Research, Development, and Demonstration Roadmap for Deep Borehole Disposal

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign
Bill W. Arnold, Palmer Vaughn,
Robert MacKinnon, Jack Tillman,
Dennis Nielson, Patrick Brady,
William Halsey, and Susan Altman
Sandia National Laboratories
August 31, 2012
FCRD-USED-2012-000269
SAND2012-8527P

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy‟s National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

EXECUTIVE SUMMARY

The research, development, and demonstration (RD&D) project presented in this roadmap is intended to advance deep borehole disposal (DBD) from its current conceptual status to potential future deployment as a disposal system for spent nuclear fuel (SNF) and high-level waste (HLW). The objectives of the DBD RD&D roadmap include providing the technical basis for fielding a DBD demonstration project, defining the scientific research activities associated with site characterization and postclosure safety, and defining the engineering demonstration activities associated with deep borehole drilling, completion, and surrogate waste canister emplacement. The activities, schedules, and cost estimates presented will provide the United States (U.S.) Department of Energy (DOE) and policymakers with information on the resource commitments and budget necessary to deploy the DBD demonstration project.

DBD of SNF and HLW has been considered as an option for geological isolation for many years, including original evaluations by the U.S. National Academy of Sciences in 1957 (NAS, 1957). The generalized DBD concept is illustrated in Figure ES-1. The concept consists of drilling a borehole (or array of boreholes) into crystalline basement rock to a depth of about 5,000 m, emplacing waste canisters containing SNF or vitrified HLW from reprocessing in the lower 2,000 m of the borehole, and sealing the upper 3,000 m of the borehole. As shown in Figure ES-1, waste in the DBD system is several times deeper than for typical mined repositories, resulting in greater natural isolation from the surface and near-surface environment. The disposal zone in a single borehole could contain about 400 waste canisters of approximately 5 m length. The borehole seal system would consist of alternating layers of compacted bentonite clay and concrete. Asphalt may also be used in the shallow portion of the borehole seal system.

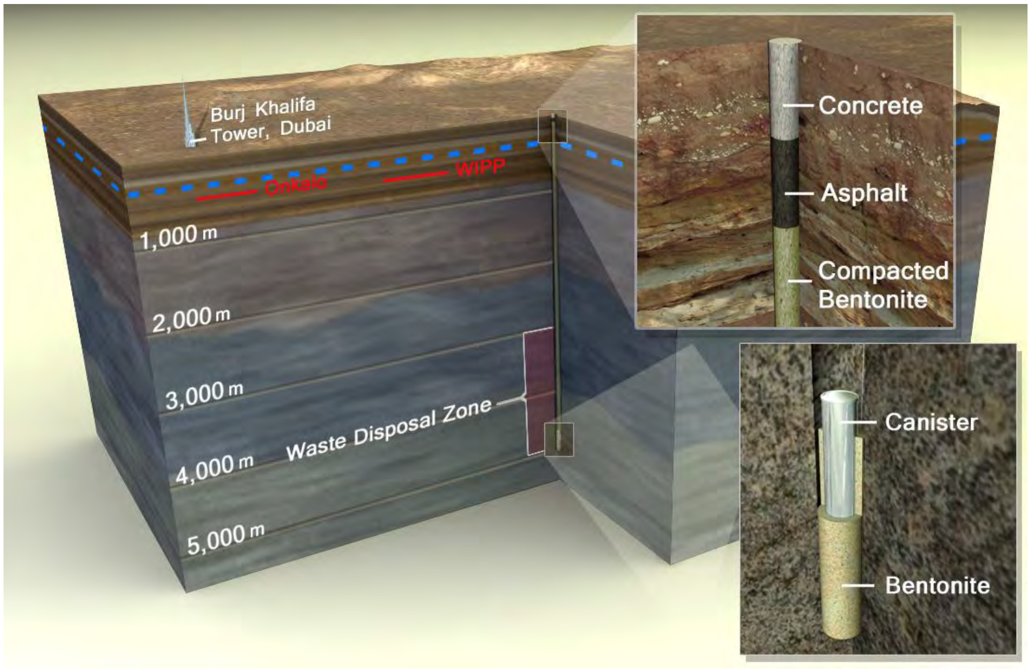


Figure ES-1. Generalized Concept for Deep Borehole Disposal of High-Level Radioactive Waste and Spent Nuclear Fuel.

Numerous factors suggest that DBD of SNF and HLW is inherently safe. Several lines of evidence indicate that groundwater at depths of several kilometers in continental crystalline basement rocks has long residence times and low velocity. High salinity fluids have limited potential for vertical flow because of density stratification and prevent colloidal transport of radionuclides. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the retardation of key radionuclides. A non-technical advantage that the deep borehole concept may offer over a repository concept is that of facilitating incremental construction and loading at multiple regional locations.

This DBD RD&D Roadmap is a plan for RD&D activities that will help resolve key uncertainties about DBD and allow for a comprehensive evaluation of the potential for licensing and deploying DBD for SNF and HLW. The full-scale field DBD demonstration presented in this report will serve as a DBD laboratory and proof of concept and will not involve the disposal of actual waste. The demonstration will have four primary goals: demonstrate the feasibility of characterizing and engineering deep boreholes, demonstrate processes and operations for safe waste emplacement down hole, confirm geologic controls over waste stability, and demonstrate safety and practicality of licensing. There are four major RD&D tasks:

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.

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.

Science Thrust – This task will identify and resolve data gaps in the deep borehole geological, hydrological, chemical, and geophysical environment that are important to postclosure 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.

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.

A 5-year high-level milestone schedule showing key milestones is provided in Figure ES-2.

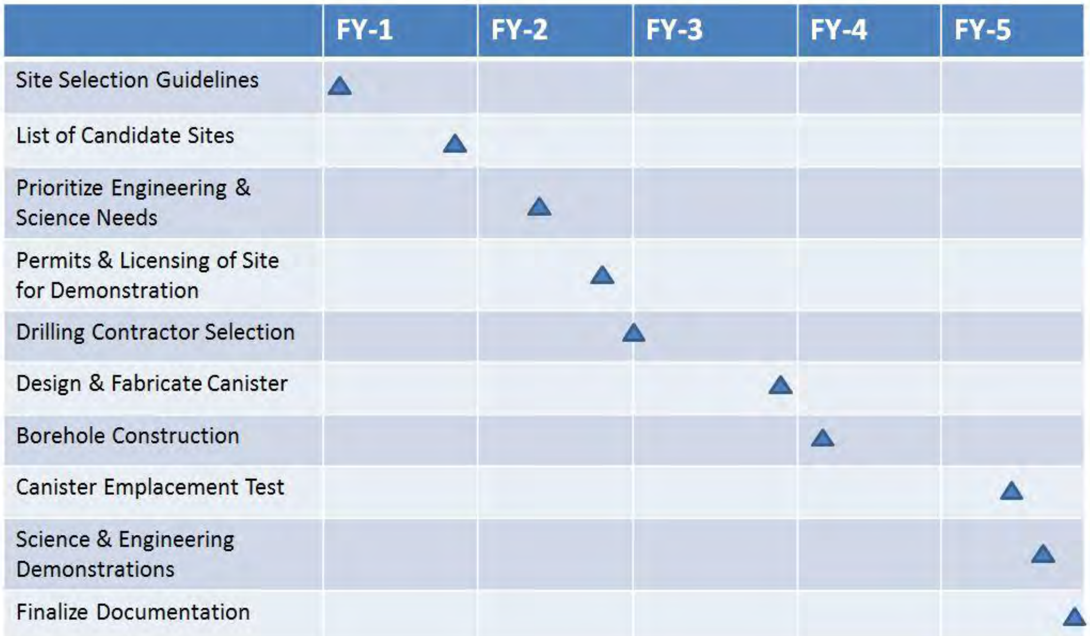


Figure ES-2. High-Level Milestone Schedule for Deep Borehole Disposal RD&D Demonstration Project.

