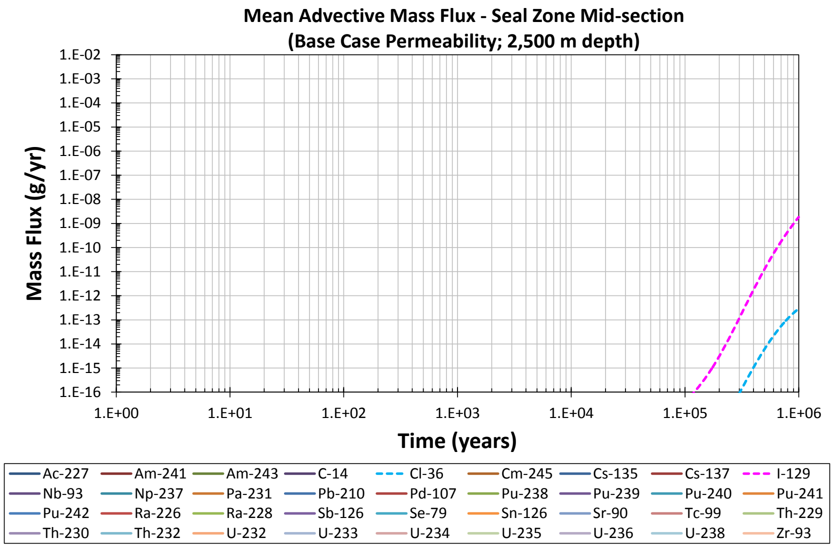


Figure 4-16. Model result of the reference case for mean total mass flux at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.



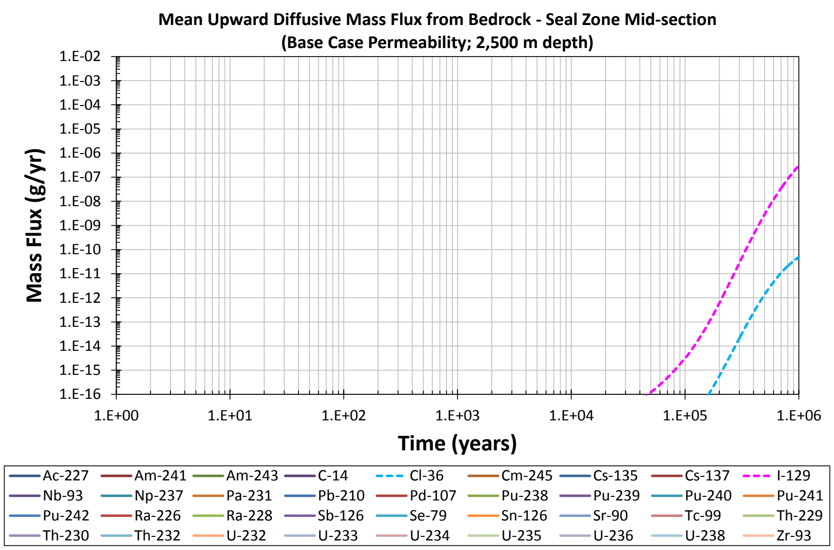
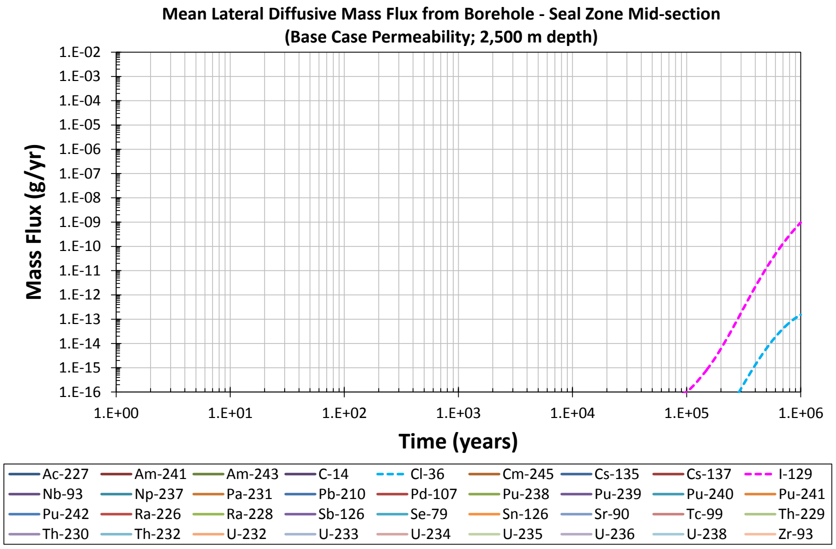


Figure 4-17. Model result of the reference case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.



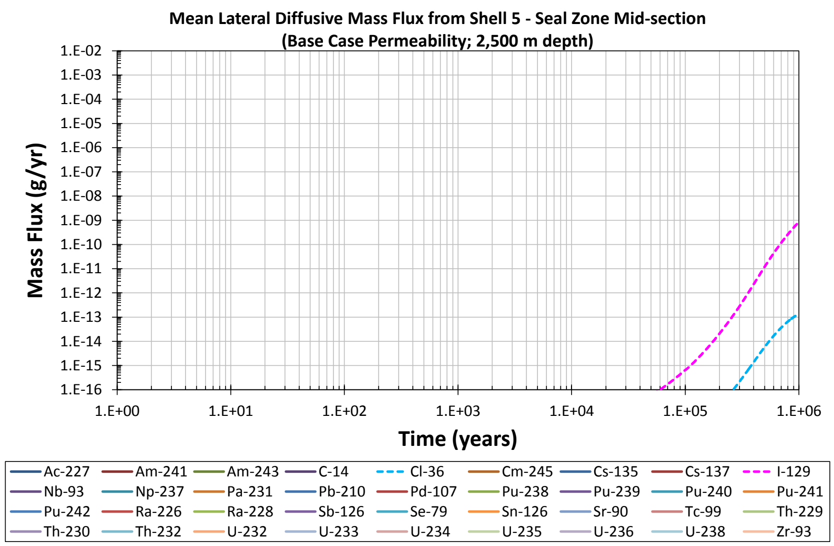


Figure 4-18. Model result of the reference case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (upper) and from Shell Region R5 to R6 (lower) at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

Releases from the top of Seal Zone (2,000 m depth)

Figure 4-19 shows the model result of negligibly small mean total mass fluxes of I-129 at the top of the seal zone (2,000 m depth). Cl-36 also has calculated mass releases but at much lower rates than I-129, and is not shown in the figure. The model analysis shows no calculated radionuclide mass fluxes at the mid-section of the upper zone (1,000 m depth).

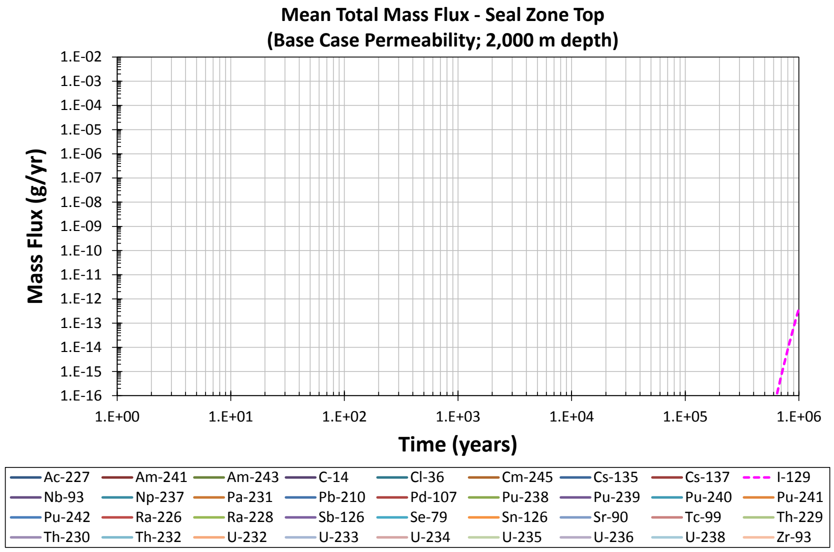


Figure 4-19. Model result of the reference case for mean total mass flux at the top of seal zone (2,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

4.4.2.2 Sensitivity Analysis

Sensitivity analyses were conducted to evaluate the DBD system responses to changes in the model parameters of the following four cases:

- Groundwater flux in the borehole calculated with the permeability values from a study by Stober and Bucher (2007) (referred to as Alternative Permeability Case).
- Reference Case vertical groundwater flux in the borehole increased by a factor of 10 (referred to as High Groundwater Flux Case).
- SNF degradation rate increased by a factor of 100 (referred to as Enhanced SNF Degradation Case).
- Reference Case vertical groundwater flux in the borehole increased by a factor of 10 and SNF degradation rate increased by a factor of 100 (referred to as Combined High Groundwater Flux & Enhanced SNF Degradation Case).

<u>Alternative Permeability Case</u>

An empirical relationship for the permeability of the crystalline basement as a function of depth was reported by Stober and Bucher (2007). The permeability relationship (referred to as Stober and Bucher permeability in this report) was used as an alternative permeability function, and a sensitivity analysis was conducted to evaluate effect of the alternative permeability on the deep borehole repository performance.

Figure 4-20 to Figure 4-22 show the vertical groundwater flux in the central borehole of an 81-borehole array at varying depths as a function of time for the disposal zone, seal zone, and upper zone respectively, from the results of the thermal-hydrologic model calculations using the Stober and Bucher permeability. While the time-history profiles of the vertical water flux of the alternative permeability are similar to those of the base-case permeability (Figure 4-10 to Figure 4-12), the alternative-case permeability fluxes are lower than the base-case permeability fluxes for all three zones. Similarly to the base-case permeability flux, the discontinuous water flux curves for the seal and upper zones for early time periods are due to the negative water flux (i.e., downward water flux). The water flux variations along the depth of the disposal zone are smaller than the base-case, indicating that permeability changes of the alternative permeability case at the disposal zone depth are smaller than the base-case. In the PA analysis, for all three zones the water flux at 10^5 years are used for the time periods from 10^5 year to 10^6 years.

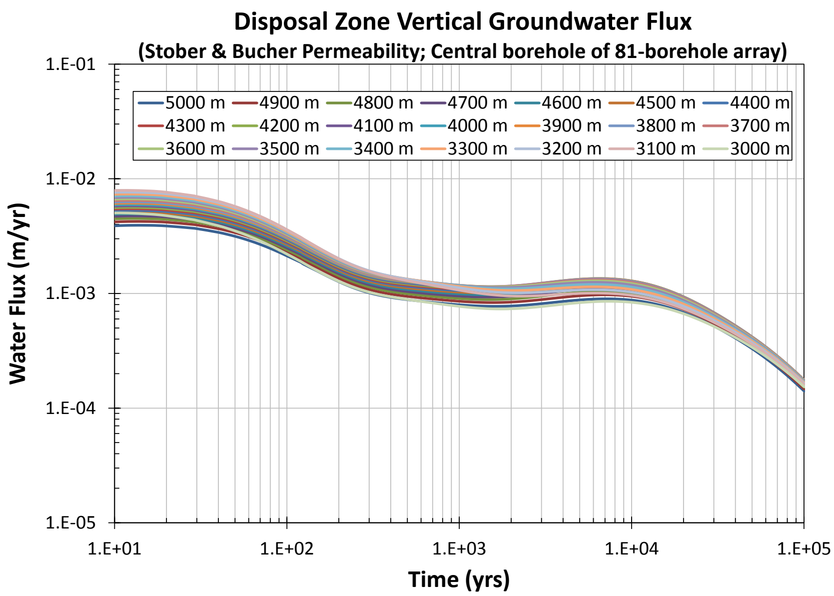


Figure 4-20. Vertical groundwater flux at varying depths in the disposal zone of the central borehole of an 81-borehole array for disposal of commercial SNF calculated with the alternative permeability function of Stober and Bucher (2007) in the borehole and surrounding bedrock.

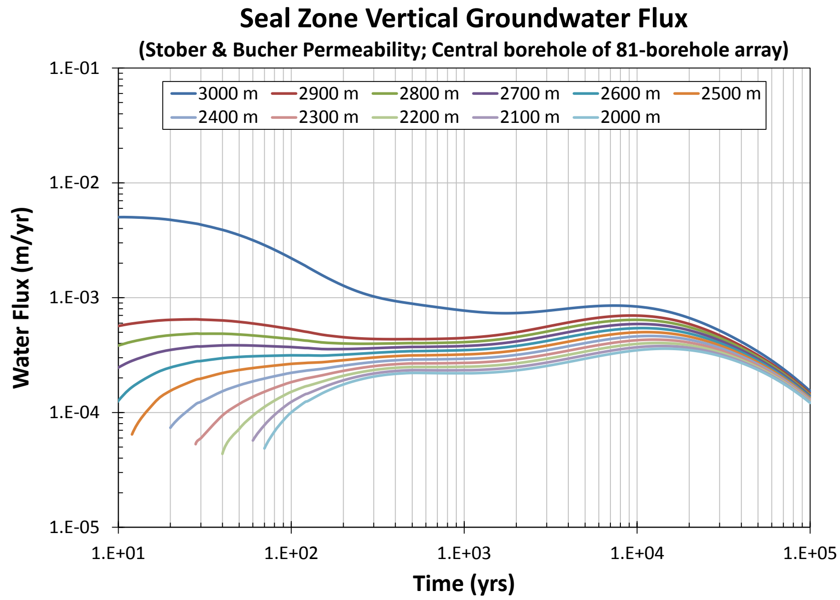


Figure 4-21. Vertical groundwater flux at varying depths in the seal zone of the central borehole of an 81-borehole array for disposal of commercial SNF calculated with the alternative permeability function of Stober and Bucher (2007) in the borehole and surrounding bedrock.

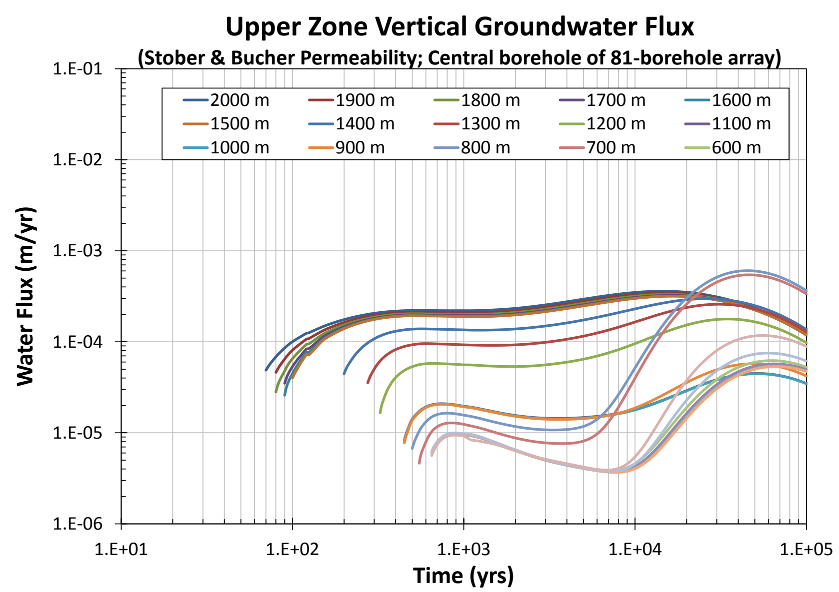


Figure 4-22. Vertical groundwater flux at varying depths in the upper zone of the central borehole of an 81-borehole array for disposal of commercial SNF calculated with the alternative permeability function of Stober and Bucher (2007) in the borehole and surrounding bedrock.

Releases from the top of Disposal Zone (3,000 m depth)

Figure 4-23 to Figure 4-25 show the model results of the alternative permeability case at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF. As expected from the groundwater flux profiles of the alternative permeability case, the borehole system responses in terms of the radionuclide mass fluxes are similar to the reference case mass fluxes. Figure 4-23 shows the model result of the alternative permeability case for the mean total mass flux at the top of disposal zone (3,000 m depth). The mean total mass flux increases steadily with time, and the upward advective flux in the borehole (upper figure of Figure 4-24) dominates the total mass flux for up to ~10^5 years. Afterward, the upward diffusive mass flux from the surrounding bedrock dominates the total mass flux (lower figure of Figure 4-24). For up to ~10^5 years, the mean total mass flux of the alternative permeability case is slightly lower than the reference-case total mass flux, after which it becomes about the same as the reference-case mean total mass flux. For the entire simulation time period, I-129 is the dominant radionuclide contributing to the total mass flux, with a peak mean total upward radionuclide mass flux of ~2×10^{-4} g/yr at the top of the disposal zone (Figure 4-23)

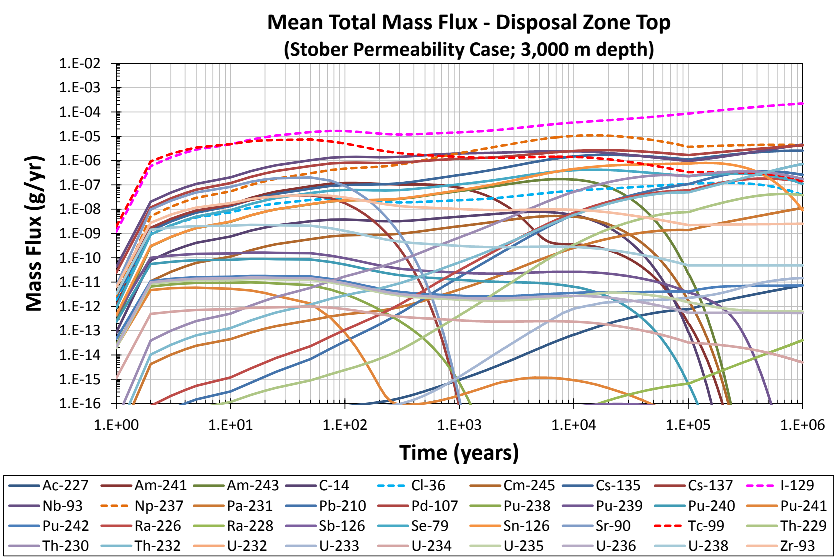


Figure 4-23. Model result of the alternative permeability case for mean total mass flux at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

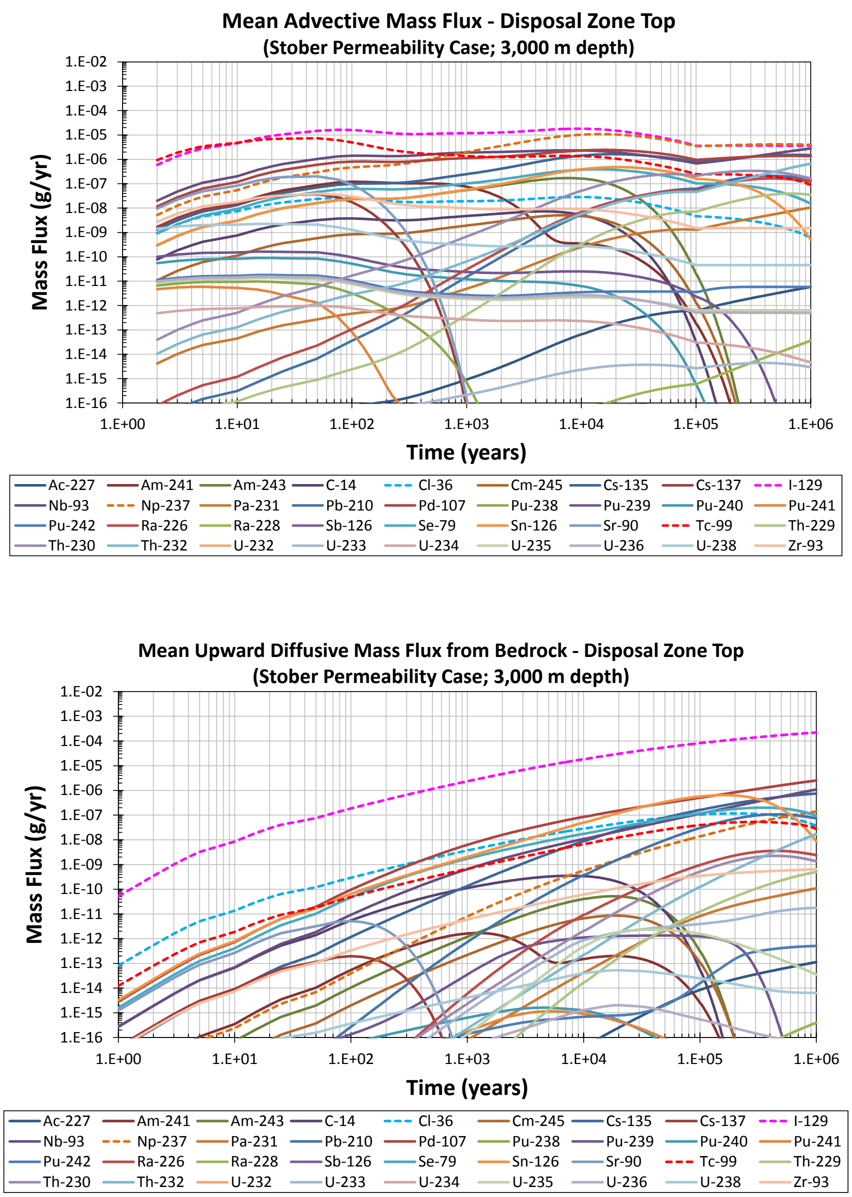
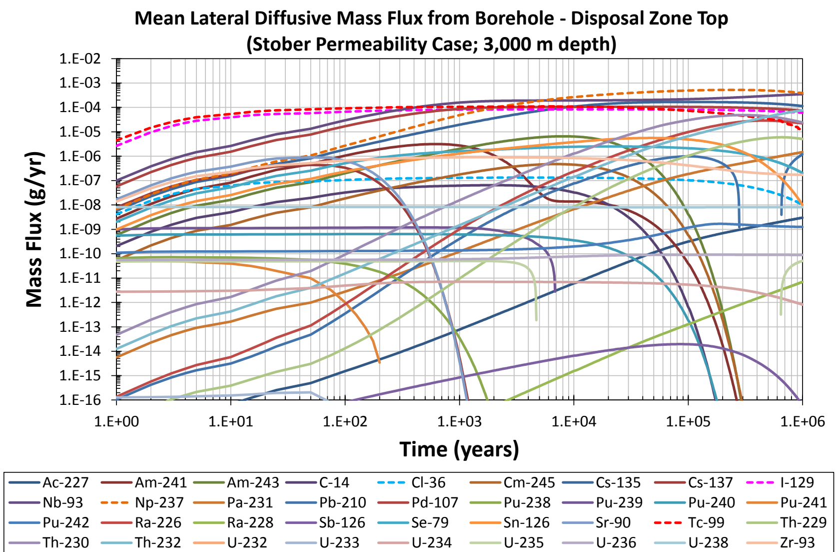


Figure 4-24. Model result of the alternative permeability case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

The lateral diffusive mass flux into the surrounding bedrock (Figure 4-25) is close to the reference case diffusive flux (Figure 4-15). The peak mean lateral diffusive flux from the borehole into the bedrock is dominated by the Np-237 mass flux at ~5×10^{-4} g/yr at ~200,000 years (upper figure of Figure 4-25), and the peak mean lateral flux is greater than the total upward flux (Figure 4-23). The discontinuous curves (upper figure of Figure 4-25) are due to the back-diffusive mass flux (i.e., negative diffusive flux), and is not shown in the figure with the mass flux (*y*-axis) on a log scale. As with the reference case, the mean lateral diffusive flux in outer bedrock shells is dominated by I-129 , since other radionuclides are retarded by sorption on the bedrock materials. The mean diffusive mass flux from Shell Region R5 (second to the last shell; see Table 4-13) reaches a steady state at ~5×10^{-5} g/yr after ~10^{5} years (lower figure of Figure 4-25).



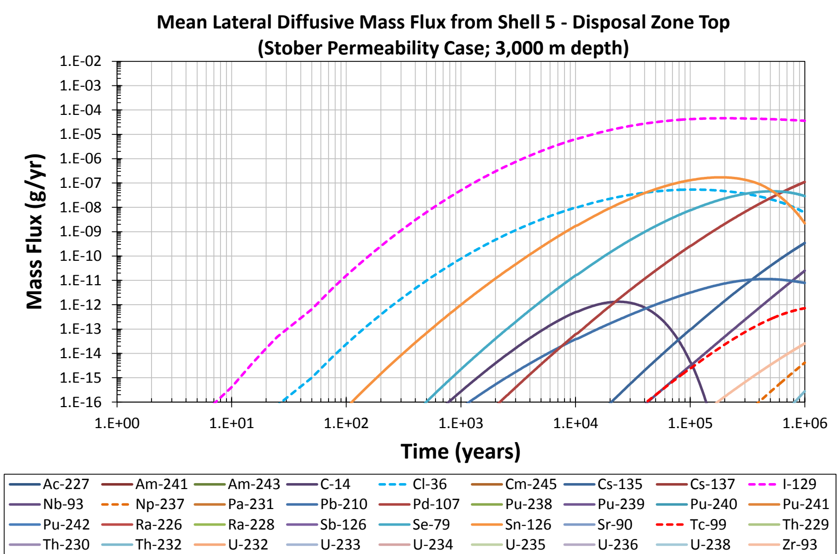


Figure 4-25. Model result of the alternative permeability case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (left) and from Shell Region R5 to R6 (right) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

Releases from the mid-section of Sean Zone (2,500 m depth)

The mean total mass fluxes of radionuclides at the mid-section of the seal zone (2,500 m depth)) of the central borehole of an 81-borehole array are shown in Figure 4-26 and are very close to the reference case model results (Figure 4-16). The mean mass fluxes are reduced significantly compared to those at the top of the disposal zone (Figure 4-23), and only I-129 and Cl-36 have significant calculated mass fluxes. The mean total flux is dominated by the I-129 mass flux and continues to rise until the end of the simulation with the peak mean mass flux at ~3×10^{-7} g/yr at 10^6 years. The lateral diffusive mass flux into the surrounding bedrock is very similar to the reference case model results (Figure 4-18), and are not shown.