The science thrust of the DBD RD&D roadmap is aimed at data gaps in the deep borehole geological, hydrological, chemical, and geophysical environment that are important to postclosure safety of the system, materials performance at depth, and construction of the disposal system. The identification of data gaps and associated data collection and characterization methods relies on a process that includes identifying a comprehensive list of features, events, and processes (FEPs) for geologic disposal, screening each of the FEPs for potential relevance to deep borehole disposal, and identifying related information needs and data collection and characterization methods. Data gaps are addressed in the DBD RD&D roadmap by a proposed combination of surface-based, borehole, and laboratory testing and characterization activities.

The engineering thrust of the DBD RD&D roadmap is focused on the conceptual design, analysis, and demonstration of key components of borehole drilling, borehole construction, waste canisters, handling, emplacement, and borehole sealing operations. Planning for drilling a deep demonstration borehole will concentrate on using existing technology, insuring technical success and achieving these aims within budget. Although the objectives of depth and completion diameter are not beyond existing drilling capabilities, experience in drilling a hole that incorporates all of the objectives is very limited. The DBD RD&D roadmap presents information relevant to a demonstration project on a reference deep borehole design and logging, reference waste canister design, testing, loading, handling, and emplacement. Information is also presented on borehole seal design and operational retrievability.

The DBD RD&D roadmap also presents a systematic approach to identify and prioritize RD&D science and engineering activities during the demonstration phase of the DBD concept. This approach is similar to the systems engineering approach developed previously for the Used Fuel Disposition Campaign Research and Development (R&D) Roadmap (U.S. DOE, 2011) and involves the ranking of candidate activities against multiple metrics and combining these multiple rankings into an overall priority score using objective functions and a set of weighting factors on the individual metric components. The prioritization of RD&D activities will also be informed by analysis and insights gained from existing and new safety analyses, including both qualitative and quantitative information. Such prioritization provides an important link between DBD demonstration activities and the demonstration of postclosure safety of the DBD concept.

The legal and regulatory framework, demonstration site selection, and business management plan are important elements of the DBD RD&D program that are also outlined in the roadmap. Legal and regulatory issues and requirements will be addressed for the DBD demonstration project during the site selection process. Experience has shown that acquiring permits often results in project delays and is responsible for changes in borehole design. Since the demonstration borehole will be unique, in terms of both size and purpose, it is important that regulatory agencies be presented with realistic plans that take into account existing regulations. Identifying the location for a DBD borehole will focus on a process that locates the demonstration borehole at a site that is representative of the geology and other characteristics in which future DBD might be carried out. Demonstration site selection should also be consistent with principles outlined in the Blue Ribbon Commission on America‟s Nuclear Future recommendations, including a consent-based approach that employs stakeholder outreach and is staged, adaptive, and transparent. A sound business management plan, which will be an evolving document that describes the key elements of business planning, outlining the processes, skills, tools and techniques will be utilized for the DBD RD&D project. The project team will be comprised of various organizations from National Laboratories, industry and academia.

Based on preliminary scheduling and cost analysis, implementation of the DBD RD&D plan for the DBD demonstration project would require approximately five years and a $75 million budget. Successful completion of a DBD demonstration project would demonstrate the feasibility of engineering and characterizing deep disposal boreholes, demonstrate processes and operations for safe waste emplacement in the borehole, confirm geologic, chemical, and hydrologic controls on waste isolation, and demonstrate safety and practicality of licensing. The early phase of the DBD demonstration project would include evaluation of existing and available boreholes within the U.S., examination of lessons learned from deep drilling, mechanical and geologic media issues, identification of site selection guidelines, and assessment of regional geologic conditions.

CONTENTS

FIGURES

TABLES

ACRONYMS

AI	acoustic impedance
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
AVO	amplitude variation offset
BHA	bottom hole assembly
BOPE	blow-out prevention equipment
BRC	Blue Ribbon Commission
BWR	boiling water reactor
CSH	calcium-silicate-hydrate
DBD	deep borehole disposal
DOE	Department of Energy
DRZ	disturbed rock zone
DST	drill stem testing
EIS	environmental impact statement
FEP	features, events and processes
FMI	formation micro-imager
GIS	geographical information system
HLW	high-level waste
IADC	International Association of Drilling Contractors
ID	inside diameter
KTB	Kontinentales Tiefbohrprogramm der Bundesrepublik, Deutschland
LCM	lost circulation material
LEU	low enriched uranium
LLNL	Lawrence Livermore National Laboratory
MIT	Massachusetts Institute of Technology
MWD	measurements while drilling
NAS	National Academy of Sciences
NEPA	National Environmental Policy Act
OD	outside diameter

PA	performance assessment
PWR	pressurized water reactor
QA	quality assurance
QC	quality control
R&D	research and development
RD&D	research, development, and demonstration
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SP	spontaneous potential
U.S.	United States
UFDC	Used Fuel Disposition Campaign
WBS	work breakdown structure
WOB	weight-on-bit

RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN FOR DEEP BOREHOLE DISPOSAL

1. INTRODUCTION AND BACKGROUND

1.1 Introduction

The United States (U.S.) has focused its past efforts on disposing spent nuclear fuel (SNF) and high-level waste (HLW) in a geologic repository. SNF in this report refers to used nuclear fuel for which a final decision has been made for geologic disposal. More recently, the U.S. Department of Energy (DOE) has been investigating Deep Borehole Disposal (DBD) as an alternative for disposal of SNF and HLW because of a recommendation by the Blue Ribbon Commission (BRC). The Blue Ribbon Commission (BRC 2012, p. 30) recommended “further RD&D to help resolve some of the current uncertainties about deep borehole disposal and to allow for a more comprehensive (and conclusive) evaluation of the potential practicality of licensing and deploying this approach, particularly as a disposal alternative for certain forms of waste that have essentially no potential for re-use.”

Deep Borehole Disposal of SNF and HLW has been considered as an option for geological isolation for many years, including original evaluations by the U.S. National Academy of Sciences in 1957 (NAS 1957). Reconsideration of the DBD option for SNF, HLW, and excess fissile materials has occurred periodically over the last several decades. More recently, advances in drilling technology that have decreased the cost and increased the reliability of drilling large-diameter boreholes to a depth of several kilometers have increased the feasibility of DBD.

This DBD Research, Development, and Demonstration (RD&D) Roadmap is a plan for RD&D activities that will help resolve key uncertainties about DBD and allow for a comprehensive evaluation of the potential for licensing and deploying DBD for SNF and HLW. This roadmap is a “living” plan and will be revised to update the prioritization and status of activities and RD&D needs as progress is made or as necessary to reflect improved understanding. The full-scale DBD demonstration presented will serve as a DBD laboratory and proof of concept and will not involve the disposal of actual radioactive waste or materials. The demonstration will have four primary goals: demonstrate the feasibility of characterizing and engineering deep boreholes, demonstrate processes and operations for safe waste emplacement down hole, confirm geologic controls over waste stability, and demonstrate safety and practicality of DBD as a disposal concept.

The DBD RD&D Plan documented in this report distinguishes between a DBD Demonstration Project and a broader DBD Program. A DBD Demonstration Project is a key early element of a DBD Program and is focused on demonstrating the viability of the DBD concept. A DBD Program consists of all elements necessary to establish proof of concept of DBD and demonstrate its implementation and safety. This RD&D Plan focuses on activities for a DBD Demonstration Project, but also provides more general information on the additional RD&D activities needed for success of a DBD Program. For example, a more detailed plan is provided for the activities supporting selection of a site for a DBD Demonstration Project; whereas, a more general discussion is included for activities supporting site selection of an actual deep borehole waste disposal facility. In general, science thrust activities play a more important role in the early phases of a DBD Demonstration Project, and engineering thrust and engineering demonstration activities are given more emphasis in later phases of a DBD Program.

1.2 Background

Borehole disposal has long been recognized as a means for isolating hazardous materials from the environment. It is widely and routinely used for the disposal of liquid hazardous waste, particularly within the petroleum industry. As noted above, deep borehole disposal has been recommended for consideration as an alternative disposal method for SNF and HLW since the 1950s. The DBD concept addresses the need for isolation of these wastes from the biosphere, from potential inadvertent human intrusion, and with regard to security and non-proliferation of nuclear weapons.

Although relatively simple in concept, actual implementation of deep borehole disposal of SNF and HLW requires assessment of several elements of the disposal system that have yet to be done or attempted, the major element being the drilling of a borehole of sufficient diameter and depth. Several previous studies have evaluated various components of the system with regard to feasibility and made recommendations for technologies to be employed.

1.2.1 Deep Borehole Disposal Concept

The generalized DBD concept is illustrated in Figure 1-1. The concept consists of drilling a borehole (or array of boreholes) into crystalline basement rock to a depth of about 5,000 m, emplacing waste canisters containing SNF or vitrified HLW from reprocessing in the lower 2,000 m of the borehole, and sealing the upper 3,000 m of the borehole. As shown in Figure 1-1, waste in the DBD system is several times deeper than for typical mined repositories, resulting in greater natural isolation from the surface and near-surface environment. The disposal zone in a single borehole could contain about 400 waste canisters of approximately 5 m length. The borehole seal system would consist of alternating layers of compacted bentonite clay and concrete. Asphalt may also be used in the shallow portion of the borehole seal system.

Numerous factors suggest that DBD of SNF and HLW is inherently safe. Several lines of evidence indicate that groundwater at depths of several kilometers in continental crystalline basement rocks has long residence times and low velocity. High salinity fluids have limited potential for vertical flow because of density stratification and prevent colloidal transport of radionuclides. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the retardation of key radionuclides. A non-technical advantage that the deep borehole concept may offer over a repository concept is that of facilitating incremental construction and loading at multiple regional locations. Drilling and testing at a demonstration borehole location will not include any used nuclear materials or high level nuclear waste in the demonstration. Siting of a demonstration borehole need not include all the regulatory compliance issues associated with siting a repository for nuclear materials disposal.

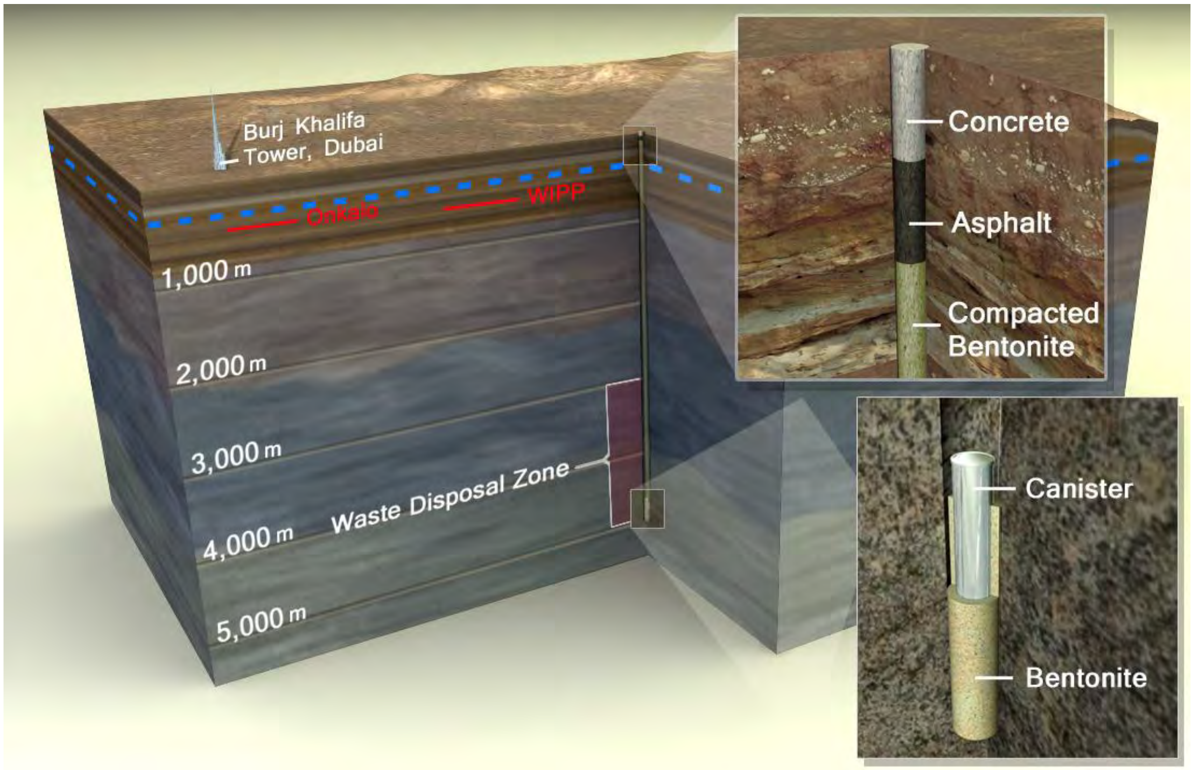


Figure 1-1. Generalized Concept for Deep Borehole Disposal of High-Level Radioactive Waste and Spent Nuclear Fuel.

1.2.2 Previous Research

The evolving feasibility and cost of drilling deep boreholes have been evaluated by several studies, based primarily on experience from the petroleum industry, geothermal drilling, and scientific boreholes, such as the Gravberg-1, Kola, and Kontinentales Tiefbohrprogramm der Bundesrepublik, Deutschland (KTB) wells. Woodward-Clyde Consultants (1983) developed a reference deep borehole disposal system design that included a borehole with a diameter of 20 inches (0.51 m) to a depth of 20,000 ft (6100 m) based, in part, on projections of drilling technology thought to be available by the year 2000. Juhlin and Sandstedt (1989) concluded that deep boreholes with a diameter of up to 0.80 m suitable for disposal of spent nuclear fuel could be drilled and constructed to a depth of 4 km, but at a total disposal cost greater than for the KBS-3 mined repository concept (SKB, 2011). Juhlin and Sandstedt also discussed the impacts of anisotropy in horizontal stress on borehole stability and the formation of borehole breakouts, which may result in conditions that interfere with drilling or waste emplacement at depths greater than 1 to 2 km. Ferguson (1994) concluded that boreholes of an unspecified diameter could be drilled to a depth of 4 km for the disposal of excess plutonium. LLNL (1996) described a deep borehole disposal system for surplus fissile materials, in general, and excess weapons plutonium, in particular, concluding that the disposal system would be effective for proliferation resistance and isolation of radionuclides from the biosphere. The LLNL (1996) study also outlined the research and development (R&D) effort needed for facility design, site characterization, licensing, emplacement, and closure of the deep borehole disposal system and described specific facility requirements. Harrison (2000) proposed a borehole with a final depth of 4000 m and a diameter of 0.762 m as a feasible design for a deep borehole disposal system. A review of previous work on deep borehole disposal by Nirex (2004) generally supports the feasibility of constructing the necessary deep boreholes. A more systematic analysis of borehole diameter versus depth in completed boreholes by Beswick (2008) suggests that a borehole diameter of 0.30 m is readily achievable to a depth of 5000 m and a diameter of 0.50 m may be achievable, but that diameters of greater than 0.50 m are, in practice, not obtained with current drilling technology. Beswick (2008) also emphasizes the constraints of borehole stability at depths of several kilometers.

Multi-lateral boreholes are routinely used in the petroleum industry and a fanned array of inclined or horizontal boreholes from a central borehole has been suggested for a deep borehole disposal system by Chapman and Gibb (2003) and Gibbs (2010). A multi-lateral borehole system could potentially reduce drilling costs, limit the surface footprint of a borehole disposal program, and would result in a single seal system in the central access borehole. However, a multi-lateral system increases the complexity of the waste emplacement process and is not recommended by Beswick (2008).

Various designs for casing in the borehole have been proposed in previous studies. The reference borehole design in Woodward-Clyde Consultants (1983) proposed an uncased hole in the disposal zone from 10,000 ft (3050 m) to 20,000 ft (6100 m) depth and removable casing in the seal zone between 4,000 ft (1220 m) and 10,000 ft (3050 m) depth. The Juhlin and Sandstedt (1989) design proposed a densely perforated "high void ratio" casing in the disposal zone to assure penetration of grouts or sealing material into the annulus between outer surface of the casing and the borehole wall. Intermediate depth casing in the Juhlin and Sandstedt (1989) design would be removed for setting the seals. Beswick (2008) suggested the possible use of expandable casing or well screen in the disposal zone, which is deformed outward to conform to the borehole wall by an oversized mandrel that is drawn upward through the casing.