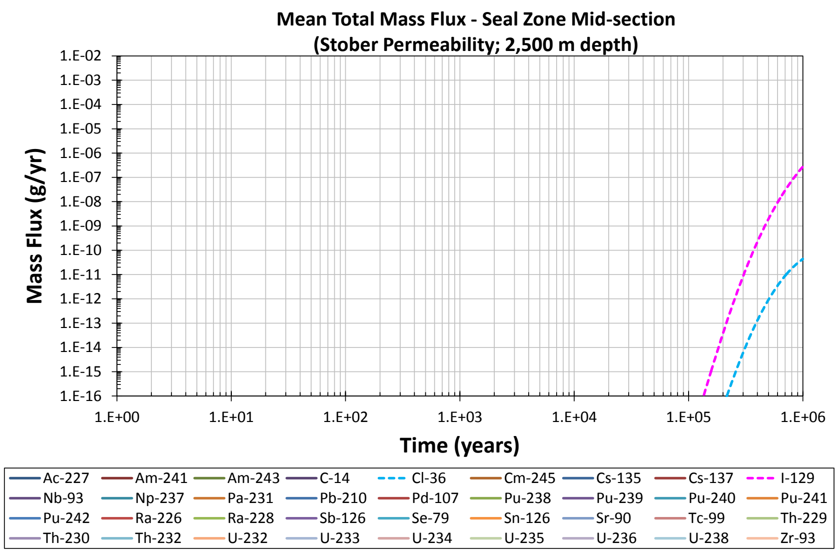


Figure 4-26. Model result of the alternative permeability case for mean total mass flux at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

Releases from the top of Seal Zone (2,000 m depth)

Figure 4-27 shows the model result of the mean total mass flux at the top of seal zone (2,000 m depth) of the central borehole of an 81-borehole array, and only a negligibly small mass flux of I-129 is released from the seal zone top. As in the reference case, no calculated radionuclide masses are observed at the mid-section of the upper zone (1,000 m depth).

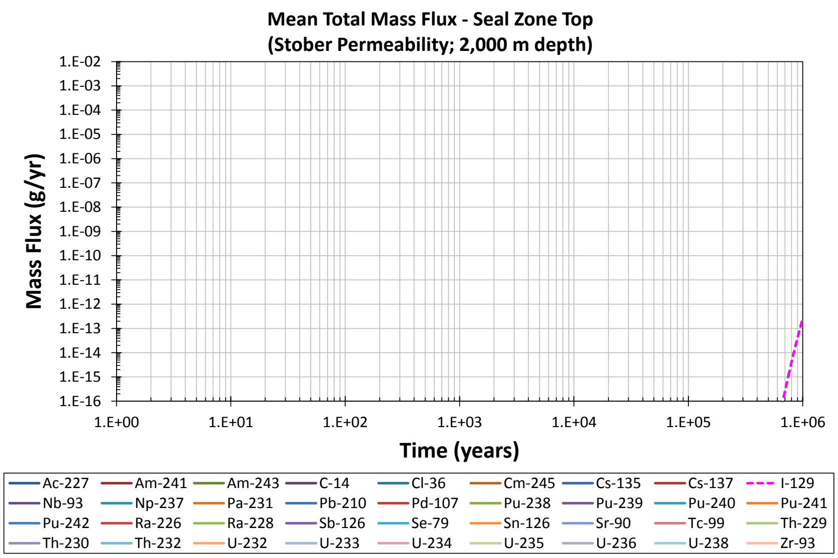


Figure 4-27. Model result of the alternative permeability case for mean total mass flux at the top of seal zone (2,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

High Groundwater Flux Case

The sensitivity of the deep borehole disposal concept to vertical groundwater flux was examined by increasing the flux by a factor of 10 relative to the reference case (Figure 4-10 to Figure 4-12). Note that the reference-case groundwater flux is for the central borehole of an 81-borehole array.

Releases from the Top of Disposal Zone (3,000 m depth)

Figure 4-28 to Figure 4-30 show the model results of the high groundwater flux case at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF. Figure 4-28 shows the model result for the mean total RN mass fluxes. The peak mean total mass flux is ~5×10^{-4} g/yr, dominated by ^{129}I, and reached at much earlier times (at ~100 years and again at ~10^4 years) than the reference case (Figure 4-13). The mean total mass fluxes are dominated by advective mass flux in the borehole for the entire simulation period; the advective mass flux is greater than the upward diffusive flux from the surrounding bedrock due to the high water flux in the borehole (Figure 4-29). Note that the discontinuous curve for the I-129 diffusive mass flux from the surrounding bedrock (lower figure of Figure 4-29) is due to the back-diffusion (i.e., negative diffusive mass flux transporting the mass downward) that results from higher I-129 dissolved concentrations in the bedrock region around the borehole right above the top of the disposal zone; a higher mass flux of I-129 is transported advectively upward in the borehole during the time periods when the back-diffusion occurs (lower figure of Figure4-29).

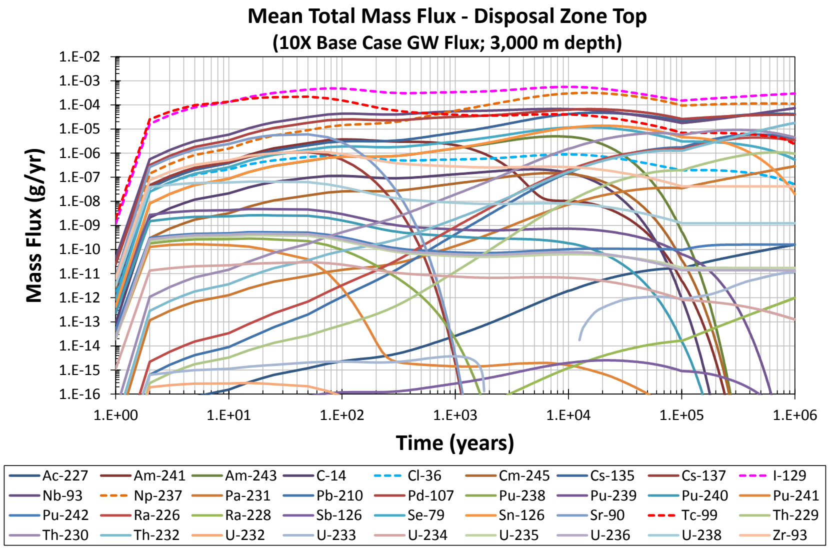
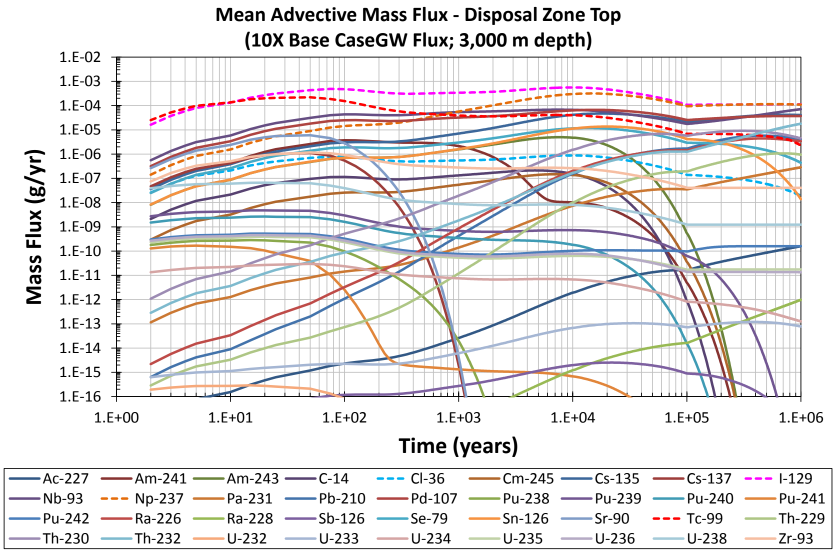


Figure 4-28. Model result of the high groundwater flux case for mean total mass flux at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

The mean lateral diffusive mass flux from the borehole to the surrounding bedrock (upper figure of Figure 4-30) is about the same order of magnitude as the mean total upward mass flux (Figure 4-28), and this demonstrates the importance of lateral diffusional transport into and within the surrounding bedrock. The mean lateral diffusive mass flux is dominated initially by Tc-99 and later by Np-237. Note that discontinuous lateral diffusive mass flux curves of some radionuclides in the figure are due also to the back-diffusion from the bedrock region right next to the borehole (Shell Region R2, Table 4-13). The mean lateral diffusive flux in outer bedrock shells is dominated by I-129, since other radionuclides are retarded by sorption on the bedrock materials. Figure 4-30 (lower figure) shows the mean diffusive mass flux from Shell Region R5 (second to the last shell; see Table 4-13), and the I-129 mean mass flux has reached a steady state at ~5×10^{-5} g/yr after ~10^5 years.



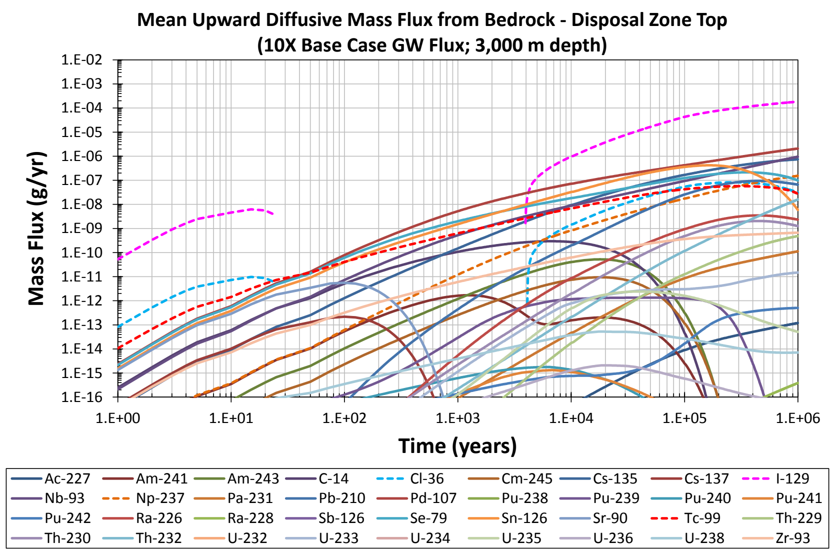
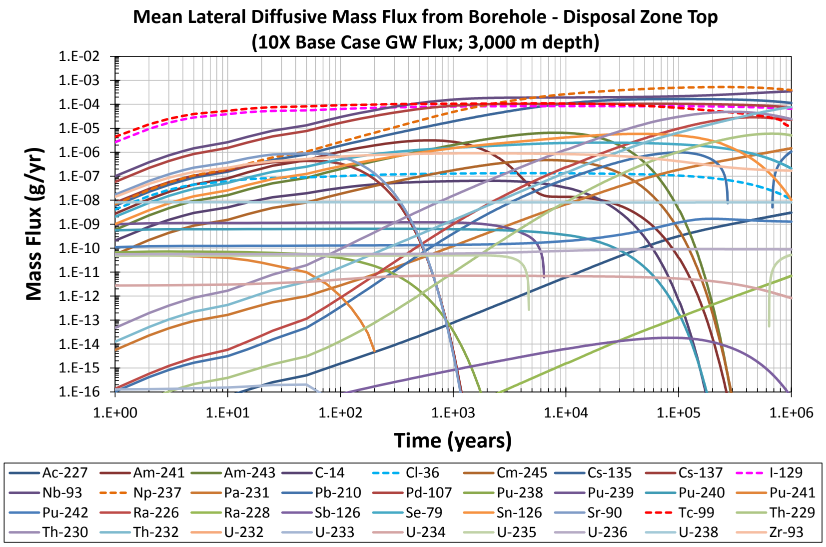


Figure 4-29. Model result of the high groundwater flux case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.



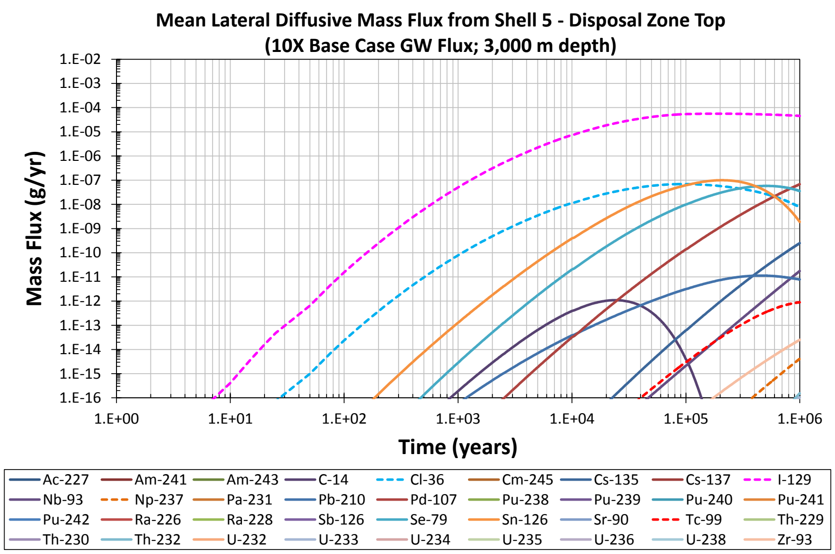


Figure 4-30. Model result of the high groundwater flux case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (upper) and from Shell Region R5 to R6 (lower) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

Releases from the Mid-Section of Seal Zone (2,500 m depth)

Figure 4-31 to Figure 4-33 show the model results of the high groundwater flux case at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array. Figure 4-31 shows the model result of the mean total mass flux of radionuclides, and the mean total mass fluxes are significantly lower than the mean total mass flux at the top of the disposal zone (Figure 4-28), since the radionuclide transport is retarded in the seal zone as the radionuclides sorb on the seal zone materials.

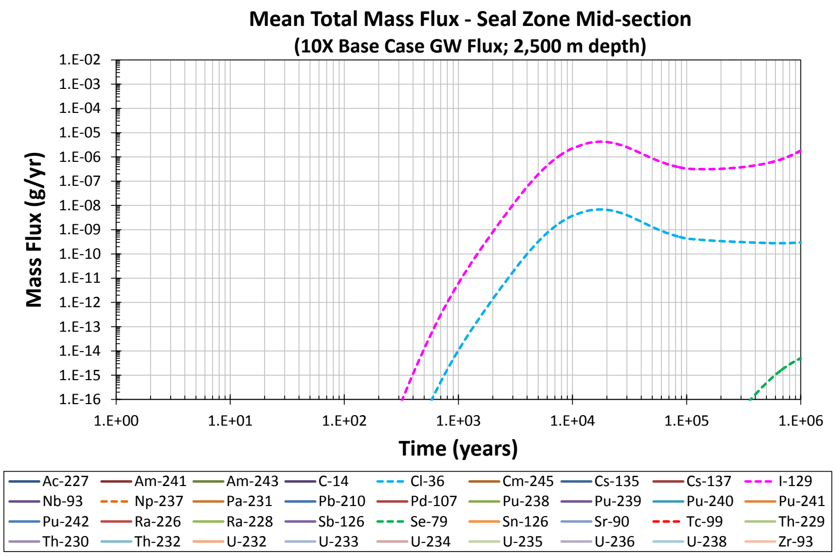
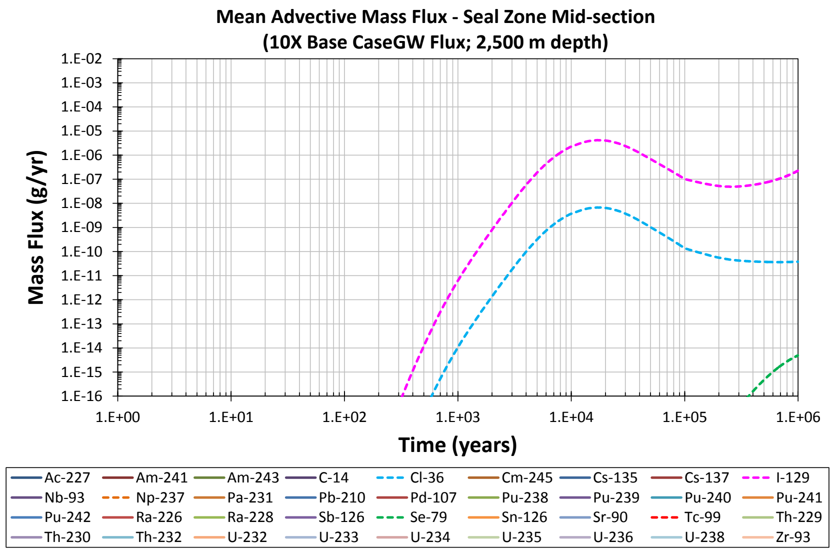


Figure 4-31. Model result of the high groundwater flux case for mean total mass flux at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

The peak mean total d mass flux is dominated by I-129 (~5×10^{-6} g/yr at ~2×10^{4} years), and the Cl-36 peak mean mass flux (~7×10^{-9} g/yr at ~2×10^{4} years) is secondary to the I-129 peak mean mass flux. As shown by comparing Figure 4-31 and Figure 4-32, the mean total mass flux is dominated by the advective mass flux for up to ~10^{5} years and by the diffusive mass flux afterwards. Other radionuclides (Sn-126, Se-79, Tc-99 and Pb-210 in decreasing order) have calculated mass fluxes at the mid-section of the seal zone, but they are not shown in the figure because they are negligibly small.

The I-129 mean lateral diffusive mass flux from the borehole to the surrounding bedrock (Figure 4-33) is about the same order of magnitude as the I-129 mean total upward mass flux, and this shows the importance of the lateral diffusional transport into and within the surrounding bedrock in the evaluation of the deep borehole disposal concept and the system performance. The mean lateral diffusive mass fluxes in the surrounding bedrock shells (Figure 4-33) are about the same, indicating a steady-state has reached.



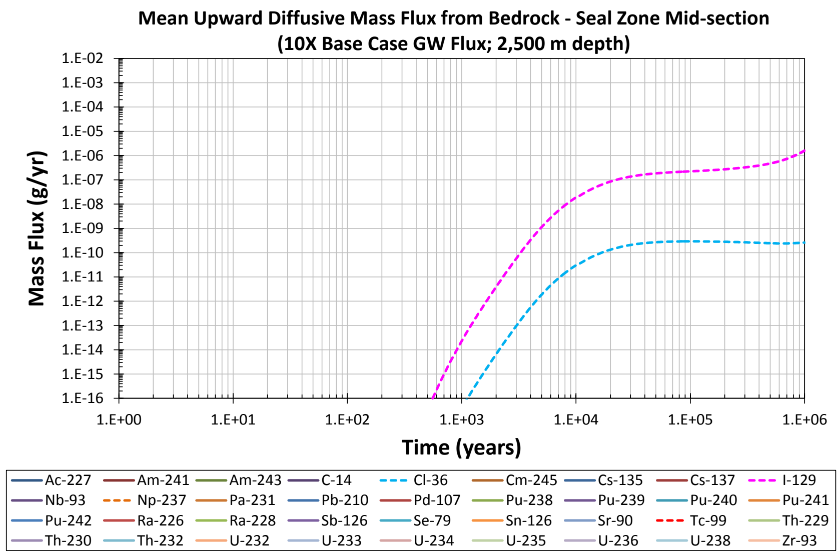
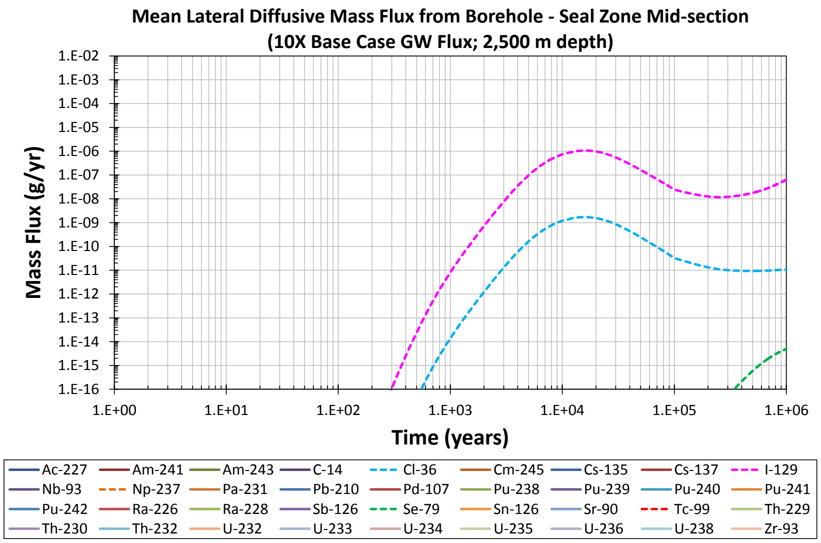


Figure 4-32. Model result of the high groundwater flux case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.



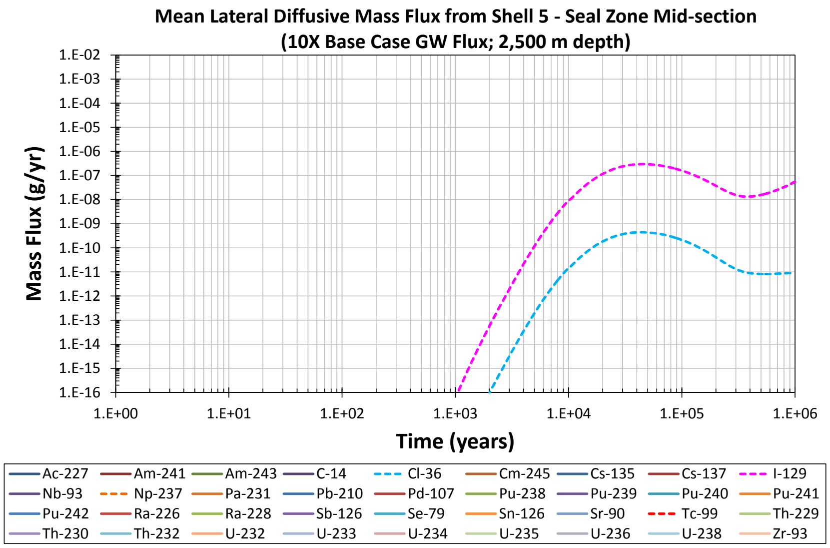


Figure 4-33. Model result of the high groundwater flux case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (left) and from Shell Region R5 to R6 (right) at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

Releases from the Top of Seal Zone (2,000 m depth)

Figure 4-34 to Figure 4-36 show the model results of the high groundwater flux case at the top of the seal zone (2,000 m depth) of the central borehole of an 81-borehole array. The mean total upward mass flux (Figure 4-34) is dominantly by I-129 with the peak of ~8×10^{-9} g/yr at ~3×10^{4} years, and the Cl-36 peak mean mass flux (~1.5×10^{-11} g/yr at ~3×104 years) is much lower. No other radionuclide mass fluxes are observed. The mean total mass flux is dominated by the advective mass flux in the borehole for up to ~10^5 years and by the diffusive mass flux from the surrounding bedrock afterwards (Figure 4-35).

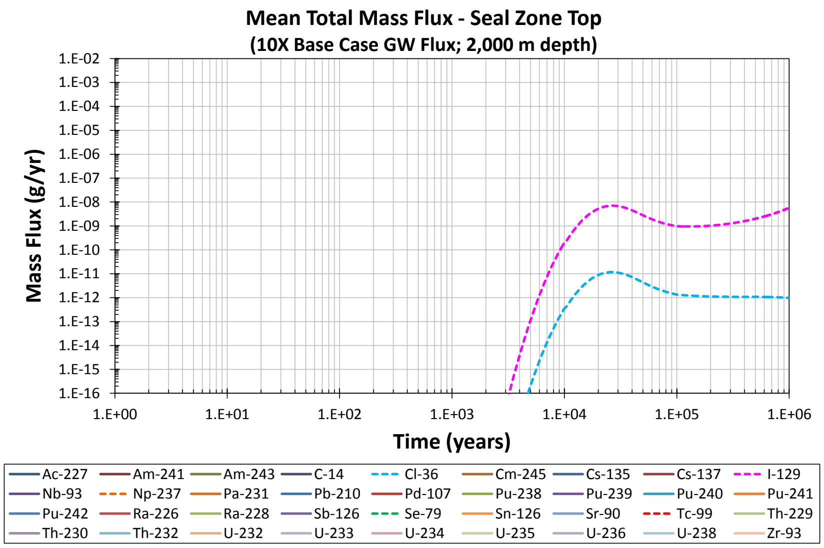
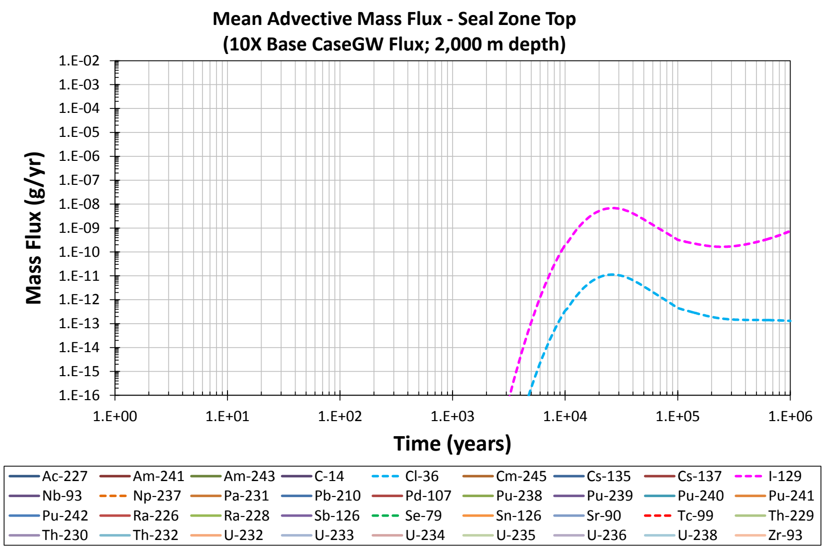


Figure 4-34. Model result of the high groundwater flux case for mean total mass flux at the top of seal zone (2,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

The I-129 and Cl-36 lateral diffusive mass fluxes from the borehole to the surrounding bedrock (upper figure of Figure 4-36) are about the same order of magnitude as the I-129 and Cl-36 total upward mass fluxes (Figure 4-34), showing that the radionuclides diffuse into the surrounding bedrock at about the same rate of the upward total mass flux.