The reference waste canister design in Woodward-Clyde Consultants (1983) is a carbon steel canister that is 10 ft (3.0 m) in length and 12.75 inches (0.32 m) outside diameter (OD). The Woodward-Clyde Consultants design assumes that the canisters will contain a fill material in addition to the used fuel assemblies to resist deformation of the canister from hydrostatic pressure. The Juhlin and Sandstedt (1989) study considered alternative canister designs constructed with titanium or copper, 5 m in length with an inside diameter (ID) of 0.390 m and an OD of 0.500 m. The base canister design in Juhlin and Sandstedt (1989) includes a support matrix to fill voids within the canister. Hoag (2006) presented a waste canister for deep borehole disposal designed to contain a single pressurized water reactor (PWR) assembly or multiple boiling water reactor (BWR) assemblies. The Hoag (2006) design is 5 m in length with an OD of 0.340 m and an ID of 0.315 m; and would be constructed of T95 or C95 steel casing. The waste canister proposed in Hoag (2006) would be filled with a silicon carbide grit as packing material to resist external hydrostatic pressure on the waste canister. Canisters would be connected with external buttress threaded coupling tubing in the Hoag (2006) design.

Woodward-Clyde Consultants (1983) contains a relatively detailed design for the surface facilities that would be used for the transfer of waste canisters from transportation casks to insertion into the disposal borehole. The Woodward-Clyde design requires a separate waste canister emplacement rig that includes an elevated drill floor, a shielded room below the drill floor to position the transportation cask over the borehole, and a subsurface basement for insertion of the unshielded waste canister into the borehole.

The waste emplacement design in Woodward-Clyde Consultants (1983) calls for pumping cement grout to surround the waste canister string after it is positioned in the waste disposal zone. The Juhlin and Sandstedt (1989) waste emplacement procedure includes the introduction of higher density bentonite mud at the bottom of the borehole prior to lowering the waste canister string into the disposal zone. Beswick (2008) noted that the deployment of high-density mud at each stage of waste canister emplacement would not be difficult to engineer. Beswick (2008) suggests the use of bridge plugs and compacted bentonite blocks between the waste string stages to support the load of overlying canisters and serve as a barrier to flow.

An alternative high-temperature waste emplacement strategy has been suggested by Gibb (1999) and Gibb et al. (2008b). In this strategy a greater mass of waste is emplaced in a larger diameter borehole and the heat output of the waste is sufficient to melt the surrounding granitic host rock. As heat output from the waste declines the melt would recrystallize, encapsulating the waste in a low-permeability rock mass and sealing the borehole. Another lower-temperature approach described in Gibb et al. (2008a) involves the introduction of metal alloy shot in the borehole around the waste canisters to serve as a high-density support matrix. The metal alloy would have a melting temperature of less than 200 °C (392 °C), would be melted by decay heat from the waste, and would support the waste canisters by buoyancy. As temperatures decline the high-density support matrix would serve as an additional barrier to the release of radionuclides.

The reference design for borehole seals in Woodward-Clyde Consultants (1983) includes the emplacement of alternating plugs of a gravel- and bentonite-pellet slurry; and cement grout. Juhlin and Sandstedt (1989) suggested emplacement of highly compacted cylindrical bentonite blocks in bentonite mud within the primary seal zone. The Juhlin and Sandstedt design includes separate asphalt and concrete seals in the upper 500 m of the disposal borehole.

Several design elements and operational procedures relevant to the deep borehole disposal concept were successfully developed and implemented in the Spent Fuel Test – Climax program at the Nevada Test Site (Patrick 1986). Although this program was a test of disposal in a mined repository in granite, the canisters containing commercial PWR used fuel assemblies were lowered to and retrieved from the underground test facility via a borehole. The 11 stainless steel waste canisters had a diameter of 0.36 m and length of about 4.5 m and each contained a single PWR fuel assembly. The surface handling of loaded waste canisters was accomplished with a truck and transport cask system in which the cask was raised to a vertical position over the borehole for insertion of the canister. Canisters were lowered through a cased borehole with an inside diameter of 0.48 m using a wire-line hoist to a depth of about 420 m. After emplacement of the waste canisters in the floor of the underground test facility and a test duration of about 3.5 years, the canisters were retrieved and hoisted back to the surface through the same borehole. Test operations were conducted successfully, safely, and with minimal radiation exposure to workers.

1.2.3 Current Status

Active research on the DBD concept continues at several institutions, including Sandia National Laboratories (SNL), Massachusetts Institute of Technology (MIT), and the University of Sheffield in the United Kingdom. SNL has published a review and preliminary performance assessment of DBD (Brady et al., 2009), a reference design (Arnold et al., 2011), and site characterization for DBD (Vaughn et al., 2012a). Additional performance assessments of DBD have been conducted by DOE under the Used Fuel Disposition Campaign (UFDC) (Clayton et al, 2011 and Vaughn et al, 2012b). MIT has supported several graduate students over the past decade in the area of DBD (e.g., Anderson 2004, Hoag 2006, Sizer 2006, Moulton 2008, Gibbs 2010, and Bates et al., 2011). Research at MIT has included engineering analyses of DBD, exploration of alternative engineering designs, system studies, and supporting laboratory experimental work. Research at the University of Sheffield has been directed at thermal management of waste disposal in deep boreholes to create seals via melting of the host rock and melting of a supporting metal alloy (Gibb et al., 2008b and Gibb et al., 2008a).

2. SCOPE AND OBJECTIVES

2.1 Scope

The demonstration project will confirm the safety, capacity, and feasibility of the DBD concept for the long-term isolation of SNF and HLW. The demonstration will serve as a DBD laboratory and proof of concept and will not involve the disposal of actual waste. The DBD RD&D Plan is organized around a proposed full-scale demonstration project consisting of drilling and completing a deep borehole to 5 km depth, associated scientific research and testing, engineering demonstration of surrogate waste emplacement, and documentation of the feasibility, practicality, and safety of the DBD concept as a disposal system.

2.2 Summary of Objectives

The DBD demonstration project will have four primary goals: demonstrate the feasibility of characterizing and engineering deep boreholes, demonstrate processes and operations for safe waste emplacement down hole, confirm geologic controls over waste stability, and demonstrate safety and practicality of the DBD concept. A comprehensive RD&D effort over several years will be required to achieve these four primary goals. The objectives of this RD&D Roadmap are to:

- Provide the technical and programmatic basis for fielding a full-scale DBD demonstration project. A demonstration project of this kind is required to advance this disposal option from its current conceptual status to potential future deployment as a disposal system for SNF and HLW. The demonstration project would consist of constructing the deep borehole itself, associated operational testing, down-hole scientific sampling and testing, and supporting experimental programs without employing nuclear waste materials in demonstration of capability for the disposal concept.

- Define the scientific research and development activities associated with site characterization and postclosure safety for DBD (science thrust), including long-term monitoring. Scientific investigations will be systematically prioritized in a risk-informed manner, with highest priority placed on those activities essential to confirming the safety and long-term waste isolation capability of the DBD concept. The approach to the prioritization is defined and implemented in an example. Complete prioritization of activities will occur in the early phase of the demonstration.

- Define the engineering demonstration activities associated with deep borehole drilling and completion and surrogate waste canister emplacement (engineering thrust). Engineering development will be prioritized in a risk-informed manner similar to the approach used for the science thrust, with highest priority placed on those activities essential to assuring postclosure and operational safety. In addition, every effort will be made to utilize existing drilling and borehole construction methods to meet the requirements of DBD.

- Foster collaboration with industry, academia, national laboratories, and international participants. Demonstration of DBD will require expertise in a diverse range of technical fields and management methods and collaboration with a broad range of participants will be essential for success.

- Inform nuclear waste disposal regulators and policymakers. Implementation of DBD will require new regulations. The form of those regulations could be informed by this RD&D roadmap by providing the technical rationale for engineering design and scientific investigations.
- Provide policymakers with information on the resource commitments and budget necessary to field the DBD demonstration project.

2.3 General Roadmap for Project Execution

A 5-year high-level milestone schedule for Deep Borehole Disposal RD&D is provided in Figure 2-1. A detailed schedule is provided in Appendix F. Figure 2-1 shows the major RD&D milestones leading up to the demonstration and its completion, including final project documentation. There are four major RD&D tasks:

<u>Demonstration Site Selection</u> – 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 were to 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.

<u>Borehole Drilling and Construction</u> – This task will develop a borehole design, establish borehole requirements, and implement a contract for construction of the borehole, and ensure that the drilled and completed borehole meets requirements.

<u>Science Thrust</u> – This task will identify and resolve data gaps in the deep borehole geological, hydrological, chemical, and geophysical environment that are important to postclosure 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.

<u>Engineering Demonstration</u> – 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.

A Project Execution/Project Management Plan, in accordance with DOE O 413, will be prepared to document the actions and processes necessary to define, prepare, integrate, and coordinate all project activities and plans. The plan will define how the project is executed, monitored and controlled, and completed. The project team will direct the performance of the planned project activities, and manage the various technical and organizational interfaces that exist within the project. The project team will also coordinate all elements of drilling, logging, testing, and engineering involved in the project.

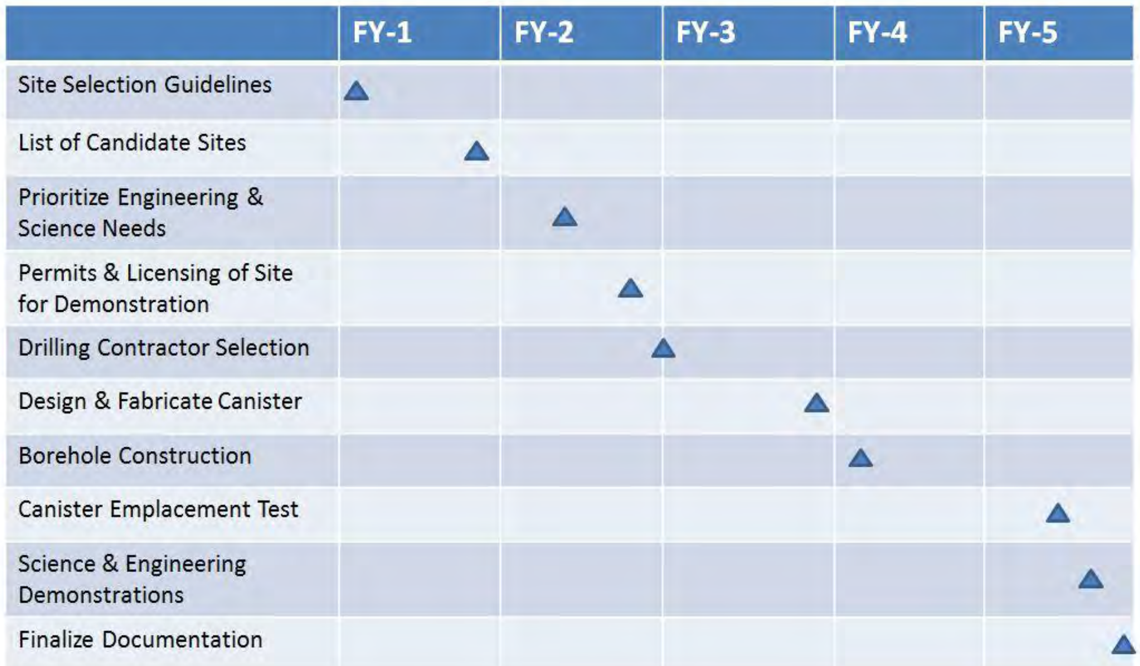


Figure 2-1. High-Level Milestone Schedule for Deep Borehole Disposal RD&D Demonstration Project.

3. SCIENCE THRUST/SITE CHARACTERIZATION

The science thrust of the DBD RD&D roadmap is aimed at data gaps in the deep borehole geological, hydrological, chemical, and geophysical environment that are important to postclosure safety of the system, materials performance at depth, and construction of the disposal system.

3.1 Identification of Data Gaps and Characterization Methods

The identification of data gaps and associated data collection and characterization methods relies on a process that includes identifying a comprehensive list of features, events, and processes (FEPs) for geologic disposal, screening each of the FEPs for potential relevance to deep borehole disposal, and identifying related information needs and data collection and characterization methods. The overall process is summarized here, with a comprehensive FEPs list, screening results, and identified information needs presented in Appendix A.

Various programs in the U.S. and other nations have compiled exhaustive lists of FEPs for mined geologic disposal. The FEP list from the Yucca Mountain license application was adopted by Brady et al. (2009) as a reasonable starting point for evaluation of FEPs and their potential relevance to deep borehole disposal of radioactive wastes. Each of the 374 FEPs on the Yucca Mountain FEP list was considered (screened) by Brady et al. (2009) and the results are used herein as a starting point for identifying data and characterization needs. Table A-1 in Appendix A summarizes the initial screening evaluation and decision for each FEP (whether a FEP is likely to need to be included in or excluded from a full safety analysis for deep borehole disposal) and also includes a qualitative estimate of the level of effort likely to be required to provide a robust basis for the screening of the FEP. The FEPs that are highlighted in Table A-1 represent those FEPs (107 FEPs) currently considered particularly important to DBD (Brady et al., 2009). For excluded FEPs listed within Table A-1, 1 means the technical or regulatory basis is readily available and all that is needed is documentation; 2 means new technical work likely is needed, and 3 indicates a potentially significant amount of work is needed to support the screening decision to exclude the FEP. For included FEPs in Table A-1, 1 indicates that this is a normal part of modeling, 2 indicates that this is a significant aspect of the modeling, and 3 indicates possible modeling challenges. Notes entered in the “Estimated DBD Level of Effort” column provide clarification about how the FEP may need to be considered for deep borehole disposal.

Each of the FEPs in Table A-1 was evaluated for information needs and if applicable assigned characterization techniques for obtaining that information. Table A-2 presents a summary of this evaluation showing each of the identified characterization techniques and the specific FEPs that they address. The information is also presented in the master FEPs list, Table A-1, showing the characterization methods that support each of the FEPs. As seen in Tables A-1 and A-2, a total of 24 characterization methods were identified addressing 89 FEPs of which 63 were identified in Brady et al. (2009) as key FEPs for DBD The remainder of the FEPs in Table A-1 is addressed using information not coming from the characterization methods identified. Each of these characterization techniques in addition to other methods of data collection and their application to DBD are described in this section. As shown in Table A-2, a number of the characterization methods address many of the same FEPs and information needs. This apparent redundancy can provide cross-checking of the data collected or it may be possible to evaluate the list of characterization methods and the data they produce to remove the redundancy, resulting in a shorter list. The focus in this section has been to be comprehensive and further culling of the identified methods will be done during the initial phases of the DBD demonstration project. The characterization methods and information needs resulting from the FEPs evaluation described above are described next.

3.2 Geology

Geological characterization includes lithology, mineralogy, physical properties, fracture characterization, and delineation of faults and structures in the subsurface. Significant characterization information relevant to the suitability of a particular site may be obtained from surface-based methods prior to drilling. These are generally standard geophysical and logging methods from the petroleum and mineral exploration industries.

Understanding the stratigraphy of a potential DBD site is important to 1) locate the crystalline basement rock, 2) identify features such as folds, igneous intrusions, and salt domes, and 3) locate Quaternary-age volcanic rocks or igneous intrusions. Direct release of radionuclides to the biosphere could occur if the magmatic conduit for a volcanic eruption intersected the waste disposal zone. The presence of igneous rocks of Quaternary age at the surface or intersected by the borehole would indicate a potentially significant probability of future volcanic activity and associated impacts on repository performance.

Basic lithological information is central to interpreting the geology and geologic history of the site. Petrographic data (i.e., mineralogy and texture of rock types) would augment geological interpretation and provide information relevant to groundwater flow and radionuclide transport, such as porosity and sorption characteristics. Mineralogy would also identify any occurrences of potentially economically valuable minerals. Characterization of lithology assists in determination on parameters needed for flow, transport, and/or heat transport simulations. For example, average rock density is used in radionuclide transport modeling for adsorbing radionuclides and in heat transport simulations. Other important parameters that can be estimated based on lithology or mineralogy include sorption coefficients, bulk density, mechanical properties, and thermal properties.