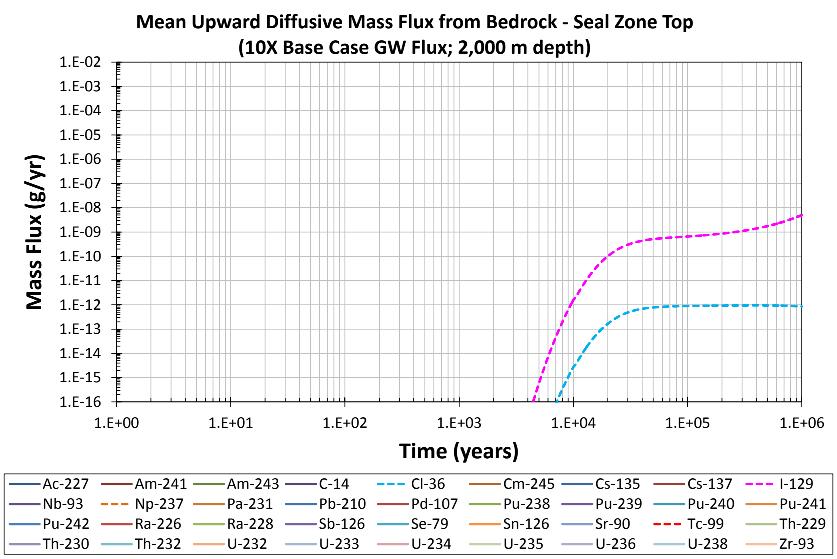
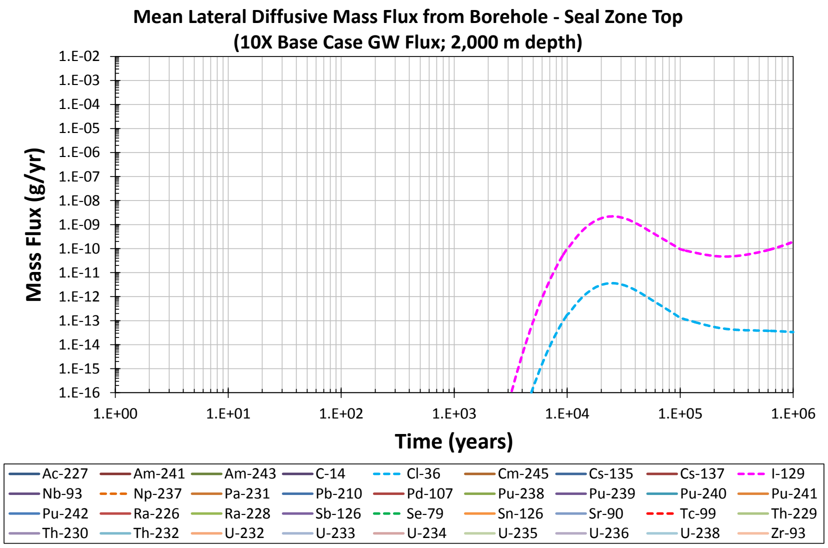


Figure 4-35. Model result of the high groundwater flux case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the top of seal zone (2,0000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.



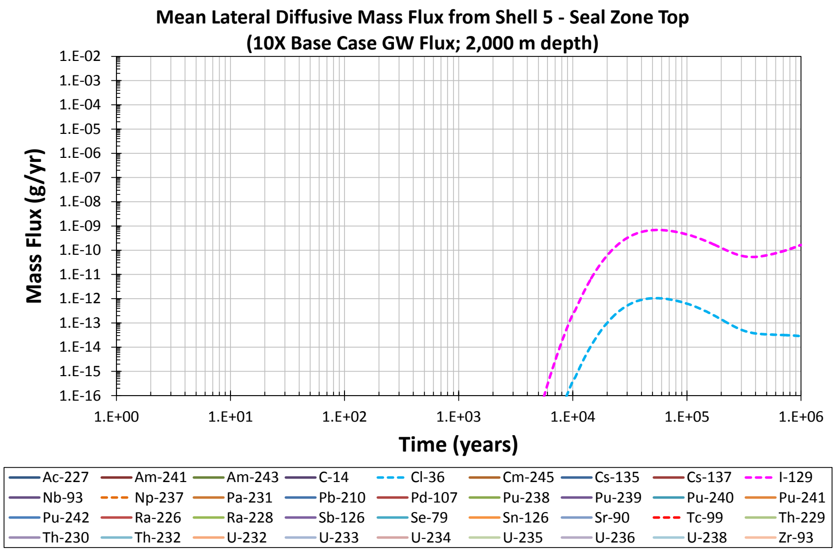


Figure 4-36. Model result of the high groundwater flux case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (upper) and from Shell Region R5 to R6 (lower) at the top of seal zone (2,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

Releases from the Mid-section of Upper Zone (1,000 m depth)

Figure 4-37 shows the model result of the mean total mass flux for the high groundwater flux case at the mid-section of the upper zone (1,000 m depth) of the central borehole of an 81-borehole array. As shown in the figure, I-129 is the only radionuclide contributing to the mass release, and the peak mean flux is only ~4×10^{-14} g/yr at 10^6 years. The Cl-36 releases are much smaller and are not shown in the figure.

The I-129 mean total upward mass flux is composed about equally of the advective flux in the borehole and the upward diffusive mass flux from the surrounding bedrock for up to ~6×10^4 years, and dominated by the diffusive flux afterwards. The I-129 mean lateral diffusive mass flux from the borehole to the surrounding bedrock is about the same order of magnitude as the I-129 mean total upward mass flux from the surrounding bedrock.

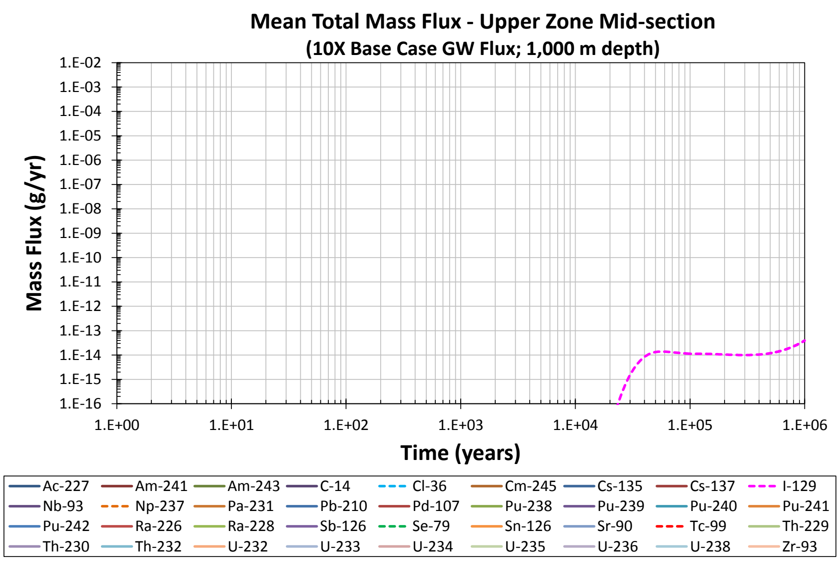


Figure 4-37. Model result of the high groundwater flux case for mean total mass flux at the mid-section of upper zone (1,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

<u>Releases at the top of Upper Zone</u>

Figure 4-38 shows the model result of the mean total mass flux of the high groundwater flux case at the top of upper zone of the central borehole of an 81-borehole array. Only I-129 and Cl-36 have calculated mass releases, and their mass fluxes are negligibly small: ~5×10^{-22} g/yr at 10^6 years for I-129 and ~1×10^{-25} g/yr at 10^6 years for Cl-36. The radionuclide fluxes are dominated by the upward diffusive mass flux from the surrounding bedrock (not shown).

Figure 4-39 shows the model result of the mean annual dose of RNs reaching the biosphere. As discussed in the beginning of Section 4.4.2, the IAEA ERB1B dose model (IAEA 2003) was used to calculate the dose. The calculated annual dose is negligibly small with the peak mean annual dose of ~$5x10^{-21}$ mrem/yr at 10^6 years due to I-129.

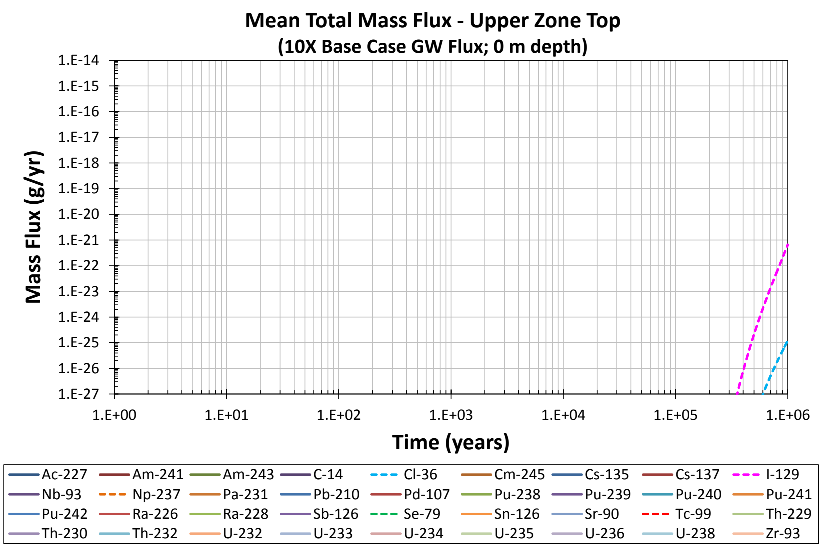


Figure 4-38. Model result of the high groundwater flux case for mean total mass flux at the top of upper zone of the central borehole of an 81-borehole array for disposal of commercial UNF.

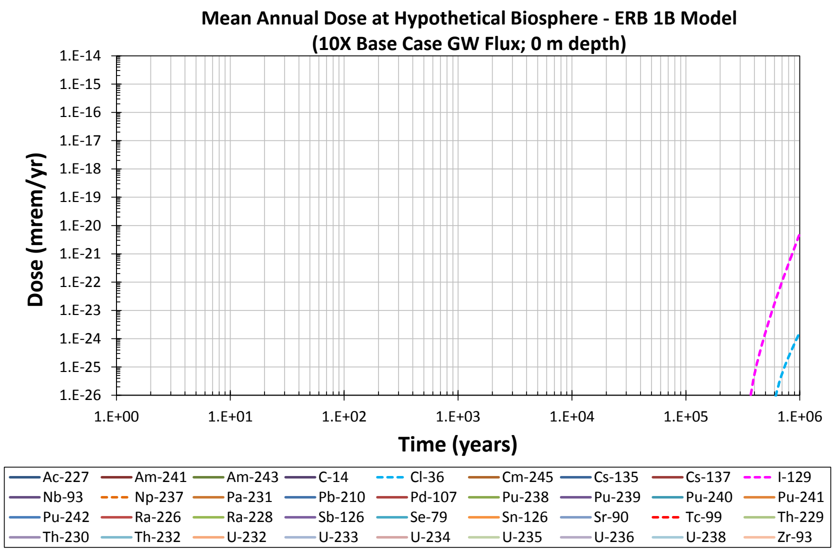


Figure 4-39. Model result of the high groundwater flux case for mean annual dose by radionuclides released from the central borehole of an 81-borehole array for disposal of commercial UNF.

Enhanced SNF Degradation Case

The deep borehole disposal concept was evaluated by increasing the UNF annual fractional degradation rate of the reference case by a factor of 100 and by analyzing the disposal system responses. The new UNF degradation rate model for the sensitivity analysis is a log-triangular distribution with a mode of 10^{-5} yr^{-1}, a minimum of 10^{-6} yr^{-1} and a maximum of 10^{-4} yr^{-1}. The new UNF degradation rates are much higher than those expected for the exposure conditions of the disposal zones, and at the maximum rate, the entire UNF inventory degrades in a short time period relative to the simulation time period. This case demonstrates the robustness of the DBD concept.

Releases at the top of Disposal Zone (3,000 m depth)

Figure 4-40 to Figure 4-42 show the model results of the enhanced SNF degradation case at the top of the disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF. Figure 4-40 shows the mean total mass flux at the top of the disposal zone, and the peak mean total mass flux reaches ~6×10^{-3} g/yr at ~100 years and again at ~10^4 years. I-129 releases dominate the mean total mass flux. The mean total mass flux is dominated by the advective mass flux in the borehole for up to ~3×10^4 years and by the diffusive mass flux from the surrounding bedrock afterwards (Figure 4-41).

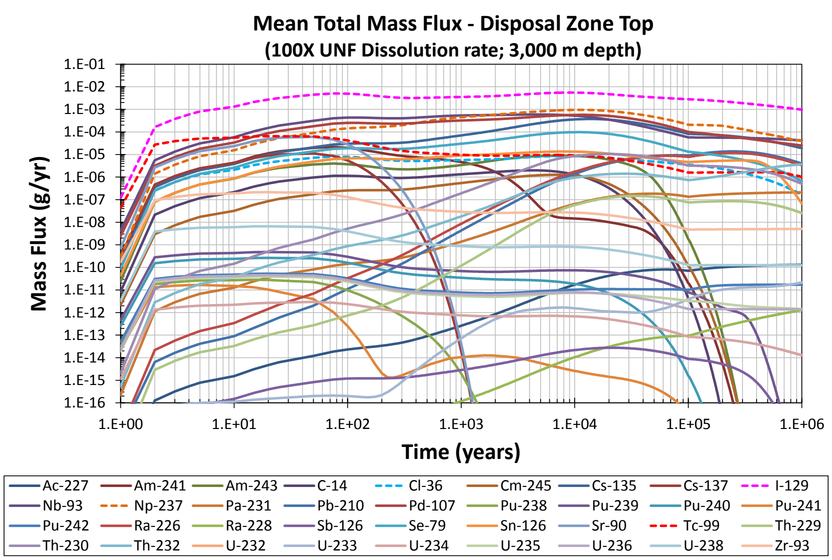
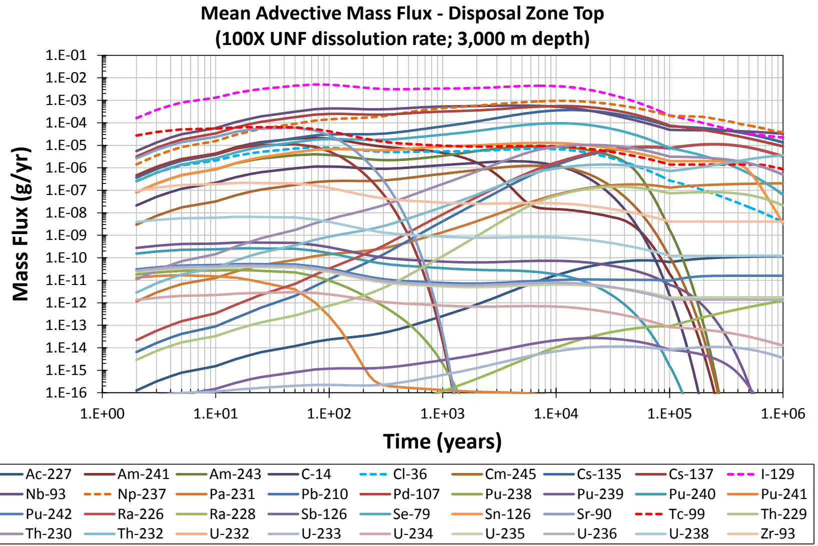


Figure 4-40. Model result of the enhanced SNF degradation case for mean total mass flux at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

The mean lateral diffusive flux from the borehole to the surrounding bedrock (upper figure of Figure 4-42) is higher than the mean total upward mass flux (Figure 4-40), and is dominated initially by the I-129 mass flux and later by the Np-237 mass flux. The peak mean lateral diffusive flux is ~0.01 g/yr at ~7×10^4 year, which is higher than the peak mean total upward mass flux (Figure 4-40). The result shows that radionuclides diffuse into the surrounding bedrock at higher rates than the upward mass flux, and demonstrates importance of lateral diffusion into the surrounding bedrock in the safety analysis of the disposal system. The dominant radionuclide for lateral diffusive mass flux changes from Np-237 to I-129 in the bedrock away from the borehole because Np-237 and other radionuclides are retarded by sorption on the bedrock materials.



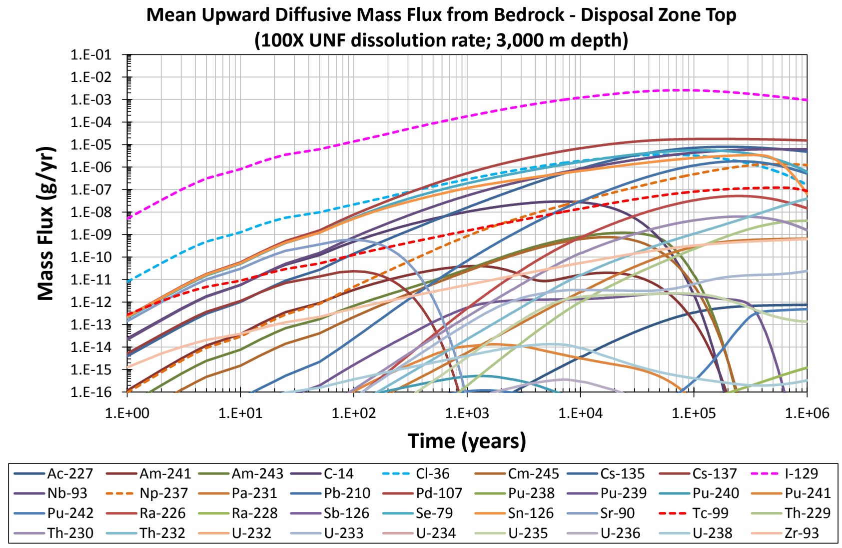
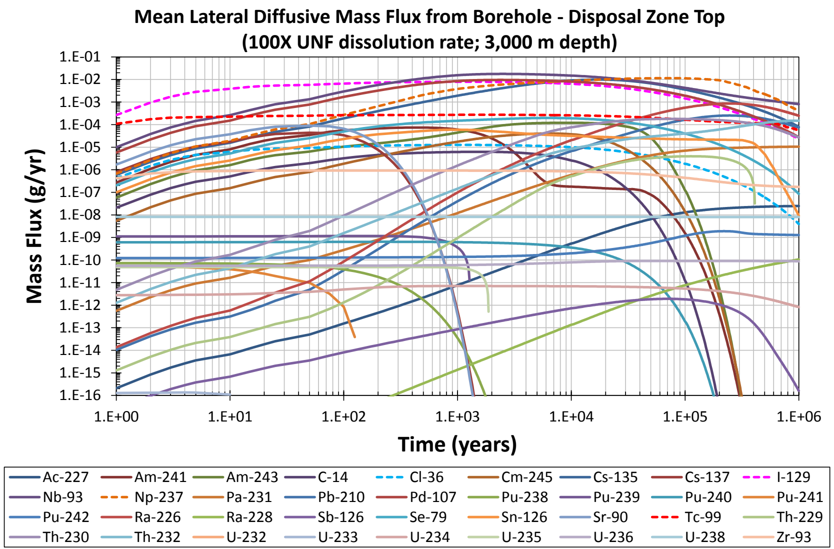


Figure 4-41. Model result of the enhanced SNF degradation case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.



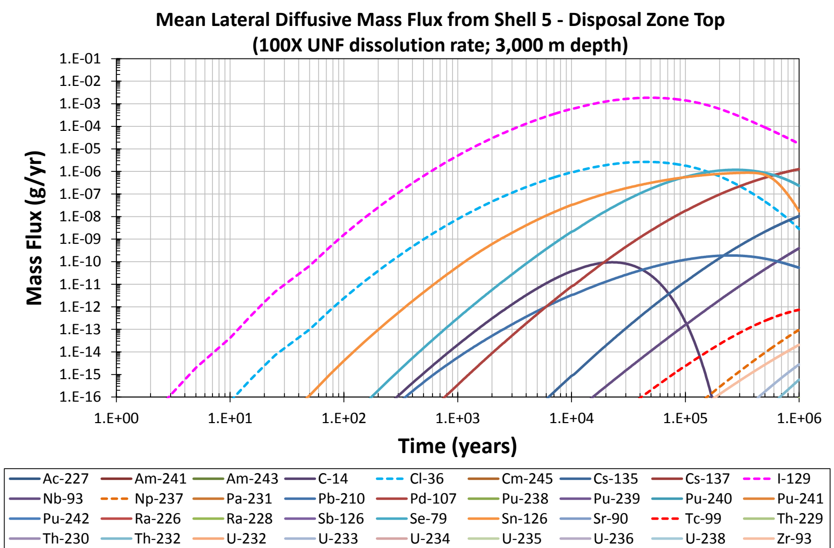


Figure 4-42. Model result of the enhanced SNF degradation case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (upper) and from Shell Region R5 to R6 (lower) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.

Releases at the mid-section of Seal Zone (2,500 m depth)

Figure 4-43 to Figure 4-45 show the model results of the enhanced SNF degradation case at the mid-section of the seal zone (2,500 m depth) of the central borehole of an 81-borehole array. The mean mass flux profiles are similar to the reference case profiles (Figure 4-16 to Figure 4-18), except that the peak mean mass fluxes are higher by about two orders of magnitude, which is consistent with the SNF degradation rate enhancement factor.

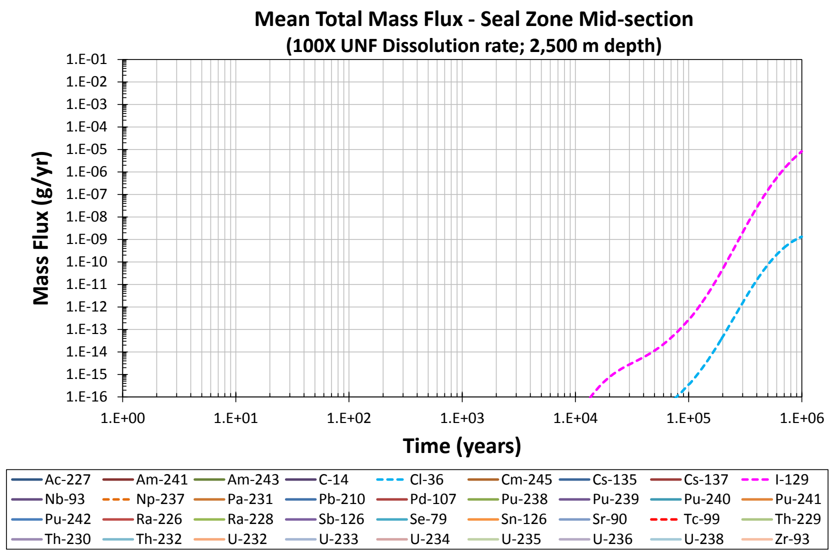
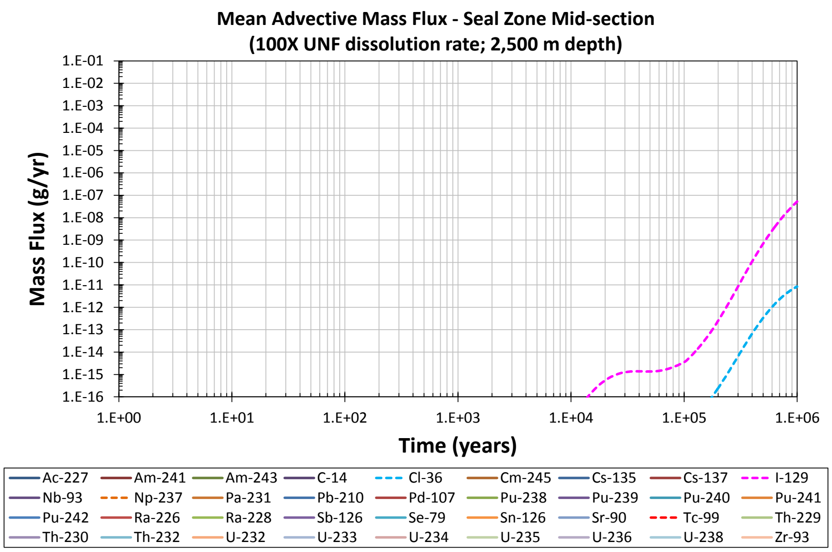


Figure 4-43. Model result of the enhanced SNF degradation case for mean total mass flux at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.

As for the reference case, the mean total mass fluxes of radionuclides at the seal-zone mid-section (Figure 4-43) are significantly lower than those at the top of the disposal zone (Figure 4-40), and only I-129, Cl-36 and Sn-126 have calculated mass fluxes; the Sn-126 mass flux is not shown in Figure 4-43 because of its very small mass flux. I-129 and Cl-36 mass fluxes continue to increase until the end of simulation. The mean total flux is dominated by the I-129 upward diffusive flux from the surrounding bedrock (Figure 4-44), and the peak mean total mass flux is $\sim 1\times10^{-5}$ g/yr at 10^6 years, which is about two orders of magnitude higher than the reference case peak mean total mass flux (Figure 4-16).

The mean lateral diffusive mass flux from the borehole into the bedrock (Figure 4-45) is about three orders of magnitude lower than the mean total upward mass flux, and the peak mean lateral flux is $\sim 3\times10^{-8}$ g/yr at 10^6 years (Figure 4-45). The mean lateral diffusive mass fluxes in the surrounding bedrock shells are about the same, indicating a steady-state has reached.



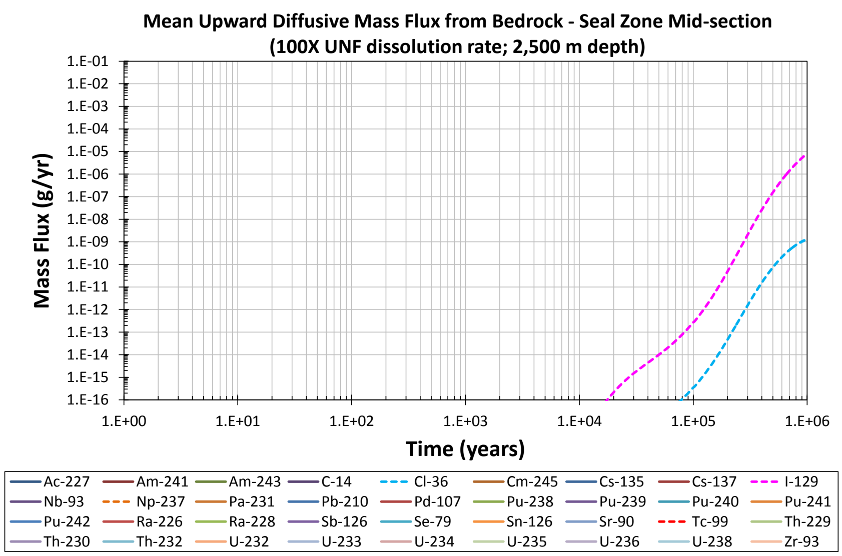
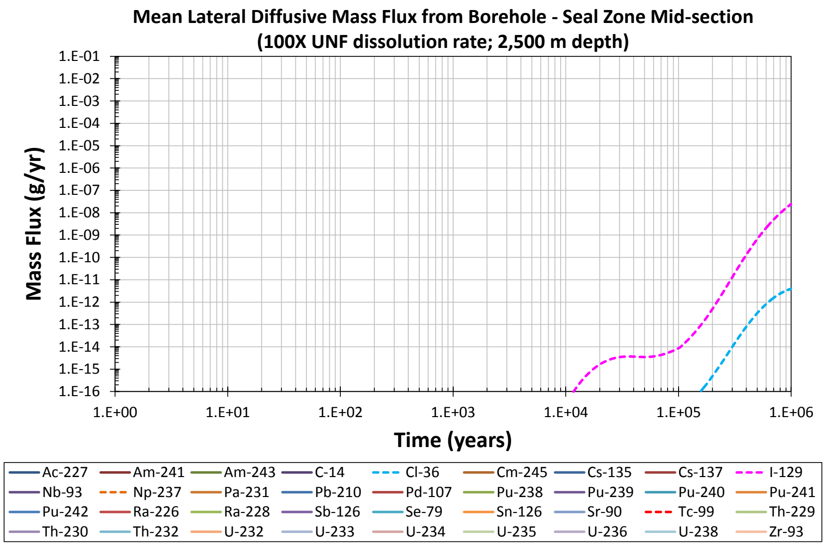


Figure 4-44. Model result of the enhanced SNF degradation case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.