Understanding faults or highly fractured zones is critical to identifying interconnected zones of high permeability from the waste disposal zone to the surface or shallow subsurface. A high-permeability pathway from the waste disposal zone to the shallow subsurface could conduct significant groundwater flow and associated radionuclide transport, particularly by thermally driven flow during the period of high heat output by the waste. In addition, it is important to evaluate the possibility of these preferential pathways intersecting boreholes at depth. The location, displacement, and orientation of faults exposed at the surface should be identified. Faults that are exposed at the surface often extend into the deep subsurface. Finally, it is important to exclude the possibility of igneous rock in the waste disposal zone overthrusting above sedimentary rocks.

It is also important to analyze fault displacement history. Any active faults near the site would be relevant to the DBD system with regard to seismic risk, tectonic stability, and potential for displacement of the borehole and damage to waste canisters. Potential evidence of Quaternary-age activity along faults should be analyzed accordingly.

Fracture network as a function of depth should be characterized. Fracture orientations and cross-cutting relationships may be useful in reconstructing the structural and tectonic history of crystalline basement rocks. Information on fracture network geometry, fracture aperture, and fracture filling may have implications for the interconnectivity of the fracture network and bulk permeability of the system.

Characterization of fractures will also assist with understanding the physical and hydrogeological properties of the system. Fracture aperture measurements can be used to estimate the flow porosity of the host rock. Identification of open fractures and fracture zones will help with understanding water quality; groundwater samples would be more likely obtained from setting packers and sampling in zones that contain open fractures. Hydraulic packer testing and push-pull tracer testing would also be more successful in borehole intervals that have open fractures.

3.2.1 Surface-Based Characterization

Surface-based characterization is conducted either on the ground surface or via airborne surveys to better understand subsurface stratigraphy and structures. These surveys measure either naturally occurring anomalies (gravitational or magnetic), variations in the electrical resistivity of the subsurface, or can measure anthropogenic alterations (such as mines or other excavations) from a seismic source. Surface geological mapping, 3D seismic imaging, gravity and magnetic surveying, and electrical resistivity profiling methods are examples of surface based characterization. More detailed descriptions of these methods are presented in Vaughn et al. (2012a).

In general, surface-based characterization is the first step to confirming that a site is potentially suitable. For example, determining the location of the basement rock using surface geological mapping and geophysical profiles will help determine if the basement rock is deep enough to make the site suitable for DBD. It can also be used to evaluate the likelihood that there will be transmissive pathways from the waste disposal zone to the surface or shallow subsurface. If it is decided that a site is potentially suitable, surface-based characterization can help guide the drilling program (e.g., estimate how deep to drill the well). During and after well drilling, borehole based characterization can be used for more detailed site characterization. In addition, some features (e.g., mineralogy, porosity, and other petrophysical characteristics) cannot be evaluated without borehole-based characterization.

3.2.1.1 3D Seismic Imaging

Seismic imaging is an exploration technique used to better understand stratigraphy and structures in the subsurface. A seismic source (e.g., dynamite explosion) is initiated and seismic waves that have traveled through the earth from the explosion are recorded by geophones when they reach the surface again. With 3D seismic imaging, a set of numerous, closely spaced seismic lines are used to allow for a high spatial resolution of data. The sources are placed in vertical and orthogonal horizontal lines to allow for higher resolution than 2D imaging.

Both inversion methods and amplitude variation with offset (AVO) can be used to interpret seismic data. Inversion calculates acoustic impedance (AI) from a seismic trace. Porosity, density, lithology, fluid saturation can all correlate with AI. AVO uses the observation that pore fluid type impacts the amplitude of a seismic reflection. The seismic data must be viewed at different angles of reflection in order to have a variable distance (or offset) between the seismic source and receiver. AVO assumes that the lithology effect on the seismic amplitude is small compared to that of the pore fluid. AVO works best with high-porosity lithologies.

In relationship to site characterization for deep borehole disposal, 3D seismic imaging could be used to determine whether the boreholes might intersect features that could potentially be leakage pathways. 3D seismic imaging would be useful for imaging the stratigraphy, depth of the crystalline basement, and potential transport features in the vicinity of the boreholes in order to characterize the potentially transmissive pathways to the biosphere.

3.2.1.2 Gravity and Magnetic Surveys

Gravity and magnetic surveys use the earth gravitational or magnetic fields, respectively to identify or map gravity or magnetic anomalies. A gravity anomaly is caused by a change in mass or rock density in the subsurface. A magnetic anomaly is a local variation in the earth‟s magnetic field due to variations in chemistry or magnetism of the rocks. They can both be used to infer locations of faults, folds, igneous intrusions, salt domes, petroleum resources, and groundwater reservoirs. The extent and depth of sedimentary basins can be determined. In addition, they can be used to help find contacts between igneous and sedimentary formations.

Data collection for a gravity and magnetic survey can be either ground-based or air-based. Gravity and magnetic surveys could be used to map deep subsurface faults and locate the crystalline basement rock, features necessary for assessing the suitability of the deep borehole demonstration project site.

3.2.1.3 Electrical Resistivity (Surface Based – Large Scale) Profile

Electrical resistivity methods use the variation in resistivity of rock types as well as the pore fluid for subsurface geological and hydrological mapping. An electrical current is sent into the earth using current electrodes and the potential difference is measured between a pair of potential electrodes. From this, the apparent resistivity, a weighted average of resistivities of the materials that the current encounters, can be measured. Electrical resistivity *profiling* uses an array of electrodes with a constant spacing. From these data, faults, conductive fluids, subsurface voids (e.g. mines, sinkholes), and paleochannels can be mapped. Electrical resistivity *sounding* involves a series of measurement where the center electrode position remains fixed, but the distance between electrodes successively increases. Resistivity sounding techniques can be used to determine the depth to bedrock, depth to groundwater, and stratigraphy. Profiling and sounding techniques can be combined to determine the lateral and vertical extent of subsurface features.

Much of the electrical resistivity data is collected at relatively shallow depths (less than 50 m below land surface). However, there are some data from 3 km below the land surface that have been collected. For deep borehole disposal, electrical resistivity profiling would be most useful for locating the contact to the crystalline basement rock.

3.2.1.4 Surface Geological Mapping

Surface geological mapping is a standard form of characterization for any radioactive waste disposal site. In the case of deep borehole disposal, surface geological mapping may be of limited significance to the characterization program and the assessment of disposal system safety due to the deep location of the waste disposal zone. Existing high-quality, local-scale geological maps are available for many potential sites. Some potential sites may require additional surface-based mapping to augment published information on the site geology.

Surface geological mapping would be used in the characterization of a deep borehole demonstration site in the following ways:

- Identification of the location, displacement, and orientation of faults exposed at the surface. Faults that are exposed at the surface often extend into the deep subsurface. Surface mapping of faults would be used to correlate these structures to inferred subsurface faults identified with surface-based geophysical methods such as 3-D seismic imaging and resistivity profiles. Major fault zones are relevant to deep borehole disposal system performance because of their potential role as preferential pathways for groundwater flow and potential intersection with boreholes at depth.
- Analysis of fault displacement history. Any active faults near the site would be relevant to the deep borehole disposal system with regard to seismic risk, tectonic stability, and potential for displacement of the borehole and damage to waste canisters. Potential evidence of Quaternary-age activity along faults would be analyzed accordingly.
- Potential correlation of lithology at the surface with rock types in the boreholes. Depending on the local geologic structure, it may be possible to correlate rocks at the surface with those found at depth. An analysis of this correlation could be important to site characterization with regard to geologic structure and variations in lithology. Such correlation would also be useful in the interpretation of surface-based geophysical imaging.

3.2.2 Borehole Characterization

Borehole characterization methods measure characteristics of the drilled borehole, the formations intersected by the borehole, and pore fluid. The methods vary with respect to the distance into the borehole that can be interrogated. Some are confined to the borehole disturbed zones. Others can penetrate deep into the surrounding formations that are intersected. The characteristics determined by interpretation of the data from these methods include chemical, thermal, hydrologic, and geologic such as rock type, formation density, porosity, permeability, fracture spacing and aperture, water quality and composition. Examples of borehole characterization methods include geophysical logging, logging of drill cuttings, coring of boreholes, hydrologic testing, thermal testing, and water sampling and analyses. Borehole logging methods include some of the standard methods listed below. These logging methods provide information on lithology, porosity, fractures, and structure for general characterization of the rocks penetrated by the borehole.