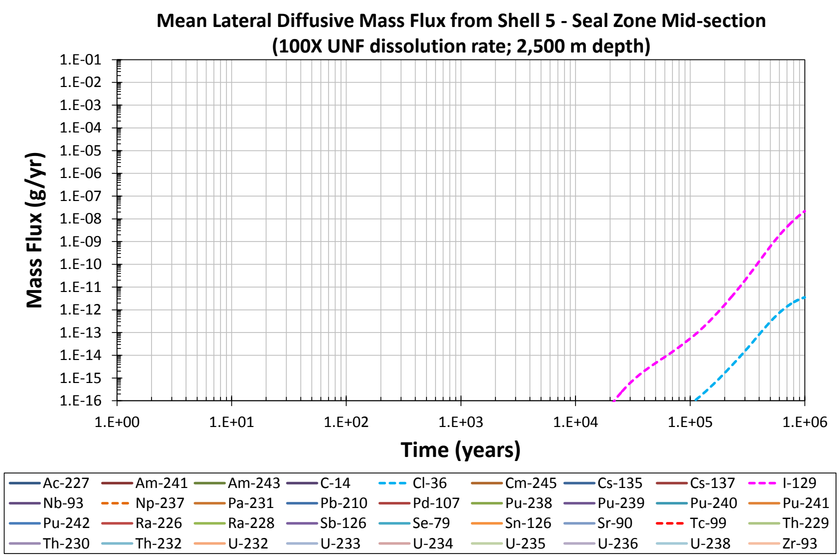


Figure 4-45. Model result of the enhanced SNF degradation case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (upper) and from Shell Region R5 to R6 (lower) at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.

<u>Releases at the top of Seal Zone (2,000 m depth)</u>

Figure 4-46 shows the model result of the mean total mass flux of the enhanced UNF degradation case at the top of seal zone (2,000 m depth) of the central borehole of an 81-borehole array. The fluxes are dominantly by the I-129 upward diffusive mass flux from the surrounding bedrock and are negligibly small. The peak mean total upward mass flux of I-129 is only ~2×10^{-11} g/yr at 10^6 years. Cl-36 also has calculated mass fluxes at much lower rates than I-129, with the peak mean mass flux at ~3×10^{-15} g/yr at 10^6 years. The model analysis shows no observed radionuclide mass fluxes at the mid-section of the upper zone (1,000 m depth).

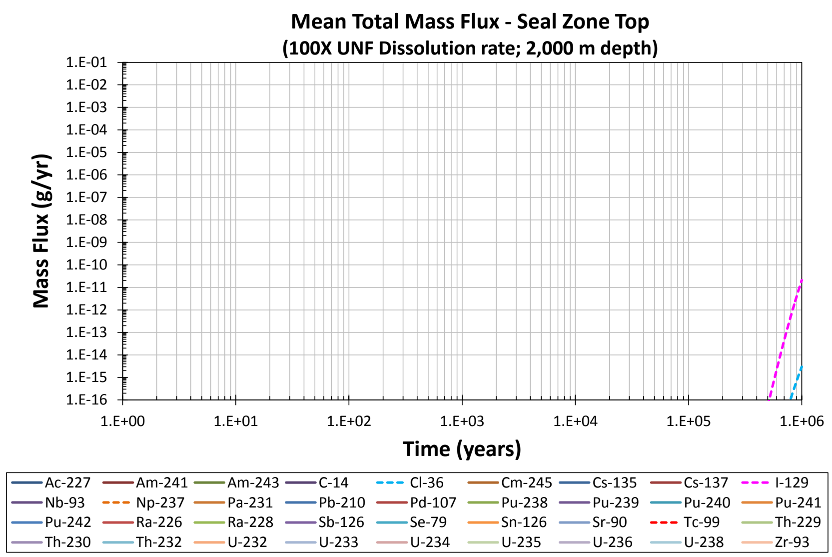


Figure 4-46. Model result of the enhanced SNF degradation case for mean total mass flux at the top of seal zone (2,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.

Combined High Groundwater Flux and Enhanced SNF Degradation Case

The deep borehole disposal concept was further evaluated by simultaneously changing two system parameters that were evaluated in the previous sensitivity analyses: 1) increase of the vertical groundwater flux by a factor of 10, and 2) increase of the UNF annual fractional degradation rate by a factor of 100. As was done in the previous sensitivity analysis, the new UNF degradation rate mode for this sensitivity analysis is a log-triangular distribution with a mode of 10^{-5} yr^{-1}, a minimum of 10^{-6} yr^{-1} and a maximum of 10^{-4} yr^{-1}. The SNF degradation rates used in this case are much higher than those expected for the geochemical conditions in the disposal zone.

<u>Releases from the top of Disposal Zone (3,000 m depth)</u>

Figure 4-47 to Figure 4-49 show the model results of the combined high groundwater flux and enhanced SNF degradation case at the top of disposal zone (3,000 m depth). The peak mean total upward mass release rate is ~0.05 g/yr at ~100 years and again at ~10^4 years, and dominated by the I-129 releases (Figure 4-47). The mean total upward mass flux is dominated by the advective mass flux in the borehole for the entire simulation period. The advective mass flux is greater than the upward diffusive flux from the surrounding bedrock due to the high water flux in the borehole (Figure 4-48), with a peak mean upward diffusive mass flux from the surrounding bedrock of ~0.001 g/yr at ~2×10^5 years, dominated by the I-129 flux. The discontinuous curves for the I-129 diffusive mass flux from the surrounding bedrock (lower figure of Figure 4-48) are due to the back-diffusion (i.e., negative diffusive mass flux transporting the mass downward) that results from higher I-129 dissolved concentrations in the bedrock region around the borehole right above the top of the disposal zone; more mass of I-129 is transported advectively upward in the borehole during the time periods when the back-diffusion occurs (lower plot in Figure 4-48).

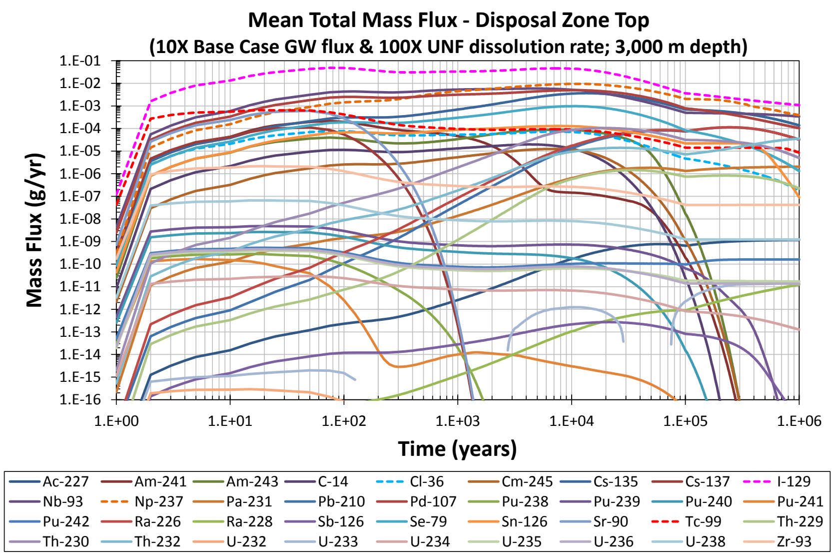
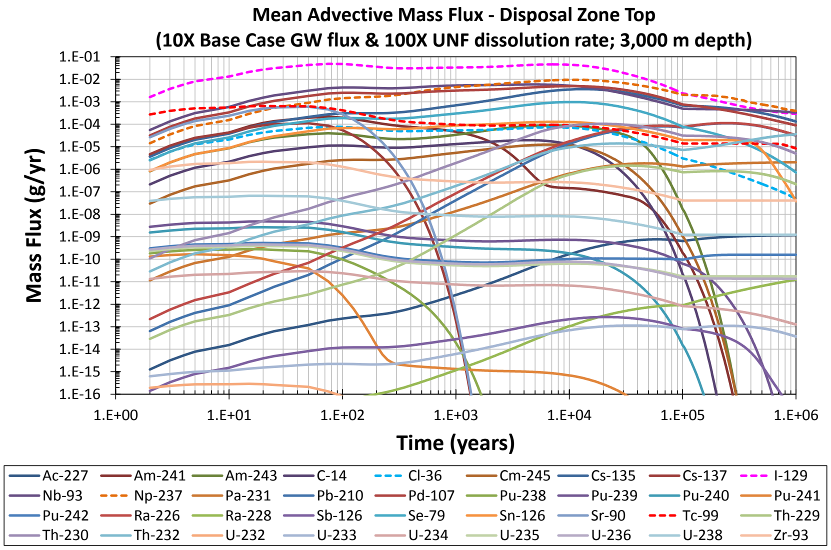


Figure 4-47. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean total mass flux at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.



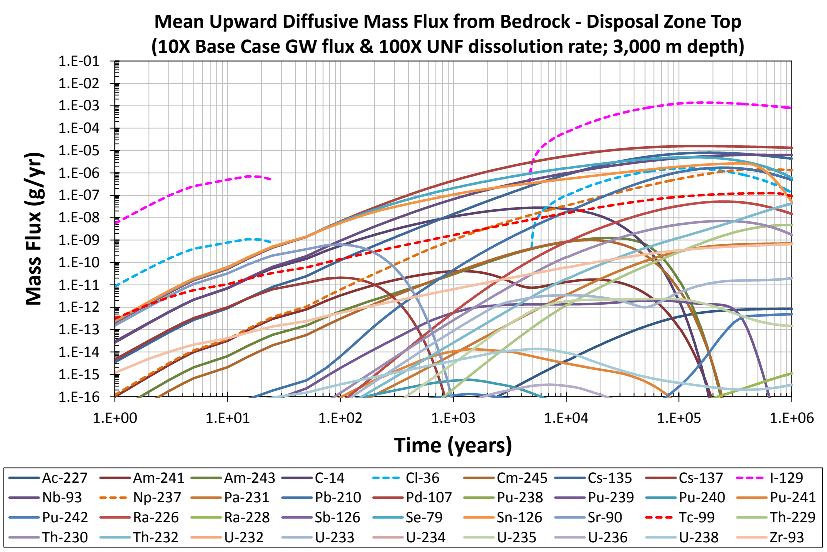
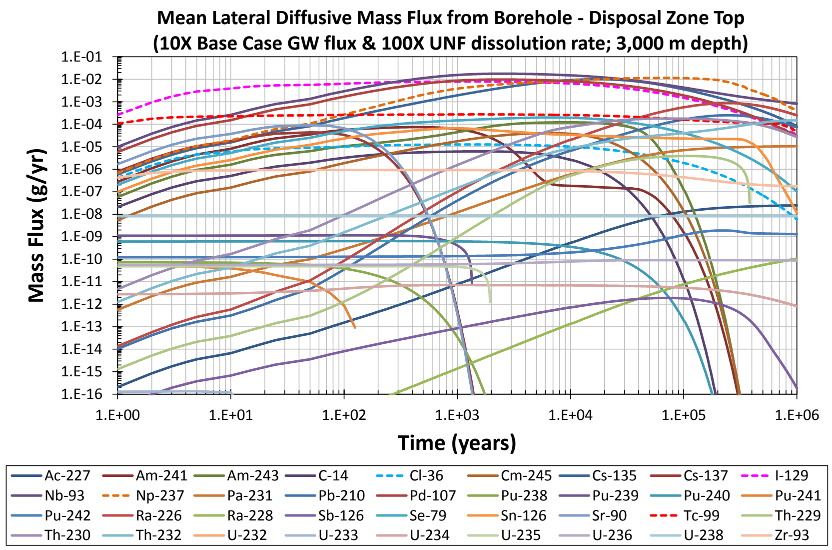


Figure 4-48. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.



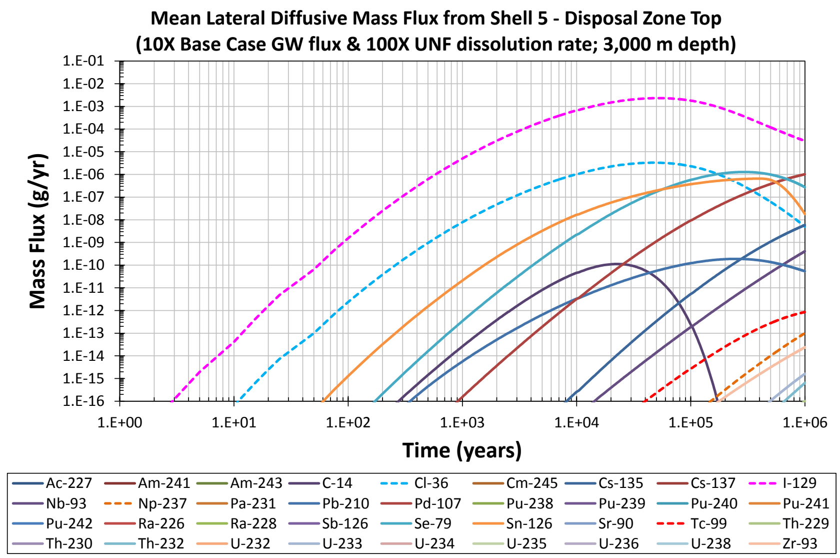


Figure 4-49. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (upper) and from Shell Region R5 to R6 (lower) at the top of disposal zone (3,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.

The mean lateral diffusive mass flux from the borehole to the surrounding bedrock (upper figure of Figure 4-49) is about the same order of magnitude as the mean total upward mass flux (figure 4-47), and this demonstrates the importance of lateral diffusional transport into and within the surrounding bedrock to the safety analysis of the deep borehole disposal system.

The mean lateral diffusive mass flux from the borehole to the surrounding bedrock is dominated initially by I-129 and later by Np-237 (upper figure of Figure 4-49), and the peak mean lateral diffusive mass flux is ~0.01 g/yr at ~10^5 years, mainly due to Np-237. There is an earlier peak mean lateral mass flux attributable to Nb-93 (~0.02 g/yr at ~2,000 years) but this radionuclide is not radioactive and does not contribute to dose. Note again that the discontinuous lateral diffusive mass flux curves of some RNs (upper figure of Figure 4-49) are due to the back-diffusion from the bedrock region right next to the borehole (Shell Region R2, Table 4-12). The mean lateral diffusive flux in outer bedrock shells is dominated by I-129, since other radionuclides are retarded by sorption on the bedrock materials. Figure 4-49 (lower figure) shows the mean diffusive mass flux from Shell Region R5 (second to the last shell; see Table 4-12).

Releases from the mid-section of Seal Zone (2,500 m depth)

Figure 4-50 to Figure 4-52 show the model results of the combined high groundwater flux and enhanced SNF degradation case at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array. The mean total upward mass fluxes are significantly lower than the mean total mass flux at the top of the disposal zone (Figure 4-50), since most radionuclides (except I-129 and Cl-36) are retarded in the seal zone as they sorb on the seal zone materials. The peak mean total mass flux is dominated by I-129 (~4×10^{-4} g/yr at ~2×10^4 years), and the Cl-36 peak mean mass flux (~5×10^{-7} g/yr at ~2×10^4 years) is secondary to the I-129 peak mean mass flux.

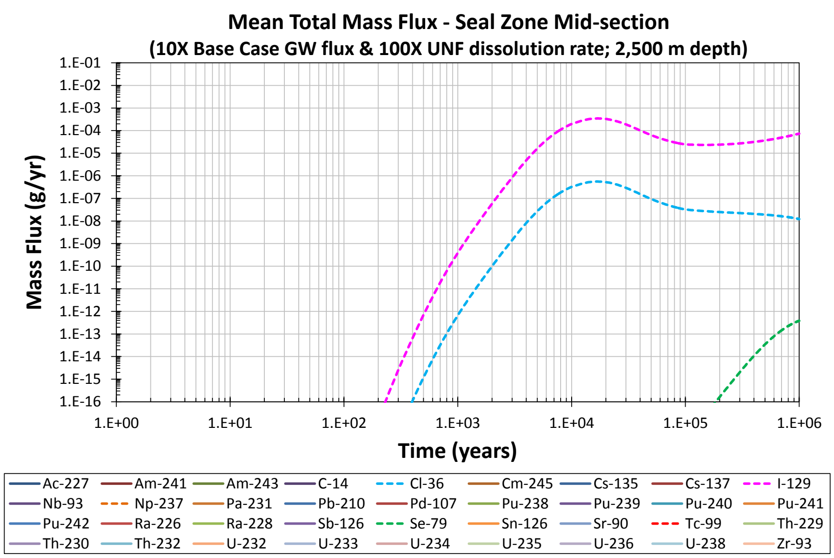
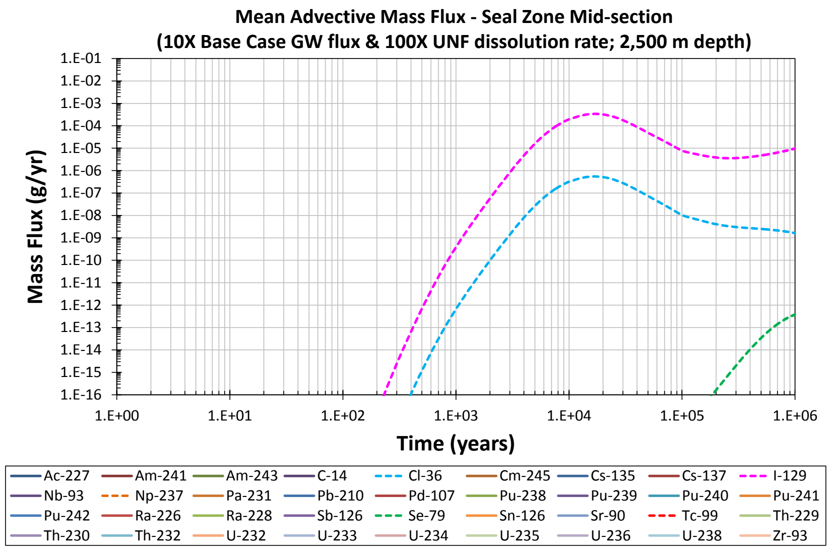


Figure 4-50. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean total mass flux at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.



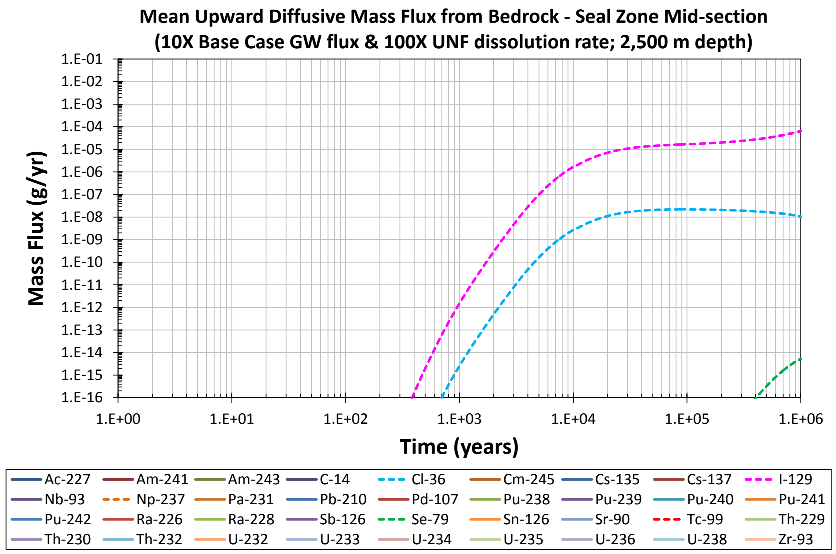
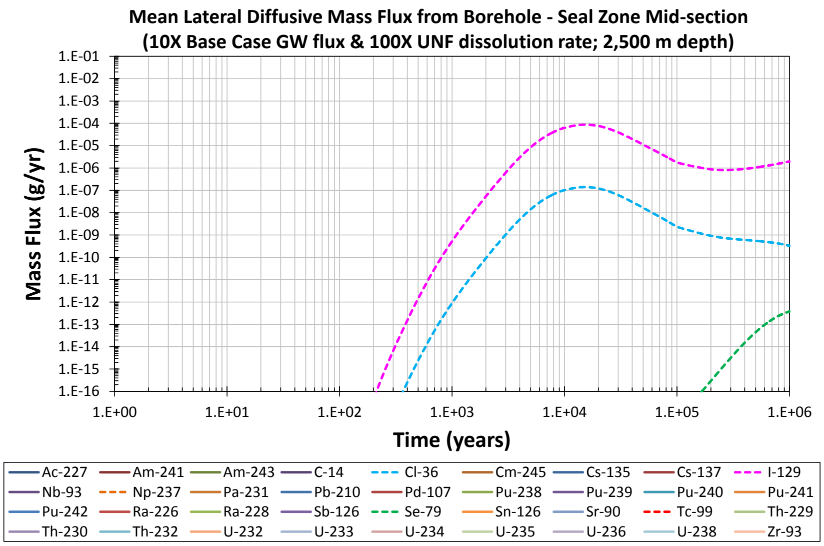


Figure 4-51. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the mid-section of seal zone (2,5000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.



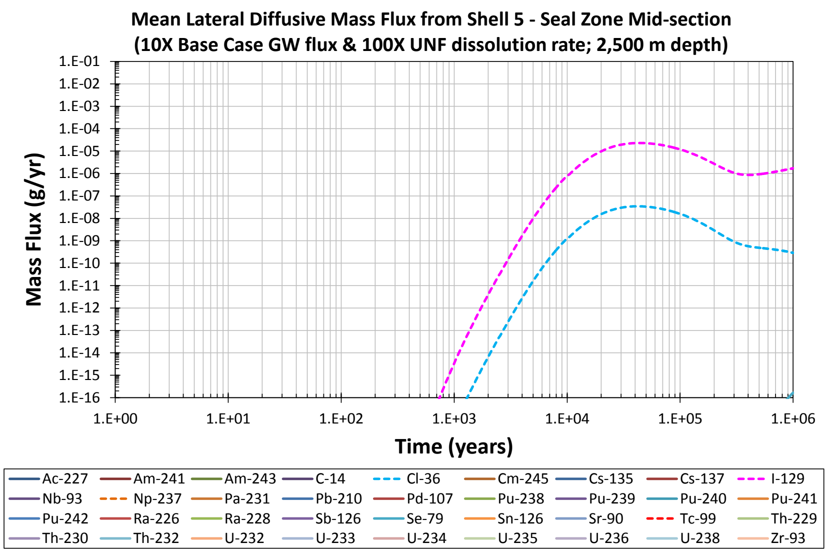


Figure 4-52. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (upper) and from Shell Region R5 to R6 (lower) at the mid-section of seal zone (2,500 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.

The mean total mass flux is dominated by the advective mass flux in the borehole for up to ~10^5 years, and the second peak mean flux at 106 years is dominated by the upward diffusive mass flux from the surrounding bedrock (~8×10^{-5} g/yr by I-129) (Figure 4-51). Other radionuclides (Se-79, Sn-126, Tc-99 and Pb-210 in the decreasing order of peak mass flux) have observed mass fluxes from the mid-section of the seal zone, but only the Se-79 fluxes are shown in the figures because other radionuclides have negligibly small release rates.

The I-129 mean lateral diffusive mass flux (~10^{-4} g/yr at ~1.5×10^4 years) from the borehole to the surrounding bedrock (Figure 4-9) is about the same order of magnitude as the I-129 mean total upward mass flux (Figure 4-52), and this shows the importance of the lateral diffusional transport into and within the surrounding bedrock in the safety analysis of the deep borehole disposal concept.

Releases from the top of Seal Zone (2,000 m depth)

Figure 4-53 to Figure 4-55 show the model results of the combined high groundwater flux and enhanced SNF degradation case at the top of seal zone (2,000 m depth). The advective mass flux in the borehole dominates for up to ~5×10^4 years, and afterward, the diffusive mass flux from the surrounding bedrock dominates (Figure 4-53 and Figure 4-54).