3.2.2.1 Gamma Ray Log

Gamma ray logging measures naturally occurring gamma radiation, which varies by lithology. The most common emitters of gamma radiation are ^{238}U, ^{232}Th and their daughter products, and ^{40}K. A common gamma-ray log cannot distinguish between radioactive elements, where a spectral gamma ray log can. Clay and shale-bearing rocks generally emit more gamma radiation because of their radioactive potassium content. These units can also concentrate uranium and thorium by ion adsorption and exchange. Therefore, gamma ray logs can be used to differentiate shale and other fine-grained sediments from other sedimentary units and other rock types. However, some carbonates and feldspar-rich rocks can also be radioactive. Gamma ray logging can be conducted in both open borehole and through steel and cement casings, though the steel or cement will absorb some of the gamma radiation.

3.2.2.2 Resistivity Log (Borehole Based)

Resistivity logging is one of many electrical logging techniques that utilize one or more downhole electrodes connected to a logging cable, a depth measuring device, a control panel, and a recorder. The recorder and depth measuring devices are synchronized so that the recording pens move laterally dependent on the electrical signal received while the chart moves vertically to reflect the depth in the borehole. In resistivity logging the electrical signal received is resistivity of the rock traversed by the borehole.

Resistivity is a fundamental material property which represents how strongly a material impedes the flow of electrical current. Resistivity is an intrinsic material property and depends on the size of the material being measured. Most rock materials are essentially insulators, while the pore fluids they contain are conductors.

Resistivity logs may be generated by induction coils or laterolog tools. The induction tools use coils and magnetic fields to develop currents in the formation whose intensity is proportional to the conductivity of the formation. Induction logging devices originally were designed to make resistivity measurements in oil-based drilling mud, where no conductive medium is present between the tool and the formation. Induction devices provide resistivity measurements regardless of whether the fluid in the well is air, mud, or water. The laterolog uses electrodes to send a current into the formation and measure voltages at different points.

3.2.2.3 Spontaneous Potential Log

Spontaneous-potential (SP) logs provide information on lithology, the presence of high permeability beds or features, the volume of shale in permeable beds, the formation water resistivity, pore water quality (e.g., salinity, ionic concentration) and correlations between wells. SP measures the difference in electrical potential between two electrodes in the absence of an applied current. The component of this difference relevant to SP is the electrochemical potential since it can cause a deflection indicative of permeable beds. Typically one of these electrodes is grounded at the surface and the other at the target location in the borehole. Saturated rock and water or conducting mud-filled holes are necessary to conduct the current between the electrodes. When drilling mud and the natural pore fluid come into contact, they set up an electrical potential. These spontaneous potentials arise from the different access that different formations provide for ions in the borehole and formation fluids. The movement of ions from the drilled formation to the borehole accounts for the majority of the measured voltage difference and thus the SP log is an indirect measure of permeability.

3.2.2.4 Neutron Porosity Log

Neutron porosity logging is a geophysical method that is widely used in the petroleum industry to estimate the formation porosity of the rock surrounding the borehole. The logging tool consists of a fast neutron source and a sensor for thermal neutrons. Fast neutrons emitted by the source interact with the nuclei of surrounding materials via elastic collisions and lose energy to a thermal level and are then detected by the sensor. Fast neutrons are converted to thermal neutrons most efficiently by collisions with hydrogen nuclei because of similar masses of the particles. The neutron porosity tool thus effectively measures the hydrogen concentration within about 20 cm of the borehole wall. For a water saturated medium, the hydrogen concentration is proportional to the porosity. The calculated value of the porosity must be corrected for borehole diameter, drilling fluid characteristics, rock type, salinity of the pore fluid, and hydrocarbon type and content.

Neutron porosity logging would be used in the characterization of a deep borehole disposal system in the following ways:

- Estimate the porosity of the host rock. Neutron logging, in conjunction with measurements on core samples and other logging methods that image fractures in the borehole wall such as FMI logs, provides an estimate of the porosity. Host rock porosity is an important parameter in the calculation of groundwater velocity and matrix diffusion, particularly in low-porosity crystalline rocks.
- Assess the lithology, alteration, and fracturing in the host rock. Neutron porosity logging contributes to the lithological and structural interpretation of the borehole, in combination with other logging methods.

3.2.2.5 Formation Micro Imager Log

Formation Micro Imager (FMI) logging uses microresistivity measurements to construct an oriented image of the electrical resistance of the rock surface exposed along the borehole wall. Measurements are made with a logging tool with multiple electrodes and are made in a borehole filled with conductive drilling fluid. The resulting image can be interpreted to determine stratigraphic strike and dip, foliation, borehole breakouts, and fracture orientations, filling, and apertures. Natural and drilling-induced fractures can usually be distinguished on FMI logs. An example FMI log and the interpretation of fractures intersecting the borehole are shown in Figure 3-1.

FMI logging is commonly performed in petroleum exploration wells and used in stratigraphic interpretation, structural analysis, and determination of *in situ* stress. Detailed information on fracture orientation, spacing, aperture, and filling from FMI logs is used in petroleum reservoir engineering. FMI logs are also used commonly in geothermal exploration and production wells that are drilled in igneous rocks for similar purposes.

FMI logging would be used in the characterization of a deep borehole demonstration project in the following ways:

- Determine the location of borehole breakouts and drilling induced-fractures. The orientation of anisotropy in horizontal stress can be inferred from breakouts and induced fractures if present in the borehole walls. The occurrence, location, and severity of borehole breakouts may have important implications for borehole construction and the emplacement of borehole seals. Identification of drilling-induced fractures may be useful in characterizing the disturbed rock zone around the borehole.

- Identification of open fractures and fracture zones. Groundwater samples would be more likely obtained from setting packers and sampling in zones that contain open fractures identified in the FMI logs. Hydraulic packer testing and push-pull tracer testing would also be more successful in borehole intervals that have open fractures.

- Characterization of the fracture network as a function of depth. Fracture orientations and cross-cutting relationships may be useful in reconstructing the structural and tectonic history of crystalline basement rocks. Information on fracture network geometry, fracture aperture, and fracture filling may have implications for the interconnectivity of the fracture network and bulk permeability of the system. Fracture aperture measurements can be used to estimate the flow porosity of the host rock.

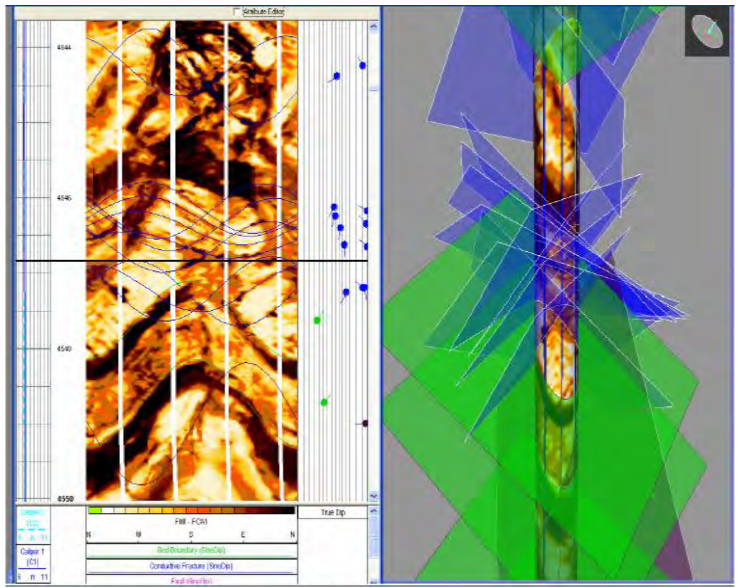


Figure 3-1. Example FMI log with Interpreted Fracture Orientations.