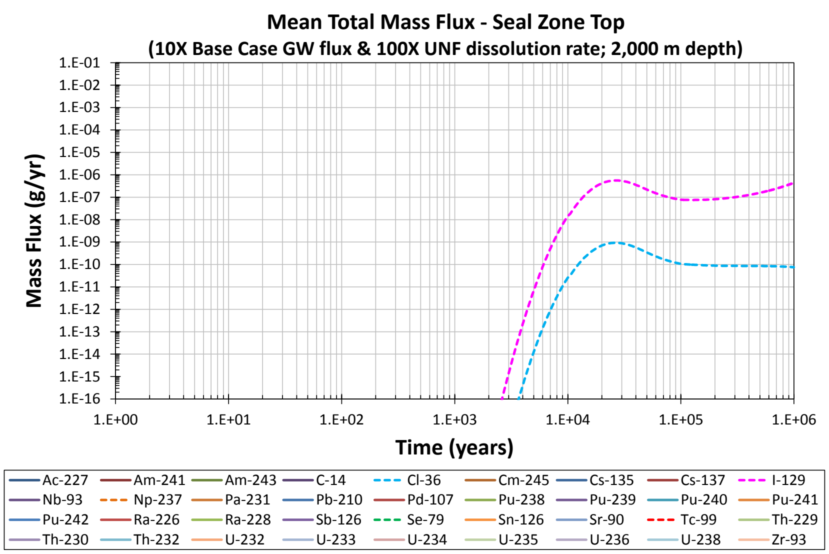
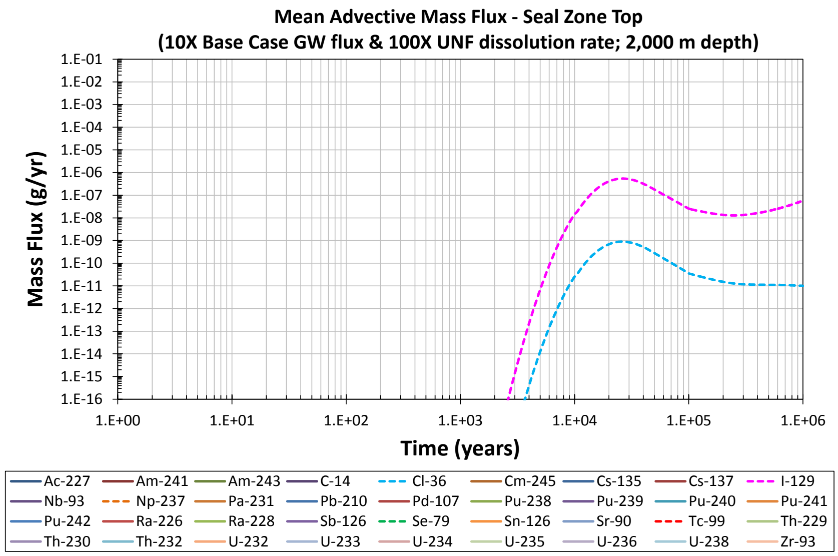


Figure 4-53. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean total mass flux at the top of seal zone (2,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.

The mean total upward mass flux (Figure 4-53) is dominated by I-129 with the first peak mean total flux of ~7×10^{-7} g/yr at ~2.5×10^4 years and the second smaller peak of ~5×10^{-7} g/yr at 10^6 years. The first peak mass flux is dominated by advective flux in the borehole, and the second peak mass flux by the upward mass flux from the surrounding bedrock. The Cl-36 peak mean total mass flux (~10^{-9} g/yr at ~2.5×10^4 years) is much lower. No other radionuclides have observed mass fluxes at the seal zone top.



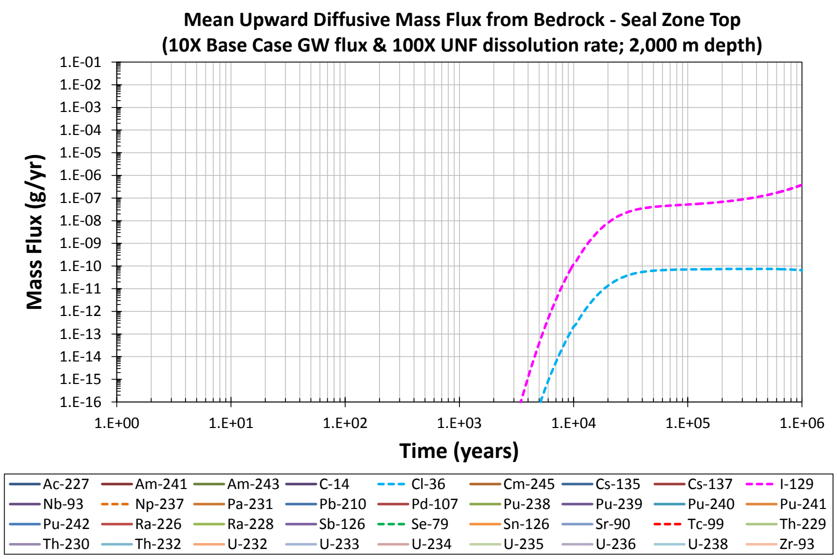
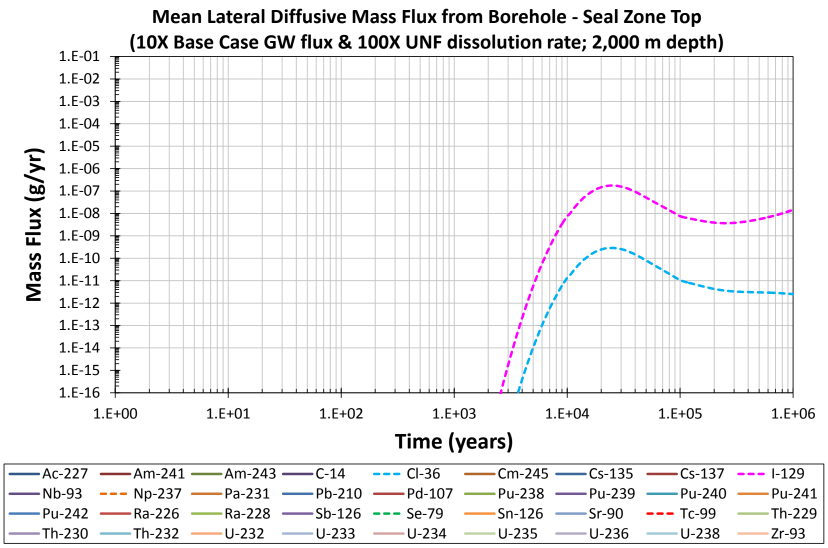


Figure 4-54. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the top of seal zone (2,0000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.



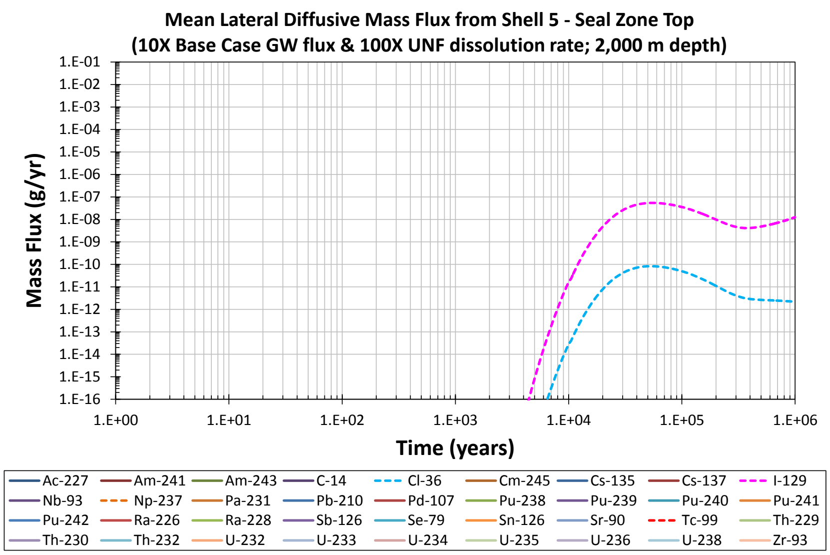


Figure 4-55. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean lateral diffusive mass flux from the borehole to surrounding bedrock (upper) and from Shell Region R5 to R6 (lower) at the top of seal zone (2,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.

The I-129 and Cl-36 lateral diffusive mass fluxes from the borehole to the surrounding bedrock (upper figure of Figure 4-55) are about the same order of magnitude as the I-129 and Cl-36 total upward mass fluxes (Figure 4-53), showing that the radionuclides diffuse into the surrounding bedrock at about the same rate of the upward total mass flux. The peak lateral diffusive flux from the borehole is ~2×10^{-7} g/yr at ~2.5×10^{4} years by I-129.

Releases from the mid-section of Upper Zone (1,000 m depth)

Figure 4-56 and Figure 4-57 show the model results at the mid-section of upper zone (1,000 m depth). Figure 4-56 shows the mean total upward mass flux, and I-129 is the dominant radionuclide contributing to the mean total mass fluxes. The peak mean total mass flux is ~4×10^{-12} g/yr at 10^6 years for I-129. The mean total releases (i.e., I-129 releases) are dominated by the upward diffusive mass flux from the surrounding bedrock (Figure 4-57). The Cl-36 releases are much smaller with the peak mean mass flux of ~2×10^{-15} g/yr at ~5.5×10^4 years. The peak mean lateral diffusive mass flux from the borehole to the surrounding bedrock (~8×10^{-13} g/yr for I-129) is about the same order of magnitude as the peak mean total upward mass flux (figure not shown).

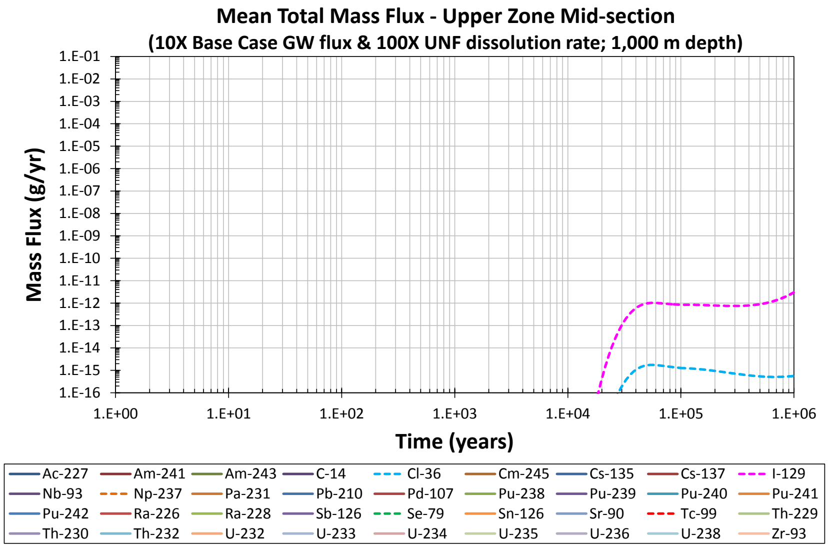
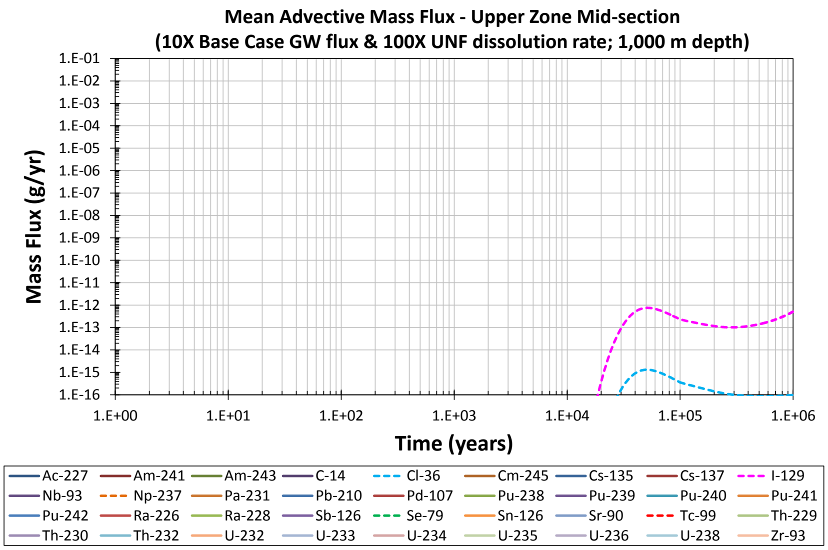


Figure 4-56. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean total mass flux at the mid-section of upper zone (1,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial UNF.

Releases from the top of Upper Zone

Figure 4-58 shows the model result of the mean total upward mass flux of the combined high groundwater flux and enhanced SNF degradation case at the top of upper zone of the central borehole of an 81-borehole array. Only I-129 and Cl-36 have observed mass fluxes, but they are negligibly small. The peak mean total mass flux for I-129 is ~5×10^{-20} g/yr at 10^6 years, and the peak rate for Cl-36 is ~1×10^{-23} g/yr at 10^6 years. The radionuclide mass fluxes are dominated by the upward diffusive mass flux from the surrounding bedrock (not shown).



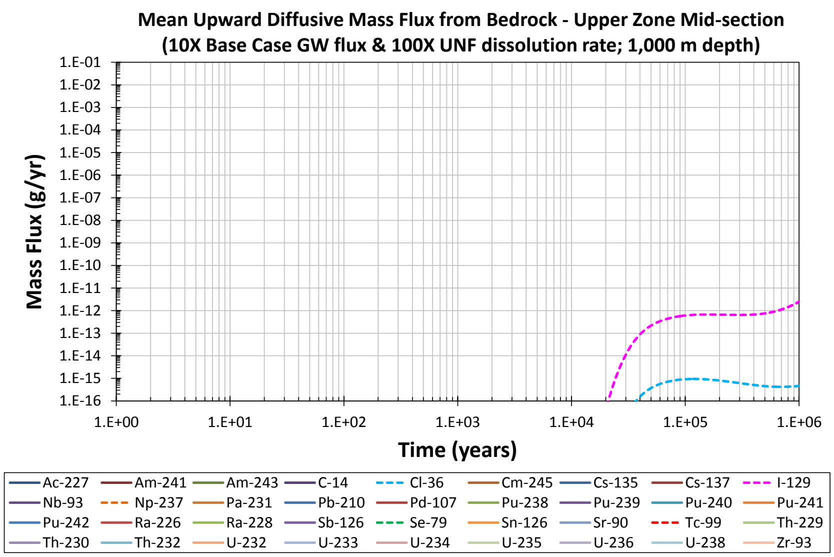


Figure 4-57. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean vertical advective mass flux in the borehole (upper) and mean total upward diffusive mass flux from surrounding bedrock (lower) at the mid-section of upper zone (1,000 m depth) of the central borehole of an 81-borehole array for disposal of commercial SNF.

Figure 4-59 shows the model result of the mean annual dose by radionuclides for this sensitivity case. The IAEA ERB1B dose model (IAEA 2003) was used to calculate the dose. The calculated annual dose is negligibly small with the peak mean annual dose of ~4×10^{-19} mrem/yr at 10^6 years for I-129.

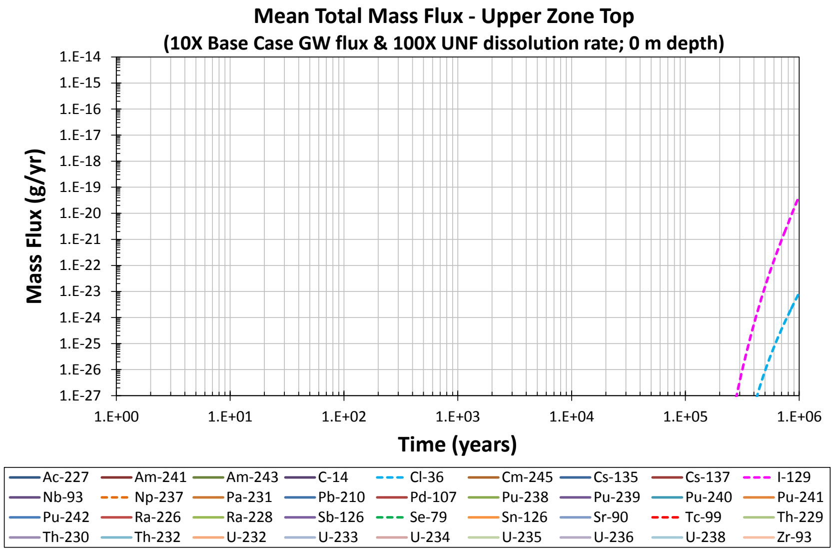


Figure 4-58. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean total mass flux at the top of upper zone of the central borehole of an 81-borehole array for disposal of commercial SNF.

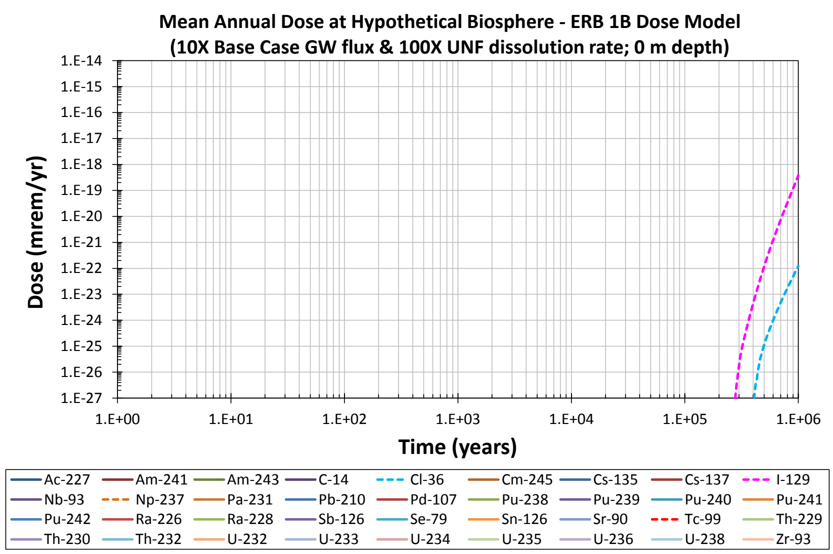


Figure 4-59. Model result of the combined high groundwater flux and enhanced SNF degradation case for mean annual dose by radionuclides released from the central borehole of an 81-borehole array for disposal of commercial SNF.

4.4.3 Summary and Discussion

The PA analysis with the updated PA model demonstrates significant lateral diffusion of radionuclides from the borehole into the surrounding bedrock and diffusional transport within the bedrock. This process makes the deep borehole disposal system more resilient and less sensitive to changes of the system parameters tested in the PA analysis. The surrounding bedrock functions as a large storage or buffer for transport of radionuclides, and most radionuclides (except I-129 and Cl-36) that have diffused into the surrounding bedrock are sorbed onto the bedrock materials, which strongly delay their transport.

In the disposal zone, lateral diffusive flux from the borehole into the surrounding bedrock is greater than the upward mass flux. In the seal zone and the upper zone (if radionuclide mass has reached the seal zone), lateral mass flux from the borehole into the surrounding bedrock is about the same order of magnitude as the upward mass flux. This demonstrates the importance of the diffusional mass transport into the surrounding bedrock for the system performance and safety analysis. This process, generally not considered for a safety case analysis for a mined geologic repository, is unique and important to the deep borehole disposal concept, and provides an additional safety attribute for the deep borehole disposal concept.

For the current deep borehole conceptual design, the PA analysis has shown that high water fluxes in the borehole are required to move more than a negligible amount of radionuclide mass to the surface. Upward diffusive mass flux alone is not enough to transport radionuclide mass to the surface environment to have a meaningful impact on the biosphere dose.

Based on the current PA analysis, it appears that the seals and plugs for the seal zone and upper zone are important, but they do not seem “critical” to the system performance. The upward radionuclide diffusive mass flux from the surrounding bedrock is greater than the advective flux in the borehole. The total upward mass flux in the seal and upper zones is dominated by the upward diffusive flux from the surrounding bedrock, rather than the upward advective flux in the borehole.

The current PA analysis provides an important insight that a more detailed representation of groundwater flows in surrounding bedrock, especially, if occurs, fracture flows, needs to be included in the safety analysis in order to better represent advective transport in the surrounding bedrock; only diffusive transport is modeled in the surrounding bedrock in the current PA analysis.

The rather coarse grid resolution for lateral diffusion (i.e., 6 cylindrical shells for a 100 m distance) implemented in the updated PA model could have overestimated the diffusive flux into the bedrock. Nevertheless, the analysis indicates the important contribution to system performance likely attributable to lateral diffusion, which is unique to the DBD concept. The impact of lateral diffusion should be evaluated with a finer grid resolution (or greater number of concentric shells).

4.5 Summary Safety Case for Deep Borehole Disposal

This section introduces an initial study conducted for a generic safety case of the deep borehole disposal of high-level nuclear waste. Details of this study are documented in Appendix A of this report. The primary objective of this study is to investigate the feasibility of developing a generic safety case for disposal of commercial spent nuclear fuel, and potentially other specialized radioactive waste forms in the lower reaches (3-5 km) of deep boreholes drilled into crystalline basement rock. A *safety case* is an integrated collection of evidence, analyses, and other qualitative and quantitative arguments used to demonstrate the safety of a disposal concept. A *generic safety case* has much of the same basic structure and objectives as an actual safety case, but it is not site specific and its primary purpose is to provide the necessary structure for organizing and synthesizing existing deep borehole science and identifying RD&D activities that should be carried out in a full-scale demonstration of the concept.

In this study, the major elements of the safety case are patterned after the NEA post-closure safety case (NEA 2004) and also include aspects of pre-closure safety as follows (see Appendix A of this report for additional detail):

- *Statement of Purpose*. Describes the current status of the deep borehole disposal concept program
- *Safety Strategy*. This is the high-level approach adopted for achieving confirmation that deep borehole disposal is safe.
- *Site Characterization and Disposal System Design*. This contains key portions of the *assessment basis* that is described in some safety case concepts (NEA 2004).
- *Pre-closure and Post-closure Safety Evaluation*. This includes a quantitative safety assessment of potential radiological consequences associated with a range of possible evolutions of the system over time.
- *Statement of Confidence and Synthesis of Evidence*. The statement of confidence is based on a synthesis of safety arguments and analyses.

The safety case outlined in this study starts with the recent design concept for a deep borehole repository developed by Arnold et al. (2011a). The primary components of the reference design include:

- Boreholes
- Borehole casing system
- Waste canisters
- Surface handling and shielding system
- Waste emplacement system
- Borehole sealing and abandonment
- Operational safety assurance and monitoring

The pre-closure safety involves a systematic examination of the site, the design, and the potential initiating events caused by underlying hazards (e.g., DOE 2008). An initiating event is a departure from normal operation that triggers an event sequence. A pre-closure safety analysis will consist of internal and external initiating event identification, event sequence analysis, radiological dose and consequence analysis, and criticality analysis. In the case of deep borehole disposal, the analysis will be supported by drilling safety data from the petroleum industry, and waste packaging, handling, and emplacement data from radioactive waste disposal programs and demonstration projects.

The post-closure safety evaluation addresses the ability of a site and repository facility to meet safety standards and to provide for the safety functions of the engineered and/or geological components. A complete safety or performance assessment includes quantification of the long-term, post-closure performance of the repository, analysis of the associated uncertainties in the prediction of performance, and comparison with the relevant design requirements and safety standards. Initial performance assessments are summarized in this report in Sections 4.3 and 4.4.

A key consideration in the assessment of post-closure safety is the identification and analysis of uncertainties that have the potential to significantly impact the understanding of the degree of safety the system offers. Sensitivity analyses from the post-closure safety assessment will provide the basis for defining the types of tests and studies needed to reduce uncertainty and for assigning priorities for further R&D work.

A deep borehole research and demonstration project would build additional confidence in the areas that would be better examined at a large scale, such as aspects of drilling operations, borehole stability, canister emplacement and retrieval, operational efficiency, sealing effectiveness, and safety. Examining coupled physical and chemical processes at a field scale would help reduce residual uncertainty in these processes.

Focused research activities at the field scale must be “risk-informed” in a systematic fashion by the current version of the generic safety case and any associated performance assessment analyses, such as uncertainty and sensitivity analyses, which generate valuable information to determine the parameters and processes that most affect repository performance. It is important that a technical management and assessment structure be put in place prior to any testing at a demonstration project site. Such a structure would first consider the overall testing needs and preferred arrangements of the site consistent with the safety case.

Finally, one important and necessary aspect of each element of the generic safety case is quality assurance (QA). All elements of a deep borehole demonstration must be properly planned, implemented, and documented, such that the technical basis for confirming the safety of the concept is repeatable, transparent, and traceable. These requirements are applicable to site characterization, general collection of data for PA, PA software and models, expert judgment activities, borehole drilling and construction, and pre-closure and post-closure demonstration activities.

5. DEMONSTRATION PROJECT PLANNING

5.1 Deep Borehole Disposal Consortium

The Deep Borehole Disposal Consortium was established through the course of two meetings in Albuquerque, New Mexico in 2011 and 2013 and consists of industrial and academic partners that were assembled to enhance efforts to complete a deep borehole demonstration. Members include Areva, CH2M-Hill, DOSECC Exploration Services, Massachusetts Institute of Technology, Olympic Research, Sandia National Laboratories, University of Sheffield, and URS. In August, 2013 a Memorandum of Understanding (MOU) was signed to enable collaboration between the parties to "promote the construction and operation of a deep borehole demonstration to evaluate the feasibility of long-term disposal of nuclear waste". The MOU establishes a legal mechanism for consortium members to collaborate and specifically identifies the following as potential areas of emphasis.

- **Stakeholder community for a deep borehole demonstration and implementation**- Individuals and organizations that support the development of deep borehole disposal will be identified and informed in ongoing communication with the consortium.
- **Functional and operational requirements for a deep borehole demonstration project**- The demonstration project will strike a balance between scientific investigations and engineering demonstration. Scientific investigations will be directed at achieving technical acceptance of the disposal concept. Engineering demonstration will resolve issues of operational safety, feasibility, and cost of deep borehole disposal.
- **Funding and location of deep borehole demonstration project**- Funding for the deep borehole demonstration will be achieved in an adaptive manner that potentially draws from industry and governmental sources. Funding may consist of both cash and in-kind support from consortium participants and outside sources. The demonstration project will be conducted at a location that is geologically appropriate, has political and social acceptance, and can be generalized to other geographical locations.
- **Future deep borehole regulations** - The consortium can inform the development of regulations through engagement with legislators and regulators on technical issues.
- **Size characterization for deep borehole disposal** - The disposal concept is based on greater isolation with depth. This isolation is demonstrated by key geological characteristics of the system and precludes the need for detailed and extensive characterization of near-subsurface processes that would interact with a shallower mined repository and engineered systems but are irrelevant to safety for deep borehole disposal. Identification of site characteristics key to waste isolation and corresponding testing methods is important to gaining acceptance of deep borehole disposal. Key characteristics that can be evaluated on a "site" basis versus those characteristics that must be determined in each disposal borehole will be delineated.

6. SUMMARY AND CONCLUSIONS

DOE is investigating deep borehole disposal as one alternative for the disposal of spent nuclear fuel and other forms of radioactive waste. The overarching goal of deep borehole disposal research for FY13 is to advance the deep borehole disposal technical basis needed to demonstrate the viability of this disposal concept and move the option of deep borehole disposal toward implementation of a full-scale demonstration project, consistent with the RD&D roadmap for deep borehole disposal (DOE 2012a). The scope of the deep borehole disposal work package consists of three tasks: (1) an evaluation of site selection guidelines for a deep borehole demonstration project, (2) an assessment of deep borehole seals and waste emplacement, and (3) development of a safety framework for deep borehole disposal.

Selection of a site for a deep borehole disposal demonstration project would be informed by numerous factors that fall into several categories, including technical factors, logistical/practical factors, and sociopolitical factors. Numerous technical factors are potentially important to drilling and construction of a deep borehole, successful completion of a deep borehole disposal demonstration project, and the post-closure safety of the disposal system. Logistical factors for a deep borehole disposal demonstration project are linked to availability of drilling and support services, which can be adapted from the petroleum industry, geothermal industry, and, to a lesser extent, deep scientific drilling activity. Analysis of social and political factors related to site selection is generally beyond the scope of this report, but early engagement with local and regional stakeholders at any potential location, particularly in the scientific and academic communities, would likely improve the chances of implementing a demonstration project. Overall, the demonstration site selection strategy is to maximize the probability of successfully completing a borehole in geological, hydrogeological, and geochemical conditions favorable for waste isolation, within budgetary and schedule constraints.

The reference deep borehole disposal concept is based on waste disposal and sealing of the borehole in crystalline basement rock. The depth to crystalline basement could be anything less than 2,000 m, with a borehole disposal zone and overlying seal zone in the crystalline basement having lengths of 2,000 m and 1,000 m, respectively, including sites with crystalline basement rocks that outcrop at the surface. The existing regional-scale database of depth to the crystalline basement indicates large areas in the conterminous U.S. with depths of less than 2,000 m to the crystalline basement (Figures 2-1 and 2-2). The regional-scale database is incomplete in structurally complex areas, primarily in the western U.S.; however, locations with depths of less than 2,000 m to crystalline basement also exist in local areas in these regions.

The lithology of the crystalline basement may be important to deep borehole disposal in terms of drilling and borehole completion, and with regard to post-closure safety of the disposal system. Directional control of drilling is generally easier in homogeneous crystalline rock, such as plutonic rocks because the drill bit can be strongly deflected by layered or foliated metamorphic rocks in which the fabric of the crystalline rock is oriented at an angle to the desired drilling direction. Plutonic rocks, and large felsic igneous intrusive rocks in particular, tend to be more homogeneous than metamorphic rocks or volcanic igneous units, resulting in more straightforward assessment of the host rock and potentially fewer heterogeneous features that could serve as preferential pathways for contaminant migration.

Major structural features such as faults, shear zones, folding, and tectonic complexes in the crystalline basement could have significant, generally negative impacts on drilling, borehole construction, and post-closure safety characteristics of a deep borehole demonstration site. Large-scale structural features in the crystalline basement are often inferred from geophysical data, such as aeromagnetic surveys, particularly where outcrops of Precambrian rocks are obscured by sedimentary cover. The midcontinent rift system in the Precambrian basement is a large tectonic feature in the north-central part of the U.S. that has significance for site selection because of thick clastic sedimentary and mafic volcanic rocks filling the rift basin and rift faults that bound this structural system.

It is important to understand regional and localized horizontal stress in order to best ensure borehole integrity and characterize the disturbed rock zone around the borehole. Differential horizontal stress can result in borehole breakouts at greater depths, potentially interfering with drilling, setting casing, and borehole seals integrity, and creating zones of higher permeability along the borehole walls. Data exist on the directions of minimum and maximum horizontal stress, but information on the magnitudes of stress generally does not exist.

Rates of uplift, as indicators of tectonic stability, are available at regional scales (for example, for isostatic uplift following continental glaciation). However, tectonic uplift rates would generally have to be determined on a site-specific basis.

Geothermal heat flux and geothermal gradient are important for siting a deep borehole disposal demonstration project or disposal system because they determine or influence: 1) temperature conditions at depth that can affect drilling, emplacement operations, EBS materials characteristics, and waste form characteristics, 2) potential for future human intrusion by drilling for geothermal resource exploitation, and 3) as indicators of ambient vertical groundwater flow in the regional flow system. Significant variations in geothermal heat flux and gradient occur at the regional scale, with generally higher values occurring in the western U.S.

Groundwater flow is dominantly driven by topographic relief in most flow systems, with flow rates and depths of active groundwater flow being generally greater in areas with higher topographic relief. Large areas of high topographic relief are predominantly in the western U.S., the Appalachian Mountains, and the northeastern U.S. The safety of deep borehole disposal would be less sensitive to regional groundwater flow conditions than a mined repository because of the deeper disposal depth. However, consideration of factors related to topographically driven groundwater flow rates as a guideline for demonstration project site selection could increase the probability that conditions favorable to waste disposal would be encountered at a selected borehole site. In particular, lack of topographic driving forces would decrease the likelihood of upward hydraulic gradients in fluid potential and increase the likelihood of very old, highly saline fluids at depth.

Fault movement and volcanism that were active in the Quaternary pose potential direct risks to deep borehole disposal and are indicators of active tectonism. However, being close to a Quaternary fault or volcano does not disqualify a site for a deep borehole demonstration project. It means that the area should be studied in greater detail to determine the likelihood of active faulting or volcanism at the borehole site.

The presence of mineral or other resources at the depth of deep borehole disposal would potentially impact disposal system performance through direct intrusion by future exploratory drilling and mining activities. Little is known about the potential for mineral resources in deep crystalline basement rocks, particularly in areas where the basement is overlain by sedimentary rocks. Overall, there is a low probability of mineral deposits at a given site that could be economically exploited in crystalline basement rocks of the U.S. at depths of several kilometers.

Deep drilling is now common within the petroleum industry, but there are few examples where large diameter wells have been drilled in crystalline bedrock to depths of 5,000 meters. Although rigs large enough to drill a reference design borehole are not common, there are at least seven drilling contractors in the US that have this capability. These rigs are located in the western and southwestern US. Drilling support services are available through companies that work with the petroleum drilling sector. The supply chain within the US is robust and it is expected that services and supplies can be procured by competitive bid addressed to a number of different suppliers for each type of equipment or service.

The details of the legal and regulatory requirements for permitting a DBD demonstration project are different in different states and for Federal versus private land; however, the project team will utilize compliance with the National Environmental Policy Act as guidance to inform the decision on site selection. The project scope and duration are not of a magnitude that would generally require an Environmental Impact Statement, so planning should be conducted for an Environmental Assessment, which is considerably less rigorous than an Environmental Impact Statement. Drilling, land, and water use permits are also generally subject to state regulation and are routinely granted for other drilling operations in most states.

Key objectives of the borehole seals effort are to use *ex situ* testing to: 1) demonstrate performance of bentonite seals; 2) measure brine/cement impact on bentonite permeability; 3) build the technical basis for rock-welding of seals, and 4) identify (any) effects of waste package corrosion on seals. Avoiding bentonite shrinkage is one key to assuring low seal permeabilities. Another is demonstrating that cement will not undergo large-scale volume changes over several thousand years. Bentonite volume is reduced by high ionic strength and/or the introduction of divalent cations, such as Ca^{+2}, Mg^{+2}, and Fe^{+2} (produced during the anoxic corrosion of steel casing).

Research on alternative seals has been directed at the main seals emplaced above the waste disposal zone and at the sealing and support matrix that surrounds the waste canisters. Rock welding in the main seals zone by partial melting and recrystallization of crushed rock within the borehole and of the surrounding host rock would likely produce a robust seal of the borehole and the excavation damage zone. A rock welding seal would be highly durable because, unlike bentonite and cement, it would be in chemical and mineralogical equilibrium with the physical and chemical conditions at depth. Modeling work indicates that a rock melt volume of sufficient size to form such a seal could be generated with an electrical resistance heater, with a modest power requirement (about 11 kW) and in a reasonable time. The shape and size of the rock weld can be controlled by varying the length and diameter of the heater. Materials such as bentonite, cement grout, and low melting temperature metal alloys have been investigated as sealing and support matrices; however, challenges remain concerning the operational emplacement and suitability of these materials. Research is continuing to address these challenges and to evaluate candidate formulations with regard to rheology, setting or thickening time, hardening and mechanical properties, geochemical reactions, and durability. The rate at which waste canisters could be emplaced may be limited by a number of factors, including the practicality of emplacing multiple canisters simultaneously, the rate at which packages can be delivered to the wellhead, fluid displacement limitations, efficiency and safety of the lowering mechanism, and the risk of boiling conditions near the surface for waste canisters with high heat output.

The technical bases for the safety framework have been updated or reevaluated with regard to thermally driven groundwater flow, nuclear criticality and operational safety. Large-scale thermal hydrologic modeling has been updated to incorporate more realistic geological and hydrogeological conditions, and to provide input to an updated PA model of the deep borehole disposal system. Results indicate an extended period of elevated temperatures beyond 1,000 years following waste emplacement for arrays with more than 9 disposal boreholes, with a secondary peak temperature occurring at several thousand to 10,000 years. Simulated vertical upward groundwater flux in the borehole and disturbed rock zone occurs in the waste disposal zone for an extended period of time. Significant, but lower vertical flux also occurs above the waste disposal zone through potentially degraded seals and/or the surrounding disturbed rock zone. Criticality safety is not a design, operation or permitting issue for conducting the demonstration project, because the use of actual nuclear fuel is not anticipated.

A systematic approach to the prioritization of RD&D activities uses information from several previous PA analyses and from the updated PA model documented in this report. The focus of this analysis is primarily on post-closure safety of the deep borehole disposal system. A synthesis of existing PA analyses has identified the more important processes with regard to disposal system safety and the associated characterization activities.

The updated deep borehole disposal PA model incorporates the simulated vertical flow rates from the updated thermal-hydrologic modeling and includes a significant conceptual improvement relative to previous PA modeling through the implementation of lateral radionuclide diffusion between the borehole groundwater pathway and the surrounding rock. The updated PA model is implemented in the GoldSim software code and is similar to previous modeling described in Lee et al. (2011) and Vaughn et al. (2012b) with regard to aspects other than lateral matrix diffusion. Base-case simulations with the updated PA model demonstrate lateral diffusion of radionuclides from the borehole into the surrounding bedrock and indicate no releases of radionuclides to the biosphere and zero dose within 1,000,000 years of deep borehole disposal. Sensitivity analyses for a case in which the vertical groundwater flow rates are increased by a factor of 10 and the waste form degradation rate is increased by a factor of 100 show a negligibly small peak mean annual dose at 1,000,000 years of about 4×10^{-19} mrem/yr, primarily from releases of I-129.

The primary objective of the safety framework task is to build confidence in the safety of disposing spent nuclear fuel and/or other forms of radioactive waste in a deep borehole disposal system. The initial safety framework summarized in Section 2.3 and documented as a stand-alone report in Appendix A focuses on a generic safety case for the deep borehole disposal concept. This safety framework is developed using information collected and analyses conducted prior to and during the course of the deep borehole demonstration.

The Deep Borehole Disposal Consortium was established during the course of two meetings in Albuquerque, New Mexico in 2011 and 2013 and consists of industrial and academic partners that were assembled to enhance efforts to complete a deep borehole demonstration. A Memorandum of Understanding (MOU) was signed to enable collaboration between the parties to “promote the construction and operation of a deep borehole demonstration to evaluate the feasibility of long-term disposal of nuclear waste.” Members having signed the MOU include

Areva, CH2M-Hill, DOSECC Exploration Services, Massachusetts Institute of Technology, Olympic Research, Sandia National Laboratories, University of Sheffield, and URS.

Important conclusions from this milestone report include the following:

- Evaluation of technical and logistical site selection guidelines indicates that there are large areas within the conterminous U.S. that are favorable for the location of a deep borehole disposal demonstration project, in particular, and long-term deep borehole disposal, in general.
- Specific requirements for experimental evaluations of bentonite and cement as seals materials have been identified.
- Numerical modeling of rock melting and the formation of rock welding seals indicates that this is a potentially viable alternative borehole sealing method.
- Higher priority science and engineering R&D activities for a deep borehole demonstration project have been identified, based on importance to post-closure safety.
- Updated thermal-hydrologic modeling of a multiple-borehole disposal system and updated PA modeling that includes lateral diffusion from the borehole indicate no radionuclide releases to the biosphere within 1,000,000 years for the undisturbed base-case scenario.
- A Deep Borehole Disposal Consortium consisting of Sandia National Laboratories, industrial, and academic partners was established to “promote the construction and operation of a deep borehole demonstration to evaluate the feasibility of long-term disposal of nuclear waste.”
- A generic safety case study has been documented and indicates that a defensible safety case can be developed for deep borehole disposal of high-level nuclear waste, assuming that the demonstration project confirms the technical bases underlying the deep borehole disposal concept.

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Appendix A. Draft Safety Case for Deep Borehole Disposal of High-Level Radioactive Waste

DRAFT GENERIC SAFETY CASE FOR DEEP BOREHOLE DISPOSAL OF HIGH-LEVEL NUCLEAR WASTE

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Abstract

The primary objective of this study is to investigate the feasibility and utility of developing a generic safety case for disposal of high-level nuclear waste, including commercial spent nuclear fuel (SNF) and United States Department of Energy (DOE) high-level radioactive waste (HLW) waste forms, in the lower reaches (3-5 km) of deep boreholes drilled into crystalline basement rock. A *safety case* is a formal compilation of evidence, analyses, and arguments that substantiate and demonstrate the safety of a proposed or conceptual repository. A safety case also provides the necessary structure for organizing and synthesizing existing knowledge in order to help DOE prioritize its future research and development (R&D) activities. It is concluded that an initial safety case for potential licensing could be readily compiled by capitalizing on a full-scale deep borehole demonstration, and the extensive technical development and licensing experiences from prior work on the Waste Isolation Pilot Plant (WIPP) and other repository development programs.

This study provides additional information that could be used to inform DOE's decision making regarding management of these nuclear wastes. Furthermore, the safety case discussed herein is not intended to either recommend or preclude specific geographic locations for deep borehole disposal facilities. Rather, this study simply presents an approach for accelerated development of a safety case for the deep borehole disposal concept using the currently available technical basis. This approach includes a summary of the regulatory environment relevant to deep borehole disposal of commercial SNF and DOE high-level radioactive waste forms, the key elements of a safety case, the evolution of the safety case through the successive phases of deep borehole disposal facility development, and the existing technical basis that could be used to substantiate the safety of deep borehole disposal. The potential role of a field site for deep borehole repository research is also discussed.

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Acronyms

CCA	Compliance Certification Application
DOE	Department of Energy
EBS	Engineered Barrier System
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FEPs	Features, Events, and Processes
HLW	High-Level Radioactive Waste
LWR	Light Water Reactor
NEA	Nuclear Energy Agency
NEPA	National Environmental Policy Act
NRC	National Research Council
NWPA	Nuclear Waste Policy Act
NWTRB	Nuclear Waste Technical Review Board
PA	Performance Assessment
PoS	Post-closure Safety
PrS	Pre-closure Safety
QA	Quality Assurance
R&D	Research and Development
RD	Repository Design
RH	Remotely Handled
SC	Site Characterization
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
SS	Site Selection
TMI	Three Mile Island
TRU	Transuranic
URL	Underground Research Laboratory
U.S.	United States
U.S. NRC	U.S. Nuclear Regulatory Commission
WIPP	Waste Isolation Pilot Plant

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1.0 Introduction

The primary objective of this study is to investigate the feasibility and utility of developing a safety case for disposal of commercial spent nuclear fuel (SNF)[1] and United States Department of Energy (DOE) radioactive waste forms in the lower reaches (3-5 km) of deep boreholes drilled into crystalline basement rock. A *safety case* is an integrated collection of evidence, analyses, and other qualitative and quantitative arguments used to demonstrate the safety of a repository concept. Investigating the feasibility and value of developing alternative defensible safety cases for disposal of commercial SNF and DOE high-level radioactive waste forms is motivated by the need for further RD&D to help resolve some of the current uncertainties about deep borehole disposal.

The safety case described in the report focuses more on a generic safety case of the deep borehole disposal concept feasibility. It will progress to a site specific safety case as the disposal concept advances into a site-specific phase, progressing through site selection and site investigation and characterization. The emphasis of this year's study is on commercial SNF, in part because it is the most abundant waste form in terms of the metric ton of heavy metal (MTHM). The study will progress to include other types of high-level nuclear waste including, for example, DOE SNF and Cs/Sr capsules[2].

The development and implementation of any geologic disposal concept will take place over a period of years and will generally include the following phases: site selection and characterization (including facility design), licensing, construction, operation, closure, and post-closure (NRC 2003, Sec. 3.1). However, as noted by the Nuclear Energy Agency (NEA 2004): "An initial safety case can be established early in the course of a repository project. The safety case becomes, however, more comprehensive and rigorous as a result of work carried out, experience gained and information obtained throughout the project…" The key point here is that the major elements of a safety case could be addressed with technical bases developed from a deep borehole demonstration in combination with existing technical bases, and experience from prior deep borehole and repository work.

Lessons learned from DOE's experience on the Waste Isolation Pilot Plant (WIPP)[3] and other repository studies, and collaborations with researchers at MIT and elsewhere, are applied here and add confidence to the conclusion that an initial safety case can be developed following the completion of a deep borehole demonstration project.

There is much value for DOE in developing the safety case described herein. Potential benefits include leveraging previous investments and lessons learned to potentially reduce future development costs, enhancing the ability to effectively plan for a deep borehole disposal facility and its licensing, and possibly shortening the schedule for such disposal. A safety case will provide the necessary structure for

[1] "Spent nuclear fuel (SNF)" is defined as in the Nuclear Waste Policy Act, Sec. 2: "fuel that has been withdrawn from a nuclear reactor following irradiation..."

[2] There are about 2000 capsules of ^{137}Cs as CsCl (1338 capsules) and ^{90}Sr as SrF_2 (610 capsules) in pool storage at the DOE Hanford Site.

[3] The Waste Isolation Pilot Plant is a DOE waste disposal facility designed to safely isolate defense-related transuranic (TRU) waste from people and the environment. Waste temporarily stored at sites around the country is shipped to WIPP and permanently disposed in rooms mined out of a bedded salt formation 2,150 feet below the surface. WIPP, which began waste disposal operations in 1999, is located 26 miles outside of Carlsbad, NM.

organizing and synthesizing existing deep borehole disposal science and identifying any issues and gaps pertaining to safe disposal of high-level nuclear waste in deep boreholes. This safety case synthesis will help DOE to plan its future research and development (R&D) activities for improving the defensibility of the safety case using a risk-informed approach, based in part on performance assessment analysis. Future activities, if deemed necessary, to increase the confidence in the arguments that form the basis of the safety case, may include a limited set of additional laboratory, field, and/or site investigations to reduce uncertainties in the events, processes, and properties associated with the evolution of high-level nuclear waste emplaced in a deep borehole repository.

The outline of this report is as follows. The regulatory basis relevant to disposal of commercial SNF and other DOE waste forms is discussed in Section 2. Section 3 describes the general concept of a safety case, its phased development, and the major elements that compose a safety case. Section 4 summarizes the existing technical basis, including existing site characterization information, which supports development of a safety case for deep borehole disposal; a basic design concept for disposal of commercial SNF in deep boreholes; an overview of the characteristics of commercial SNF; and the methodology and existing analyses for safety assessments before and after deep borehole repository closure. Section 5 presents the motivation for establishing a demonstration project for deep borehole repository research, which would be useful for building additional understanding and confidence in the safety case. Section 6 provides the conclusions of this study. Finally, Appendix A gives a more detailed outline of the elements of a safety case and Appendix B offers a more detailed outline of the existing technical information and understanding regarding the key elements of the safety case for disposal of commercial SNF in deep boreholes.

2.0 Regulatory Considerations for Deep Geologic Disposal of High-Level Nuclear Waste

The safety standards and implementing regulations governing development of a geologic repository are the important bases for evaluating the safety of a disposal concept for high-level nuclear waste. The current regulatory and legal framework for radioactive waste management focuses on mined geologic repositories and was not intended to be applied to the long-term performance of deep borehole repositories. Existing EPA and U.S. NRC regulations for disposal of high-level nuclear wastes in geologic repositories remain in effect, i.e., 40 CFR 191 and 10 CFR 60. These existing regulations were developed almost 30 years ago and are not consistent with the more recent thinking on regulating geologic disposal concepts that embrace a risk-informed, performance-based approach (U.S. NRC 2004). However, a safety case can still be developed based on either the existing standards (40 CFR 191 and 10 CFR 60) or possibly on generic standards that incorporate dose or risk metrics recognized internationally to be important to establishing safety. Examples of the latter are compiled in Bailey et al. (2011, Sec. 6.2), e.g., the French requirement that the dose rate should be less than 0.25mSv/yr. With respect to the existing U.S. standards (10 CFR 60, Subpart E), Section 4 of this report describes some of the waste package materials that could be used to address 10 CFR 60.113 ("substantially complete" containment for not less than 300 years nor more than 1,000 years after permanent closure of the repository). It should be emphasized, however, that the deep borehole system does not require corrosion-resistant or long-lived waste containers for it to meet safety standards. One option could be to engineer long-lived waste packages, or seek an exception from the NRC under the terms of 10 CFR 60.113(b), based on the observation that a deep borehole system meets the overall requirements by providing extraordinarily robust geologic isolation.

40 CFR part 191 requires consideration of inadvertent human intrusion by deep drilling (40 CFR part 191, Appendix C), and 40 CFR 191.14(f) that "removal of most of the wastes is not precluded for a reasonable period of time after disposal." Preliminary scoping analyses suggest that the probability of a random future borehole intersecting a disposal hole will fall below the regulatory criterion of "one chance in 10,000 of occurring over 10,000 years", assuming the upper-bound drilling rate of "3 boreholes per square kilometer per 10,000 years" proposed by the EPA for repositories in media other than sedimentary formations (both quotes from 40 CFR part 191, Appendix C.) Options for demonstrating compliance with the "removal of most of the waste" requirement need further evaluation. However, it is appropriate to note that the EPA explicitly stated when promulgating this rule 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" (EPA 1985, 50 FR 38082). Overcoring the waste emplacement region of a 10-inch disposal borehole appears to be technically possible using current technology, although is unlikely to be either "easy or cheap."

The safety case described herein assumes that the inventory would correspond to commercial SNF.

If DOE decides to ultimately pursue the development of deep geologic disposal of commercial SNF and DOE HLW, other requirements may also have to be satisfied, such as the National Environmental Policy Act (NEPA) (40 CFR 1500-1508).

3.0 Safety Case Concept

The Nuclear Waste Technical Review Board (NWTRB 2011, Section 4.4) has suggested that the U.S. repository program would benefit from international work (NEA 1999; NEA 2004; NEA 2008; IAEA 2011) regarding "what a safety case should look like." A *safety case* is an integrated collection of evidence, analyses, and other qualitative and quantitative arguments used to demonstrate the safety of the repository. Two of its major roles are as a management tool to guide the work of the implementer (e.g., DOE) through the various phases of repository system development and to communicate the understanding of safety to a broad audience of stakeholders (NRC 2003). With regard to the former, because of various technical uncertainties associated with a disposal project, the safety understanding and basis evolves through time. The safety case provides the framework to assist in prioritizing the technical work in the next phase of development, in order to reduce these uncertainties and to enhance the confidence in safety. This will be in the context of various defined decision points that may or may not result in construction and operation of the repository. As noted by the Nuclear Energy Agency (NEA 2004, p. 7):

> "A detailed safety case, presented in the form of a structured set of documents, is typically required at major decision points in repository planning and implementation, including decisions that require the granting of licenses. A license to operate, close, and in most cases even to begin construction of a facility, will be granted only if the developer has produced a safety case that is accepted by the regulator as demonstrating compliance with applicable standards and requirements."

With regard to the role of the safety case in the communication of safety arguments to a diverse group of stakeholders, the National Research Council's Committee on Principles and Operational Strategies for Staged Repository Systems (NRC 2003, p. 126) has stated:

> "The safety case is also used to develop a program with features such as robustness and conservatism and to convince the implementer itself, the regulator, stakeholders, and the general public that there is a sensible and defensible set of arguments showing that the repository will be safe. The safety case includes a broad and understandable (to stakeholders and the general public) explanation of how safety is achieved and a similar discussion of the uncertainties that result from limitations in the scientific understanding of system behavior."

The purpose of the safety case would be to make the rationale for decisions about the facility accessible and understandable to the public and to a wider range of decision makers (e.g., Congress; state and local governments) beyond the regulatory experts who already have the technical expertise to make judgments about safety. Much of the safety rationale can be developed based on past DOE experience, as well as on commonly proposed safety indicators and metrics in the international arena (e.g., Becker et al. 2002). Thus, a safety case structure and concept is the vehicle for articulating and communicating the safety of a deep borehole disposal system.

3.1 Elements of the Safety Case

Although the scope of a safety case, and the definitions and terminology used therein, differ somewhat across the various international programs (Schneider et al. 2011; Bailey et al. 2011; NEA 2009; NEA 2004), they all have the same goal of understanding and substantiating the safety of a disposal system. In this study, the major elements of the safety case are patterned after the NEA post-closure safety case (NEA 2004), but include aspects of pre-closure safety (see Appendix A for additional detail):

- *Statement of Purpose*. Describes the current stage or decision point within the program against which the current strength of the safety case is to be judged.
- *Safety Strategy*. This is the high-level approach adopted for achieving safe disposal, and includes (a) an overall management strategy, (b) a siting and design strategy, and (c) an assessment strategy. Two important principles of the safety strategy are (1) public and stakeholder involvement in key aspects of siting, design, and assessment and (2) alignment of the safety case with the existing legal and regulatory framework.
- *Site Characterization and Disposal System Design*. This contains key portions of the *assessment basis* that is described in some safety case concepts (NEA 2004), and includes a description of (a) the primary characteristics and features of the disposal site, (b) the location and layout of the deep borehole disposal system, (c) a description of the engineered barriers, and (d) a discussion of how the engineered and natural barriers (i.e., the multiple-barrier concept) will function synergistically. In the earliest phases of the program this element includes the site selection process and associated selection guidelines.
- *Pre-closure and Post-closure Safety Evaluation*. This includes a quantitative safety assessment of potential radiological consequences associated with a range of possible evolutions of the system over time, i.e., for a range of scenarios, both before and after closure of the deep borehole disposal system. It also includes qualitative arguments related to the intrinsic robustness of the site and design, insights gained from the behavior of natural and anthropogenic analogues, and sensitivity and uncertainty analyses to quantify key remaining uncertainties, which may be addressed with future R&D, if necessary.
- *Statement of Confidence and Synthesis of Evidence*. The statement of confidence is based on a synthesis of safety arguments and analyses, and includes a discussion of completeness to ensure that no important issues have been overlooked in the safety case. The statement of confidence recognizes the existence of any open issues and residual uncertainties, and perspectives about how they can be addressed in the next phase(s) of the deep borehole disposal system development, if they are considered to be important to establishing safety.

The post-closure *safety assessment*, which in the U.S. program is generally referred to as the post-closure *performance assessment* (e.g., see 40 CFR 191, the standard under which WIPP is certified), is a key part of the safety case. Performance assessment is primarily focused on a quantitative evaluation of post-closure safety through a systematic analysis of the deep borehole disposal system performance and a comparison of this performance with quantitative design requirements and safety standards, along with an estimation of how quantifiable uncertainties might affect deep borehole disposal system performance. Such an assessment requires conceptual and computational models that include the relevant features, events, and processes (FEPs) that are or could be important to safety.

The knowledge base for performance assessments in the U.S. is extensive. For example, PA methodology has been used successfully to certify the WIPP repository and DOE (2008), and has been applied to many other waste disposal projects in the U.S. and internationally, beginning in the 1970s (Meacham et al. 2011). This methodology has been applied for estimating the potential performance of deep borehole disposal of high-level nuclear waste against relevant safety guidelines (see Section 2 and references cited therein).

Demonstrating confidence in pre-closure safety is also an important element of the safety case and includes transportation safety and operational safety. These aspects of pre-closure safety should be described and analyzed in a safety case, and made available to decision makers and the public as transportation and disposal systems mature. Transportation of high-level nuclear waste (commercial SNF and other DOE waste forms), potential transportation routes, potential risks of transporting these wastes, and potential transportation accidents and consequences should be described and evaluated. Operational safety should include a description of surface facilities and their operation, a description of the pre-closure *safety assessment* methodology, and an assessment of potential occupational and public health and safety. The pre-closure safety assessment identifies the potential natural and operational hazards for the pre-closure period; assesses potential initiating events and event sequences and their consequences; and identifies 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 (DOE 2008, Chapter 1).

3.2 Phased Development of the Safety Case

The development of deep geologic disposal systems will take place over a period of years and will generally include the following phases: site selection and characterization (including deep borehole disposal system design), licensing, construction, operation, closure, and post-closure (NRC 2003). The relationship between the phases of deep borehole disposal system development and the evolution of the safety case is illustrated in Figure 1. Typical phases and decision points in the development of a deep borehole disposal system are shown across the top of the figure, while key elements of the safety case are shown along the side. As the disposal 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 from site characterization, deep borehole disposal system design, and safety assessment activities. These three key activities combine to form an iterative process wherein the safety assessment from one phase feeds site characterization and design at the next phase. Public and other stakeholder participation are important in each phase, before proceeding to the next phase of development.

As in the case of the staged development of a regional or national repository, illustrated in Figure 1, it is possible to develop a defensible safety case for disposal of commercial SNF and other DOE waste forms in deep borehole repositories, whether they are centralized or localized. The safety case for a deep borehole repository presented in this report will not only provide decision makers and stakeholders with a concise summary of existing technical information mapped to the elements of the safety case, but also the basis for any future interactions and communication with regulators, decision makers, and stakeholders. It will also provide a basis for identifying and prioritizing those activities necessary to finalize the safety case and license application.

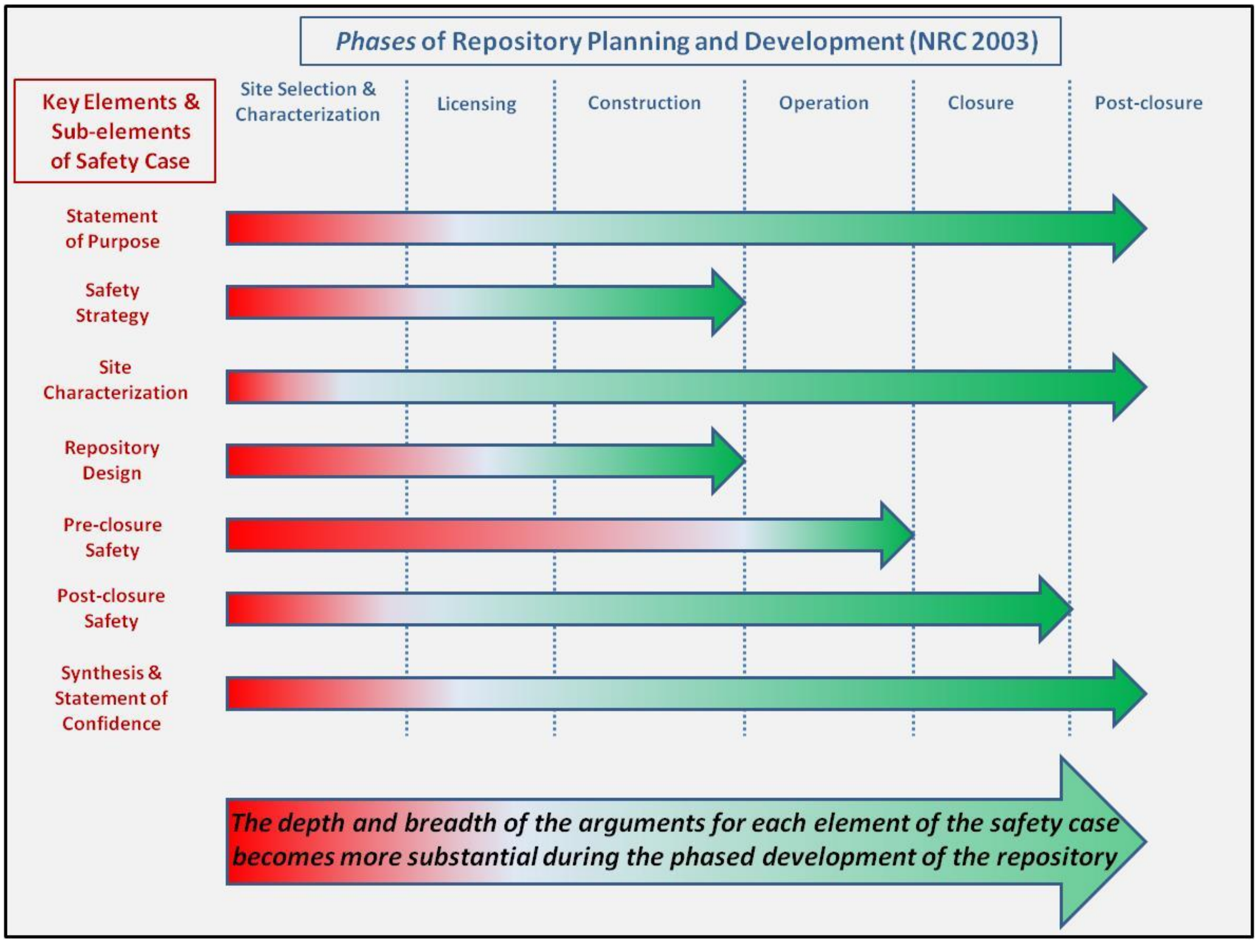

Figure 1. Evolution of the Safety Case as Part of a Phased Approach to Repository Development.

4.0 Existing Technical Bases for Deep Borehole Disposal

The National Academy of Sciences Committee on Waste Disposal conducted the first formal consideration of deep geologic disposal of radioactive waste in the U.S. in the mid-1950s (NRC 1957). Noting difficulties in deep well injection of liquid high-level radioactive waste, the committee favored disposal of solid radioactive waste in mined salt. This seminal report prompted U.S. research in salt and other mined repository concepts.

By the year 2000, investigations into deep borehole disposal of high-level nuclear waste had been sporadic (e.g., O'Brien et al., 1979; Woodward and Clyde Consultants, 1983; Juhlin and Sandstedt, 1989; Heiken et al., 1996; Gibb, 1999). MIT researchers revisited the concept (e.g., MIT 2003; Anderson 2004; Sizer 2006; Hoag 2006; Shaikh 2007; Jensen and Driscoll 2008; Moulton 2008). These studies presented compelling arguments that deep boreholes, 3 to 5 km into crystalline basement rock, could provide a next-generation repository for high-level nuclear waste. Spurred by the MIT work, SNL performed thermal-hydrologic calculations as part of a preliminary performance assessment of deep borehole disposal (Brady et al 2009; Arnold et al 2011; Hadgu et al 2011; Arnold and Hadgu 2013) and concluded that doses to the biosphere over one million years would likely be limited to ten orders of magnitude below current standards (Brady et al. 2009; Wang and Lee 2010; Clayton et al 2011; Lee et al 2011; Swift et al 2011 and 2012; Hadgu et al 2012; Vaughn et al 2012; Lee et al 2012; Section 4.4 of this report).

Advances and experience in drilling large boreholes to great depths have added confidence to the feasibility and defensibility of the deep borehole repository concept. Much of this knowledge and experience originates from the petroleum industry, geothermal drilling, and scientific boreholes (e.g., Gravberg-1, Kola, and KTB). Using this accumulated knowledge, SNL researchers conducted a cost analysis of an advanced deep borehole reference design and concluded that deep borehole disposal of high-level radioactive waste is technically feasible (Arnold et al. 2011; Vaughn et al 2012). However, a full-scale demonstration is needed to confirm the feasibility and safety of the deep borehole disposal concept.

Disposal of high-level radioactive waste in a deep borehole repository is attractive for a number of reasons, many of which also support disposal concepts for mined repositories. They include:

- Post-closure safety
  - rock at disposal depth has very low permeability (10^{-16} to 10^{-20} m^2)
  - distance to biosphere is great (3 to 5 km)
    - enhances waste isolation
    - reduces probability of human intrusion
  - natural upward driving forces are weak
    - upward movement is not favored for dense saline groundwater at depth
    - geologic ages of deep water confirm that stagnation prevails at depth
  - borehole sealing technology is effective and mature
  - upward thermally-induced flow is minimal (Brady et al 2009; Arnold and Hadgu 2013)
  - high mechanical stability of boreholes reinforced with steel casing reduces mechanical stresses on canister
    - enhances canister performance (although safety case may not take credit for the canister performance after borehole closure)
  - reducing chemical conditions limit mobility of radionuclides
    - low solubility
    - high sorption
  - colloid stability is limited due to high salinity
  - waste is highly secure upon borehole sealing

    - extremely low probability of a significant dose to the biosphere
- Feasibility of implementation
    - technology is mature
    - no need for
        - tunnels
        - underground rail or vehicle transportation systems
        - underground ventilation systems
        - underground workers
    - relatively small surface footprint due to vertical configuration
    - modularity allows flexibility in siting multiple smaller repositories
        - potential for lower transportation outlays
    - suitable sites are likely abundant across the country
    - technically feasible from a cost perspective (Arnold et al. 2011)

The remainder of this section reviews the existing technical and knowledge bases for disposing nuclear waste in deep boreholes, relying heavily on the findings of the various studies to date on the subject. The technical basis reviewed in this section specifically includes (1) the extensive hydrogeological, geochemical, thermo-mechanical, and other technical data that has been collected relevant to deep borehole disposal; (2) the well-known characteristics of the waste inventory; (3) the U.S. and international experience in developing and implementing a deep borehole repository concept; and (4) the application of current PA methodology to the evaluation of deep borehole repository performance.

Figure 2 shows the categories of information needed for the safety case and indicates that much of this information is available to build an initial safety case for deep borehole disposal of commercial SNF and other DOE waste forms. Confidence statements are provided for each of the main categories of technical information needed for a deep borehole safety case. Supporting references for each category in Figure 2 are identified in Appendix B. The references are an initial attempt and by no means complete. Additional supporting references will be added to the list as the study progresses.

Site Selection Bases	Site Characterization Bases	Repository Design Bases	Pre-Closure Safety Bases	Post-Closure Safety Bases
SS DOE Has Sufficient Methods for Collecting and Evaluating Technical, Environmental, and Socioeconomic Information for Screening and Selecting Sites for Deep Borehole Disposal of High-Level Nuclear Waste.	**SC** DOE Has Sufficient Hydrogeological, Geochemical, Thermo-mechanical, and Geophysical Information to Assess Deep Borehole Disposal of High-Level Nuclear Waste.	**RD** DOE Has a Suitable Design for Deep Borehole Disposal of High-Level Nuclear Waste.	**PrS** DOE Can Demonstrate Pre-Closure Safety for Deep Borehole Disposal of High-Level Nuclear Waste.	**PoS** DOE Can Demonstrate Long-Term Safety for Deep Borehole Disposal of High-Level Nuclear Waste.
SS1 Proven site screening methods from previous studies are applicable for a deep borehole waste facility for high-level nuclear waste. **SS2** Proven methods are available for characterizing the hydrogeological, geochemical, thermo-mechanical, and geophysical properties of deep crystalline rock and its overburden important to the performance of a deep borehole facility. Methods need to be confirmed by a full-scale demonstration. **SS3** The process for evaluating the natural environment (including flora and fauna) and potential disruptions to that environment is well established and can be used as a basis for siting a deep borehole facility. **SS4** The process for evaluating natural resources extracted for commercial purposes and the effect of those activities on repository performance is well established and can be used as a basis for siting a deep borehole facility. **SS5** The process for evaluating socioeconomic impacts (e.g., effect on population centers) is well established and can be used as a basis for siting a deep borehole waste facility.	**SC1** Hydrogeologic information about deep crystalline rock is sufficient for the assessment of deep borehole disposal of high-level nuclear waste. Information needs to be confirmed by a full-scale demonstration. **SC2** Geochemical information about deep crystalline rock is sufficient for the assessment of deep borehole disposal of high-level nuclear waste. Information needs to be confirmed by a full-scale demonstration. **SC3** Thermal-mechanical information about deep crystalline rock is sufficient for the assessment of deep borehole disposal of high-level nuclear waste. Information needs to be confirmed by a full-scale demonstration. **SC4** Geophysical information about deep crystalline rock is sufficient for the assessment of deep borehole disposal of high-level nuclear waste. Information needs to be confirmed by a full-scale demonstration.	**RD1** The volumes, waste forms, and packages for commercial SNF and other DOE waste forms are adequately known. **RD2** A reference design concept for deep borehole disposal and disposal operations has been established and can be used in the safety case for disposal of high-level nuclear waste in a deep borehole repository. **RD3** Borehole sealing requirements and methods are well established and can be used in the safety case for deep borehole disposal of high-level nuclear waste. **RD4** DOE can demonstrate drilling and borehole construction for deep borehole disposal of high-level nuclear waste.	**PrS1** DOE can demonstrate transportation safety for deep borehole disposal of commercial SNF and other DOE waste forms. **PrS2** DOE can demonstrate safe packaging and handling procedures for deep borehole disposal of high-level nuclear waste. **PrS3** DOE can demonstrate drilling safety for deep borehole disposal of high-level nuclear waste. **PrS4** DOE can demonstrate operational safety for deep borehole disposal of high-level nuclear waste.	**PoS1** Data from laboratory experiments, field studies, and natural analogues support the long-term performance of natural and engineered barriers. Data need to be confirmed by a full-scale demonstration. **PoS2** Results from long-term performance evaluations indicate long-term safety of deep borehole disposal of high-level nuclear waste. **PoS2** FEPs screening and scenario development from previous studies of deep borehole disposal of high-level nuclear waste are applicable. **PoS3** Existing modeling capabilities for long-term safety assessments can be applied to deep borehole disposal of high-level nuclear waste. **PoS4** Consideration of uncertainty in safety assessments is a mature science and can be applied to deep borehole disposal of high-level nuclear waste. **PoS5** Future research and development activities in crystalline basement rock will enable relevant uncertainties to be reduced or avoided. Future research and development activities should include a full-scale demonstration. **PoS6** Quality assurance procedures are well established and bolster confidence in the long-term safety assessment for deep borehole disposal of high-level nuclear waste.

Note: References for supporting technical bases for each category, such as “SS,” are identified in Appendix B.

Figure 2. Summary of Technical Bases Supporting the Safety Case for Deep Borehole Disposal of High-Level Nuclear Waste.

4.1 Site Selection

During the site selection process, the organization responsible for siting and development investigates one or more sites to determine suitability with respect to various screening guidelines. Preliminary site investigations, including any existing oil and gas drilling data, will produce a variety of technical data, including geologic, hydrologic, geochemical, geophysical, and thermo-mechanical data at the candidate sites. In addition to technical data, other data related to guidelines for health and safety, environmental, socioeconomic, and economic considerations (Keeney 1980) should be gathered during the siting process.

The safety case paradigm is meant to be applied to the safety evaluation of a radioactive waste disposal system, including the site selection process. Selection of a site for a deep borehole disposal demonstration project does not require the rigor of selecting a disposal site, but it should be guided by many of the same considerations related to post-closure safety. Many scientific and engineering studies to be conducted as part of a demonstration project should be performed under the geological, hydrological, and physic-chemical conditions that are relevant to safety at a deep borehole disposal site.

The down-selection process considers the geologic media (e.g., basement rock and overburden) and the location or setting.

Site selection guidelines for a demonstration project evaluated in include the following technical factors (see Section 2 of this report for detailed descriptions):

- Depth to crystalline basement – (less than 2,000 m favorable)
- Crystalline basement lithology – (felsic intrusive rocks preferred)
- Basement structural complexity – (faults, shear zones, and tectonic complexes unfavorable)
- Horizontal stress – (small differential in horizontal stress favorable)
- Tectonic uplift – (low uplift rate favorable)
- Geothermal heat flux – (low heat flux favorable)
- Topographic relief and hydraulic gradient – (low regional topographic relief favorable)
- Quaternary faults and volcanism – (Quaternary-age faulting and volcanism unfavorable)
- Mineral resources potential – (Higher potential for mineral resources in crystalline basement generally unfavorable)

For a deep borehole repository with a waste disposal zone depth from 3 to 5 km, a key selection guideline is the depth of the top of the crystalline basement rock, which should be no deeper than approximately 2 km (Arnold et al. 2011). Other important factors, namely the permeability and stability of the rock, overlap with factors of the hydrology, tectonic stability, and physico-chemical compatibility guidelines. Each factor related to these guidelines must be identified and addressed to assess the ability of the site's natural features to meet performance objectives.

An economic/social compatibility factor, unlike the guidelines noted above, does not concern the technical properties of a site's natural features. This factor, nonetheless, is equally important because it concerns the ability of disposal facility proponents to win the support of the local community and stakeholders. The economic/social compatibility factor is evaluated based on whether community stakeholders accept or reject the idea. Depending on the benefits and risks perceived by the stakeholders, deep borehole disposal may or may not have an advantage over other types of repositories.

4.2 Site Characterization

Site characterization is needed to identify site features and their properties so that the suitability and performance of the site can be assessed. Characterization activities include:

- Examination of features and properties important to the site selection guidelines (Section 4.1), focusing on the features that might threaten site suitability, and
- Measurement of parameter values important to repository performance assessment analysis.

Features requiring characterization are formally identified through the FEPs screening process (Section 4.5).

Important site characteristics include stratigraphy, depth to the crystalline basement rock, age of groundwater, redox conditions, salinity, vertical hydraulic gradients, fracturing, and the presence of igneous intrusions and exploitable natural resources. Each of these characteristics provides useful information on radionuclide transport pathways, radionuclide mobility, potential for significant disruptive events, and/or potential radionuclide migration rates.

A wide selection of proven methods is available for characterization. They include (Vaughn et al. 2012):

- Surface Based Characterization
    - 3D Seismic Imaging
    - Gravity Survey
    - Magnetic Survey
    - Electrical Resistivity Profile
- Borehole-Based Characterization
    - Geophysical Logging
        - Borehole Caliper Log
        - Gamma Ray Log
        - Resistivity Log
        - Spontaneous Potential Log
        - Temperature Log
        - Neutron Porosity Log
        - Formation Micro Imager Log
        - Anisotropic Shear Wave Velocity Log
        - Borehole Gravity Log
    - Geological and Hydrological Sampling and Analyses
        - Drill Cuttings Lithology Log
        - Intermittent Coring
        - Fluid Samples from Packer Testing
        - Borehole Hydrological Testing
            - Drill Stem Tests of Shut-In Pressure
            - Drill Stem Pump Tests
            - Packer Testing and Packer Pump Test
        - Tracer Testing
            - Vertical Dipole Tracer Testing

    - Push-Pull Tracer Testing
  - Thermal Testing
    - Waste Canister Mockup Electrical Heater Test
  - Borehole Seals Testing
    - Downhaul Force Mechanical Testing
    - Fluid Pressure Drawdown Test of Effective Permeability

Details of these methods and what they provide are discussed elsewhere (e.g., Vaughn et al. 2012). Because these characterization methods are well established and can be used to collect the hydrogeological, geochemical, thermo-mechanical, and geophysical information needed to characterize potential sites for deep borehole disposal, DOE has sufficient means for collecting sufficient information about deep crystalline rock to provide an assessment basis for deep borehole disposal of high-level nuclear waste.

The information gathered to date about the hydrogeologic, geochemical, thermo-mechanical, and geophysical characteristics of deep crystalline rock is extensive (Brady et al. 2009). These data build confidence that the deep borehole disposal concept is viable and would meet site characterization and performance standards. However, this information exists only as a compilation of data from various studies conducted at different sites and as such is not complete enough at any one site to provide sufficient characterization to address the full set of site selection guidelines for a particular site or to perform a site-specific performance assessment. While DOE has sufficient technology and methods for fully characterizing a demonstration or potential repository site and it has sufficient knowledge of the general physical and chemical characteristics of deep crystalline rock, it does not have sufficient site characterization bases for any specific site. The next step for DOE is to use the available site selection bases to identify a site where it can conduct a full-scale pilot project to comprehensively characterize a site for deep borehole disposal. A sufficiently characterized site of a full-scale demonstration project would significantly augment the site assessment bases for the deep borehole repository concept (Section 5).

4.3 Deep Borehole Disposal System Design and Waste Characteristics

Deep boreholes can be engineered to accommodate the various waste volumes and waste types in the US radioactive waste inventory (Brady et al. 2009; Arnold et al 2011). The most important feature of the engineered barrier system (EBS) for a deep borehole repository is the borehole seal. Extensive experience in the sealing of deep boreholes (gained largely from the petroleum industry) and the results of PA modeling imply that the characteristics of the waste canisters and emplaced waste are of lower importance. Many FEPs associated with the performance of the waste package, waste form, and backfill in the disposal zone can therefore be excluded.

4.3.1 Waste Characteristics

The Nation's high-level nuclear waste materials that need to be permanently disposed, including commercial SNF and other DOE waste forms, have been well characterized (DOE 2002; DOE 2008) and would be further evaluated during the development of this safety case.

Commercial SNF is the irradiated fuel withdrawn from a commercial power reactor, for which its final disposition has not been determined. The majority of the commercial SNF is stored at the power plant where it was generated.

Four different scenarios were developed for the once-through fuel cycle waste inventory analysis to evaluate the projected increases in the commercial light water reactor (LWR) SNF inventory and to provide a wide range of LWR fuel inventory for use in future analysis (Carter et al. 2011). For Inventory Scenario 1, which assumes no replacement of existing commercial nuclear generation reactors, a total of 140,000 metric tons uranium (MTU) SNF is estimated to be discharged from reactors, and this is the smallest total inventory among the four scenarios (Carter et al. 2011). Out of the total inventory, 91,000 MTU is the pressurized water reactor (PWR) SNF, with an estimated total of 209,000 assemblies, and this is equivalent to 0.435 MTU per PWR assembly. The remaining inventory (49,000 MTU) is the boiling water reactor (BWR) SNF. For simplification of commercial SNF inventory for this particular inventory scenario, if the total inventory was converted to an equivalent PWR inventory, the total inventory (140,000 MTU) is equivalent to a total of 321,540 PWR assemblies. The inventory analysis also provides estimates of the isotopic inventory of the SNF for expected ranges of the fuel burn-up, fuel enrichment and aging time after discharge from reactor (Carter et al. 2011).

DOE HLW is generated by the reprocessing of DOE SNF. DOE SNF was primarily generated by DOE production reactors, but also includes naval SNF. The majority of the DOE HLW and DOE SNF is currently stored at three DOE sites: Hanford, Savannah River, and the Idaho National Laboratory.

DOE SNF generated in production reactors supported weapons and other isotope production programs. An example of SNF existing today from production reactors is the N-Reactor fuel stored at the Hanford site. Radionuclide inventories for DOE SNF vary widely depending on the history and fuel design. Projections for the number of SNF canisters that would need to be disposed of vary depending on the fuel types, treatment and packaging arrangements and may possibly be a function of the repository design (DOE 2008; Carter et al. 2012).

DOE HLW is typically encapsulated in a borosilicate-type glass by vitrifying the HLW solid resides: mixing the waste solid residues with grits of glass forming elements (SiO_2, B_2O_3, Al_2O_3, Na_2O, etc.), melting the mixture in a glass-making furnace and pouring the melt in a stainless steel canister for solidification. Once the glass melt solidifies, the canister is sealed. A loaded, sealed HLW canister and its contents constitute the final HLW waste form to be disposed of. Well over 20,000 canisters would have to be disposed in various sizes with a range of canister inventories and heat generation rates depending on where the HLW originated, HLW loading in the glass and its age (DOE 2002; DOE 2008; Carter et al. 2012).

As described in Section 2, some DOE HLW/SNF is of commercial origin (e.g., damaged TMI SNF) and will not initially be considered in the safety case described herein, but its volume and characteristics are not sufficiently different to affect the confidence basis in a high-level waste repository safety case, if it were to be included later.

At a minimum, the waste canister design and handling procedures must provide a high level of assurance that waste canisters will not release radioactive materials during surface operations, emplacement in the borehole, and borehole sealing. Acceptable procedures and designs must also be established for, if necessary, retrieving canisters from the borehole prior to placement of the seals. Once the borehole is sealed, retrieval of waste would be difficult; thus, if regulations require waste retrievability over the long term, deep borehole disposal presents special challenges. After the seals are in place, the performance of the waste canister and waste form is not highly important compared to the performance of the seals, because the seals and natural barriers including the bedrock surrounding the borehole are expected to preclude significant radionuclide migration to the biosphere regardless of the timing of radionuclide releases from the waste canister and waste form.

The waste canisters for a deep borehole repository system must be designed to withstand significant mechanical, thermal, and hydrostatic stresses during handling, emplacement, and accidental drops. The extreme magnitudes of these stresses have been estimated and are easily handled by current waste canister designs (Arnold et al. 2011). Full testing of these waste canister designs and their handling, emplacement, and retrieval, however, requires a full-scale pilot project (Section 5).

4.3.2 Deep Borehole Disposal System Design

The safety case outlined in this paper could start with the recent design concept for a deep borehole disposal system developed by Arnold et al. (2011) for DOE. The primary components of the reference design include:

- Boreholes
    - drilled and completed to a depth of approximately 5,000 m with a disposal zone in crystalline rock between about 3,000 and 5,000 m
    - 0.43 m bottom hole diameter
    - 50 m spacing minimum at a bottom depth
- Borehole casing system
    - conductor and surface casing (cemented)
    - intermediate 1 casing (surface to 1,500 m, cemented)
    - intermediate 2 casing (from 1,500 to 3,000 m, lower 160 m cemented)
    - guidance liner (from 3,000 to 5,000 m, perforated/slotted)
    - guidance tieback (from surface to 3,000 m)
- Waste canisters
    - 0.27 m outside diameter, 4.2 m minimum length
    - coupling connections between canisters (0.3 m diameter)
- Surface handling and shielding system
- Waste emplacement system
    - waste canisters emplaced in 10 strings of 40 (length of each string about 192 m)
    - bridge plug and cement plug above each canister string
    - grouting between canisters and borehole walls (synthetic oil base mud containing bentonite)
- Borehole sealing and abandonment
    - removal of guidance tieback, guidance liner, and intermediate 2 casing
    - sealing using a series of cement plugs, ballast, bentonite, and fill
    - bridge plugs in the upper cased section and additional cement-based fill
- Operational safety assurance and monitoring

Approximately 950 boreholes would be required to dispose the projected waste inventory of commercial SNF from the current fleet of U.S. nuclear reactors if intact fuel assemblies are loaded into the waste canisters (Brady et al., 2009). This number reduces to 700 if used fuel rods are packed at a high density (Arnold et al. 2011). Spacing between disposal boreholes of at least 50 m would ensure that the thermal interference between boreholes is relatively small (Arnold et al. 2011). At 50 m spacing, the entire projected inventory could theoretically be disposed within an area of one square mile.

The concept of operations for a deep borehole repository can borrow much from the knowledge base acquired from mined repositories and pilot projects conducted in the U.S. and around the world. Between 1978 and 1983, as part of the Spent Fuel Test – Climax project, a 420 m borehole was drilled into the granitic Climax stock at the Nevada Test Site to test the lowering, storage, and retrieval of canisters containing full-size commercial PWR used fuel assemblies (Patrick, 1986). A transport cask system was used to raise the canisters to the vertical position and lower them into the borehole where they resided for 3.5 years until retrieved. The study examined the effects of radiation, temperature, and drilling damage, the handling of spent fuel, and the response of the rock. The results showed that the waste canisters affected the surrounding rock but did not threaten the stability or safety of the facility.

The challenges for the implementation of the deep borehole disposal concept center on the extreme depths of drilling and waste emplacement. Here, experience from the petroleum industry, geothermal drilling, and deep scientific boreholes is precious. Based on this information, a 5,000 m borehole is likely readily achievable with a bottom hole diameter of 0.3 m but may not be achievable at bottom hole diameters greater than 0.5 m (Beswick 2008). Various designs for borehole casing and emplacement have been proposed for deep borehole disposal and appear to be feasible and/or ready for a pilot project demonstration (Woodward-Clyde Consultants, 1983; Juhlin and Sandstedt, 1989; Hoag, 2006; Beswick, 2008; Arnold et al 2011).

The borehole sealing system is an important component of the long term safety of deep borehole disposal (Brady et al. 2009; Clayton et al 2011; Vaughn et al 2012; Lee et al 2011 and 2012; Swift et al 2011 and 2012; Section 4.4 of this report). Here, too, much knowledge and experience gained from other programs, projects, and ventures can be utilized. The functions and characteristics of the borehole sealing system are similar to those for the shaft sealing systems of mined repositories, namely:

- Limit waste constituents reaching regulatory boundaries
- Restrict water flow through the seal system
- Mechanical and chemical compatibility in situ
- Protect against structural failure of system components
- Limit subsidence and prevent re-excavation
- Utilize available construction methods and materials

The major seals of the reference design include bridge plugs, cement, and bentonite, and the processes and technologies used to emplace them are mature (Arnold et al, 2011). The oil industry primarily uses cementitious materials for sealing boreholes and has developed numerous placement techniques (Smith 1989, API 2000, Pusch 2008). Different classes and compositions of cements are used depending on depth, temperature, formation properties, and fluid properties. Plugs of bentonite and other swelling clays are routinely used to inhibit water flow and would sorb most radionuclides that have reached the seals. Bridge plugs that would meet the required specifications are commercially available (e.g., the Weatherford PBP bridge plug and the TechTool high-pressure bridge plug).

Although the various components of the repository design have strong technical bases, they have not been tested together as part of a deep borehole repository concept. A pilot demonstration project would allow testing of the repository design as a whole.

4.4 Pre-closure Safety

The analysis of safety before repository closure is a mature science based on a systematic examination of the site, the design, and the potential initiating events caused by underlying hazards (DOE 2008). An initiating event is a departure from normal operation that triggers an event sequence. A pre-closure safety analysis will consist of internal and external initiating event identification, event sequence analysis, radiological dose and consequence analysis, and criticality analysis. In this case of deep borehole disposal the analysis will be supported by drilling safety data from the petroleum industry and waste packaging, handling, and emplacement data from radioactive waste disposal programs and pilot projects.

Probably the most relevant pre-closure safety information comes from the Spent Fuel Test – Climax project (Patrick 1986) and WIPP. At the Spent Fuel Test, full-size used fuel assemblies were emplaced in a 420 m borehole and removed after 3 years (Patrick, 1986). At WIPP, there are many years of pre-closure safety information regarding waste packaging/handling at the generator sites, transportation practices while moving waste from the generator site to the disposal site, and mining practices at the disposal site (DOE 2011). In addition, experience and analyses gained related to packaging and transportation of commercial SNF and other DOE waste forms and the potential vulnerability of waste packages (DOE 2008, see Chapter 1, Repository Safety Before Permanent Closure), can also be used in pre-closure safety analyses.

Conceptual design information for the repository design discussed in the previous section could be used to identify initiating events and to conduct preliminary event sequence analyses. Representative waste containers, rather than those of specific designs or specific suppliers, can be analyzed for their failure potential associated with these event sequences. In addition, a range of container dimensions and materials can be considered within the set of representative pre-closure safety analyses for the safety case. Conceptual design information on locations and amounts of radioactive material at various locations in the borehole could be used in performing consequence and criticality analyses.

4.5 Post-closure Safety

An assessment of repository safety after closure addresses the ability of a site and repository facility to meet safety standards and to provide for the safety functions of the engineered and/or geological components, e.g., containment by engineered and natural barriers or reduction in the rate of movement of radionuclides in the engineered and natural barriers (cf. 10 CFR 63.2 & 40 CFR 191.13/14). A complete safety assessment includes quantification of the long-term, post-closure performance of the repository, analysis of the associated uncertainties in this prediction of performance, and comparison with the relevant design requirements and safety standards.

Figure 3 illustrates the steps in the performance assessment (PA) methodology that was used successfully to certify the WIPP defense TRU waste repository (DOE 1996) and DOE (2008) and has been applied to many other waste disposal projects dating back to the 1970s (Meacham et al. 2011). This same methodology could be readily applied in an assessment of safety after closure of a deep borehole repository for high-level nuclear waste including commercial SNF and other DOE waste forms. The PA methodology shown in Figure 3 organizes the types of information that build confidence in post-closure system safety, including (1) the underlying technical bases for the safety assessment models (a component of the *assessment basis* in some safety case concepts, e.g., NEA 2004), (2) the scenario and FEPs analysis that ensure a comprehensive assessment of post-closure performance, (3) a quantitative and qualitative description of barrier capability (which promotes the defense-in-depth concept), and (4) uncertainty and sensitivity analyses that help quantify where additional information is needed for the next stage of repository development.

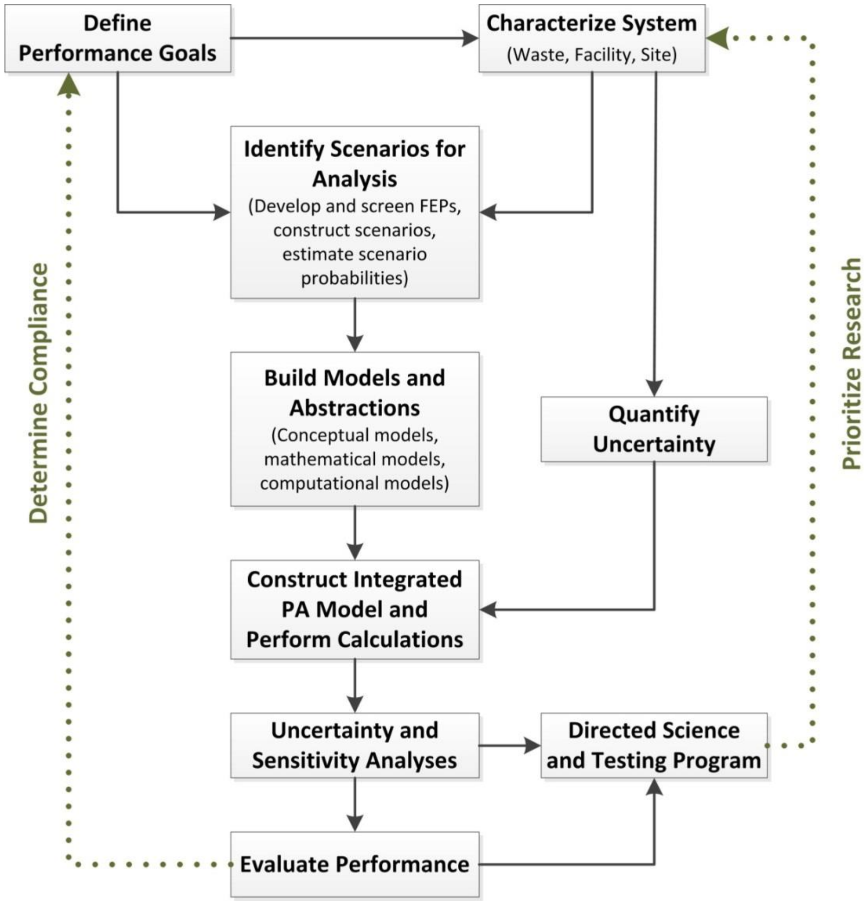

Figure 3. Performance Assessment Methodology (from Meacham et al. 2011).

Because the conceptual repository proposed in this study is deep borehole disposal, many of the FEPs and associated analyses used for mined repositories are not directly applicable. For example, drift collapse and the resulting damage to engineered barriers within the repository are excluded due to inapplicability. Inadvertent human intrusion can be excluded based on the low probability that exploratory boreholes would be drilled kilometers deep into crystalline bedrock. In addition, FEPs related to the degradation of the waste package may also be excluded from the performance assessment if no credit is taken for the performance of the waste package, as in the previous analyses (Brady et al. 2009; Clayton et al 2011; Swift et al 2011 and 2012; Lee et al 2011 and 2012; Section 4.4 of this report). Excluding FEPs like these from the performance assessment model is beneficial because they may introduce significant uncertainty and may require considerable resources to characterize and implement associated uncertainty.

Assuming negligible benefit from the performance of the waste package for deep borehole disposal, the high priority FEPs requiring further study include those involving (Brady et al. 2009, Table B-2; Sections 4.1 to 4.4 of this report):

- Placement and longevity of borehole seals
- Faults, fractures, and fault displacement at the site
- Potential for igneous intrusion at the site
- Flow and transport through seals and the excavation disturbed zone
- Radionuclide diffusion into and within the surrounding bedrock

- Chemical environment in the disposal zone
- Colloids and microbial activity
- Thermal effects on features and transport
- Gas generation
- Criticality

Of these, the criticality FEPs and some or all of the FEPs related to colloids, fault displacement, and igneous intrusion may be excluded based on low probability or low consequence depending on results of screening calculations.

The advancements in performance assessment and other new modeling capabilities, such as the effects of heat on fill materials, surrounding rock, and flow and transport as well as the existing knowledge base associated with the hydrogeology of deep crystalline rock and the origin and age of groundwater at these depths, could be used to inform and perform a safety assessment for a deep borehole repository for high-level nuclear waste. Results from preliminary post-closure safety assessments provide confidence in the safety of deep borehole disposal (Brady et al. 2009; Clayton et al 2011; Vaughn et al 2012; Swift et al 2011 and 2012; Lee et al 2011 and 2012; Section 4.4 of this report).

A key consideration in the assessment of post-closure safety is the identification and analysis of uncertainties that have the potential to significantly impact the understanding of the degree of safety the system offers. Consideration of uncertainty in the evaluation of safety after repository closure is a well-developed science (see Appendix B, Section PoS-4) that categorizes uncertainty into two major types: uncertainty related to the inherent randomness of the problem (such as random external events that affect safety, e.g., seismicity) and uncertainty related to lack of measurement data (such as the uncertain composition of the current inventory of commercial SNF and other DOE waste forms). The former type of inherent or irreducible uncertainty is often called *aleatory* uncertainty and the latter type of measurement or reducible uncertainty is often called *epistemic* uncertainty (Helton et al., 1998). Epistemic uncertainties can be reduced by data-gathering methods, including additional site characterization, design studies, fabrication and other demonstration tests, and other experiments both in the laboratory and in underground test facilities.

Sensitivity analyses from the post-closure safety assessment provide the basis for defining the types of tests and studies needed to reduce epistemic uncertainty and for assigning priorities for further R&D work in the next stage of repository development. This is a key feature of the PA methodology, as indicated in Figure 3, which results from the iterative nature of the process wherein the current performance assessment informs the research and development agenda necessary for the next phase of system characterization, design, and/or implementation. In particular, the PA methodology shown in Figure 3 does not simply encompass evaluations of repository performance and regulatory compliance, which is a more traditional definition of PA. In early stages of repository development, as disposal at a particular site or with a particular design concept is being considered, the methodology includes analyses that inform the decision maker about what is important for repository performance and what, if any, "data gaps" would need to be filled. This iterative principle has been applied to several very different disposal concepts that advanced to licensing: DOE (1996), DOE (2008), and Greater Confinement Disposal (Cochran et al. 2011). Repository programs use probabilistic performance assessments to help set priorities and to guide the research portfolio.

Finally, as mentioned in Section 3.1, with regard to the elements of the safety case concept, anthropogenic and geologic analogues provide important insight into the safety of permanent nuclear waste disposal and bolster the case for long-term, post-closure safety. For example, isotopic analysis of groundwater in crystalline rock at the depth of the disposal zone indicates the age of the groundwater and the potential for natural circulation with shallow groundwaters. The presence of quaternary-age volcanic rocks or igneous intrusions at depth or in the vicinity of the site suggests a potentially significant probability for future igneous or volcanic intrusions. Related to seals, compacted bentonite clay has been observed to be highly resistant to solute transport over geologic timescales (Neuzil 2000), and laboratory and field data indicate that concrete can provide a durable and robust solute transport barrier (Thompson et al. 1996). These types of observations are important in building confidence in the safety case.

4.6 Quality Assurance

One important and necessary aspect of each element of the safety case is quality assurance (QA). All elements of repository development must be properly planned, implemented, and documented, such that the technical basis for the safety case is repeatable, transparent, and traceable. All nuclear programs, including radioactive waste disposal facilities, follow strict QA guidelines. These requirements are applicable to site characterization, general collection of data for PA, PA software and models, expert judgment activities, waste characterization, and environmental monitoring. It is expected that any facility handling and processing high-level nuclear waste would follow similar QA requirements.

5.0 Deep Borehole Research and Demonstration Pilot Project

The safety case supports all aspects of disposal concept development and provides a framework for identifying and prioritizing work in those areas where further understanding is needed to build confidence and ensure safety. A deep borehole research and demonstration pilot project could be used to build additional confidence in those areas that would be better examined at a large scale, such as aspects of drilling operations, borehole stability, canister emplacement and retrieval, operational efficiency, sealing effectiveness, and safety. Examining coupled physical and chemical processes at a field scale would help reduce residual uncertainty in these processes.

Field testing at a pilot project site should be directed toward reducing uncertainties and addressing those technical issues that may become the focus of interveners in the licensing proceedings. These focused research activities must be "risk-informed" in a systematic fashion by the current version of the safety case and any associated performance assessment analyses, such as uncertainty and sensitivity analyses which determine the parameters and processes that most affect repository performance. Thus, any test activity potentially used to support licensing should be assigned a priority based on how much it builds confidence in the safety case and reduces uncertainties.

Finally, it is important that a technical management and assessment structure be put in place prior to any testing at a pilot project site. Such a structure would first consider the overall testing needs and preferred arrangements of the site consistent with the safety case. This would lead to identification and prioritization of demonstration and testing activities and establish their functional and operational requirements. Sequencing of tests and demonstrations, test-to-test interference, data acquisition systems, synergism between and among tests, and the method for evolving from initial tests (say of a single disposal demonstration) to a long-term pilot project facility of use to the international community, all need to be addressed prior to any planned pilot project.

6.0 Conclusions

Based on existing technical information and the results of preliminary performance assessments, an initial safety case can be developed for deep borehole disposal of high-level nuclear waste including commercial SNF and other DOE waste forms. Much of the technical basis that would be used in this initial safety case would have to be confirmed by a full-scale demonstration. This conclusion is derived from the following factors:

- The Nation has an extensive knowledge base in drilling deep boreholes and sealing boreholes and shafts; this basis derives largely from the petroleum industry and nuclear waste disposal programs (e.g., WIPP)
- Performance assessment (PA) methodology for nuclear waste disposal has been developed, matured, and applied successfully (e.g., WIPP)
- DOE has the experience to develop the safety case and associated licensing basis:
  - Managed and developed the WIPP Compliance Certification
  - DOE (2008)
  - Is actively involved in international safety case projects
- DOE has the experience needed for the construction and operation of a repository:
  - Managed materials and wastes within EPA, U.S. NRC, and DOE regulatory frameworks
  - Transported nuclear materials, including commercial SNF and other DOE waste forms, between sites
  - Developed and operated a geologic repository (WIPP)

A safety case will provide the necessary structure for organizing and synthesizing existing repository science and identifying any issues and gaps pertaining to safe disposal of high-level nuclear waste in deep boreholes. The safety case synthesis will help DOE to plan its future R&D activities for investigating deep borehole disposal using a risk-informed approach that prioritizes test activities that include laboratory and field investigations.

It should be emphasized that the DOE has not made any decisions regarding the disposition of Nation's high-level nuclear waste including commercial SNF and other DOE waste forms and is presently studying options. This study provides additional information that could be used to inform DOE's decision making regarding management of these wastes. Furthermore, the safety case discussed herein is not intended to site a repository. Rather, this study simply presents an approach for accelerated development of a safety case for a potential deep borehole demonstration or repository site for the Nation's high-level nuclear waste.

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Appendix A1: Elements of the Safety Case Concept

The five elements of the safety case, as defined in Section 3, can be described in more detail as follows (NEA 2004; Van Luik et al. 2011):

- A clear *statement of purpose* is required to set the context of the safety case relative to the decision it is informing. This includes an outline of the program and the current stage (see Figure A-1) or decision point within the program against which the safety case is used to inform. This will set the context in which the defensibility of the safety case and the importance of remaining uncertainties can be judged. It also provides the context for evaluating system performance. The current applicable regulatory performance goals (40 CFR 191 and 10 CFR 60) may evolve toward goals and safety indicators similar to those that exist for other repository programs (Bailey et al. 2011). These types of performance goals and indicators can be used at early stages for focusing the safety assessment analyses towards informing future R&D. In later stages of the program, the system performance will be compared directly to whatever safety metrics are prescribed in the regulations.
- The *safety strategy* is the high-level approach adopted for achieving safe disposal, and includes (a) an overall management strategy, (b) a siting and design strategy, and (c) an assessment strategy. Two important principles of the safety strategy are (1) public and stakeholder involvement in key aspects of siting, design, and assessment and (2) alignment of the safety case with the existing legal and regulatory framework. 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 project progresses. The siting and design strategy is generally based on principles that favor robustness and minimize uncertainty, including the use of the multi-barrier concept. Similarly, the assessment strategy must ensure that safety assessments capture, describe, and analyze uncertainties that are relevant to safety, and investigate their effects.
- *Site Characterization and Repository Design* contains many parts of the *assessment basis* element of the safety case concept commonly used internationally (NEA 2004), and includes a description of (a) the primary characteristics and features of the repository site and how they will interact with waste degradation and migration processes, (b) the location and layout of the repository (or guidelines by which the location and layout will be determined), (c) a description of the engineered barriers and how they will be constructed and emplaced, and (d) a discussion of how the engineered and natural barriers (i.e., the multiple-barrier concept) will function synergistically. The descriptions should be based on existing scientific and technical information and understanding, and include plans for reducing existing uncertainty in this technical and scientific basis. The foregoing description should be centered on the characterization of those safety-bearing components or features of the repository that are "important to waste isolation" (cf. 10 CFR 63). Site characterization and repository design evolves into implementation after a regulatory decision to authorize construction, when the development then proceeds to the construction phase (Figure 1). In the earliest phases of the repository program it includes the site selection process and associated selection guidelines.

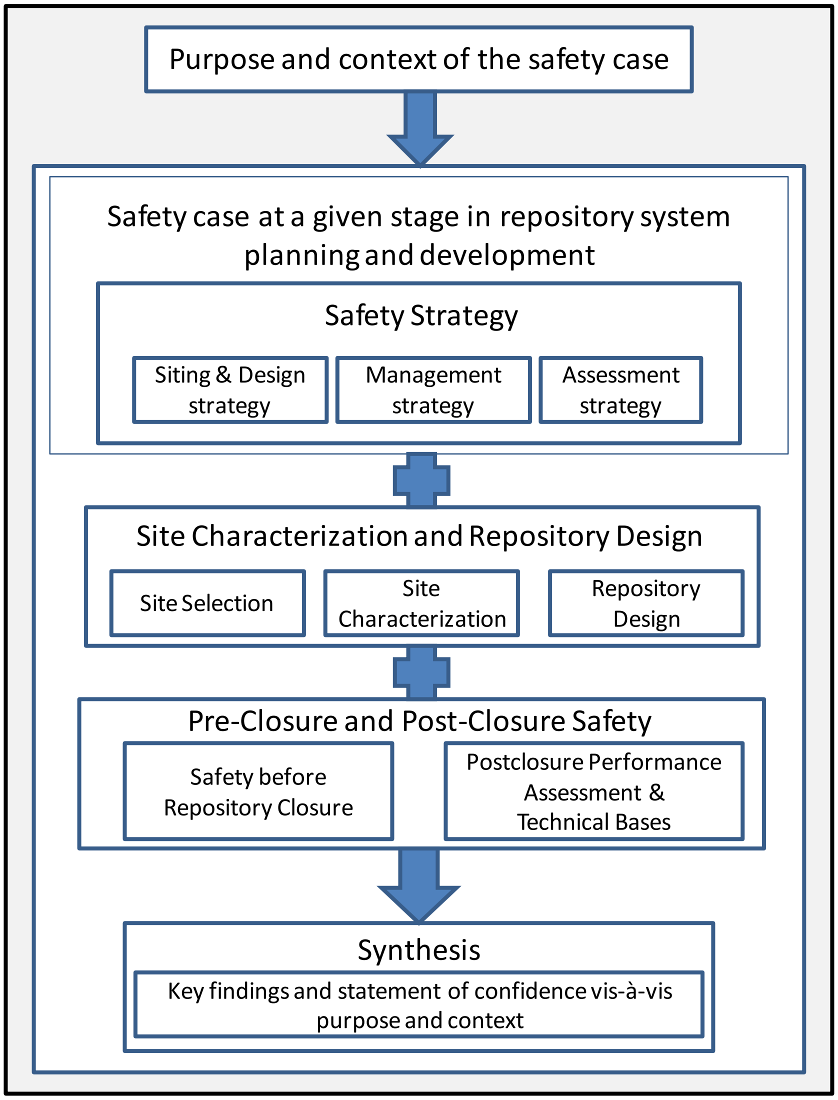

Figure A-1. An Overview of the Elements of a Safety Case (modified from NEA 2004, Fig. 1).

- The *evaluation of pre-closure and post-closure safety* provides a quantitative assessment ("safety assessment") of potential radiological consequences for a range of scenarios both before and after closure. This requires a methodological approach to evaluating the numerous processes, features and other technical issues against a set of safety standards and metrics. Most national regulations give safety standards in terms of dose and/or risk metrics, and the evaluation of these safety metrics appears prominently in safety or licensing cases that are intended for regulatory review. The evaluation of safety includes both pre-closure and post-closure safety analyses, and generally uses sensitivity and uncertainty analyses to determine those uncertain phenomena to which the safety metrics are most sensitive. Another component of the safety analysis is the *modeling basis*, which includes the conceptual model, methods of analysis, computer codes and models, and databases that are currently available to support the numerical modeling of the evolution of the disposal system and the quantification of its performance (NEA 2004), as well as the QA framework by which the computer models and codes are validated and verified. Other evidence and arguments that support the system safety analyses include (a) the intrinsic quality and robustness of the site and the design, (b) insights gained from the study of natural and man-made analogues to the repository components, (c) a strategy to manage and address the key residual uncertainties identified by the uncertainty and sensitivity analyses, and (d) a performance confirmation program to monitor the repository for a period of time after the waste has been emplaced.

- A *statement of confidence* is required to justify a positive decision to proceed to the next phase of planning or implementation. It is based on a *synthesis* of the analyses and arguments developed and the supporting evidence gathered, and includes a discussion of completeness to ensure that all important issues have been addressed. The statement of confidence recognizes the existence of open issues and residual uncertainties, and perspectives about how they can be addressed in the next phase(s), if they are determined to be important to safety. The audience of the safety case must decide whether it believes the reasoning that is presented is adequate, and on that basis whether it shares the confidence of the safety case author.

Appendix B1: Supporting Bibliography for Existing Technical Bases for Deep Borehole Disposal of HIGH-LEVEL NUCLEAR WASTE

This appendix provides a supporting bibliography for Section 4 of this document. The references cited below are organized according to the subsection titles from Section 4 and, in particular, to the categories listed in Figure 2 (i.e., SS, SC, RD, PrS and PoS). Note that some references are listed in multiple categories as the references have information relevant to them.

B1.1 Site Selection (SS) Basis

This section provides supporting references for site selection studies and processes conducted in a broad sense for crystalline basement rocks that are applicable to screening and evaluating a site for a deep borehole repository, utilizing siting factors appropriate for a radioactive waste repository. These included the evaluation of ecology, socioeconomics, geology, hydrology, seismic and igneous activity, geomechanical, geochemical, and thermodynamic properties of crystalline rock, and a collection of general science activities not easily categorized in the previously mentioned disciplines. The section also includes references related to the site characterization activities for WIPP and other projects that could be applicable for a deep borehole repository.

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B1.5 Post-closure Safety (PoS) Basis – Safety After Repository Closure

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