3.2.2.6 Borehole Gravity Log

Borehole gravity logging makes highly sensitive measurements of the acceleration of gravity as a function of depth in the borehole. Minute differences in gravity are used to calculate the average density of the rock formation surrounding the borehole. Borehole gravity logging determines the average density of the formation over a relatively large volume and is sensitive to density for distances of 10‟s of meters into the rock. In combination with information on rock grain density and fluid density, borehole gravity logging results can be used to estimate total porosity, averaged over a similarly large volume. Rock grain density can be measured on core samples and fluid density would be determined from groundwater samples. Note that estimates of porosity from borehole gravity logging apply further into the rock formation than those from neutron logging.

Borehole gravity logging would be used in the characterization of a deep borehole disposal system in the following ways:

- Estimate host rock density. The value of average rock density is used in radionuclide transport modeling for sorbing radionuclides and heat transport simulations.

- Estimate host rock porosity. The total host rock porosity provides information on the groundwater volume that exists as mobile and immobile phases. Values of mobile and immobile porosity are used in radionuclide transport modeling.

- Potential identification of fault zone and mineral alteration. Structurally complex regions and fault zones in crystalline rock often have greater fracture intensity, lower bulk density and higher porosity than intact rock. Mineral alteration, including the presence of hydrous mineral phases, also may be associated with fault zones and may be detected by borehole gravity logging.

3.2.2.7 Drill Cuttings Lithology Log

Standard logging of drill cuttings lithology provides a record of rock type and mineralogical and textural characteristics encountered during the drilling process. This information can later be correlated with geophysical logging to calibrate the geophysical signal with geology in the borehole. Samples of drill cuttings would be stored for potential additional geochemical and petrophysical analysis. Logging of drill cuttings also provides real-time information on downhole lithology that is potentially useful to drilling operations and to the deployment of intermittent coring and other tests at geologically important intervals of the borehole.

The usefulness of data obtained from drill cuttings is limited by uncertainty about the depth from which the cuttings come. Drill cuttings must be transported by the drilling mud from the drill bit to the surface resulting in a delay between the time that they are cut and when they are sampled (this delay is a function of the depth from which they are formed). There is also mixing of cuttings during transport to the surface. Reverse circulation drilling methods tend to isolate drilling mud and cuttings from contamination by other rock fragments from the borehole wall, but such fragments can still be mixed with drill cutting samples.

Drill cutting logging would be used in the characterization of a deep borehole disposal system in the following ways:

- Provide a semi-continuous vertical profile of bedrock lithology. Basic lithologic information from the borehole is central to interpreting the geology and geologic history of the site. Petrographic data (i.e., mineralogy and texture of rock types) would augment geological interpretation and provide information relevant to groundwater flow and radionuclide transport, such as porosity and sorption characteristics. Mineralogy would also identify any occurrences of potentially economically valuable minerals.

- Provide samples for laboratory testing. Estimates of parameters such as sorption coefficients, bulk density, and bulk chemistry can be made from drill cuttings.

- Provide information for drilling operations. Choices of bit type, drilling mud composition, and weight on the bit could be influenced by rock type encountered during drilling.

3.2.2.8 Intermittent Coring

Intermittent coring would be necessary to obtain intact samples of the host rock for detailed analysis and testing. Continuous coring of deep boreholes for waste disposal would be unnecessary and prohibitively expensive. Coring would be conducted at regular intervals and at depths of particular geological interest, such as major transitions in lithology identified from drill cuttings. For larger-diameter disposal boreholes, smaller-diameter advance coring would be conducted, followed by overdrilling to continue the borehole. Side-wall coring is also possible for locations of particular interest that are identified by logging or testing after the drilling has been completed for that interval.

Rock core would be used for a wide range of mineralogical, petrophysical, geochemical, mechanical, thermal, and hydrologic testing. Intermittent coring would be used in the characterization of a deep borehole disposal system in the following ways:

- Provide mineralogy of the various lithologies encountered. Mineralogy is basic geologic information that allows assessment of petrogenesis. Mineralogy is also relevant to radionuclide sorption.
- Provide petrophysical characteristics of the various lithologies encountered. Petrophysical characteristics of core can be correlated to geophysical logging to improve the accuracy of the geophysical logging.
- Provide geochemical characteristics of the various lithologies encountered. Geochemical (e.g., bulk composition of major, minor, and trace elements) and fluid inclusion studies will provide information on the geologic history of the system, which is relevant to the long-term stability of the site and isolation of the waste.
- Provide mechanical characteristics of the various lithologies encountered. Mechanical properties of the host rock are relevant to borehole stability and the effectiveness of seals.
- Provide thermal characteristics of the various lithologies encountered. Thermal properties of the host rock affect the temperatures of the waste canisters and related corrosion rates. Temperatures from waste heat are also relevant to thermal-hydrologic processes.
- Provide hydrological characteristics of the various lithologies encountered. Permeability of the host rock is relevant to potential fluid migration and radionuclide transport.

3.3 Hydrogeology

Hydrogeological characteristics, including permeability, flow porosity, fluid pressures, vertical hydraulic gradient, solute transport properties, and characteristics of the disturbed rock zone would be determined for the host rock and overlying strata using the testing described in this section. These hydrogeological characteristics are relevant to the long-term isolation of radionuclides in the DBD system. In particular, deep overpressured conditions would be detrimental to safe performance of the disposal system. Some of these methods are standard testing techniques, but some would require adaptation to provide the information needed for DBD. Particular care would be required in obtaining representative samples of deep fluids that have not been contaminated by drilling activities.

3.3.1 Drill Stem Tests of Shut-In Pressure

Drill stem testing (DST) is a primary testing method in the drilling industry. It provides three basic pieces of information on the host formation: formation pressure, formation permeability, and water chemistry. DST equipment consists of a down-hole pressure measurement and recording device, flow control valves that can be controlled from the surface and a sampling device placed on the drill stem.

Ambient fluid pressure in the rock formation surrounding the borehole is measured by determining the shut-in pressure. After the packer system is inflated to isolate the test interval from the rest of the borehole, a control valve is opened to allow equilibration of fluid pressure within the drill stem and the formation. Fluid pressures are monitored during the equilibration process until a stable measurement is obtained. Fluid pressures within the formation may have been altered during drilling and the equilibration process must allow such anomalous pressures to dissipate.

Accurate measurements of ambient formation pressure are necessary to determine vertical hydraulic gradients in the system and to develop an overall conceptual model of groundwater flow in the hydrogeological system. Fluid pressure measurements in combination with factors that affect fluid density (primarily temperature and salinity) as a function of depth are used to calculate the overall fluid potential along the vertical extent of the borehole. Vertical gradients in fluid potential indicate the driving force for vertical fluid movement in the system and the occurrence of overpressured or underpressured conditions, relative to hydrostatic conditions. Overpressured conditions would indicate the long-term potential for upward migration of groundwater containing dissolved radionuclides from the DBD system. Hydrostatically stable or underpressured conditions between the disposal zone and the shallow groundwater system are thus favorable natural conditions for the safety of the DBD system.

3.3.2 Drill Stem Pump Tests

Drill stem pump tests are conducted with the drill string still in the borehole and are conducted for shorter periods of time than packer pump tests. Pumping tests are used to determine the hydrologic properties of formations and performance characteristics of wells. The former is of interest here. The properties determined include hydraulic conductivity (horizontal and vertical), specific storage or storativity, and transmissivity (hydraulic conductivity times thickness).

Drill stem pump tests typically consist of relatively rapid drawdown in pressure in a short packed interval of the open borehole followed by a pressure recovery period. Fluid injection tests can also be performed. The hydrologic properties are estimated from the pumping test by curve fitting the drawdown data against solutions of various well flow equations in a process sometimes called type curve fitting. The more straightforward type curve analyses use the Theis solution. More complex analyses are based on solutions that relax one or more of the Theis assumptions. Different representations of the formation and corresponding solution to the flow are selected. The data are compared to each representation and formation parameters are extracted from the best fit.

Results from drill stem pump tests may have significant uncertainties because of the generally short duration of the tests, the relatively small volume of rock interrogated by the testing, potential impacts of drilling fluids on hydraulic conductivity near the borehole, and potential leaks from packers.

3.3.3 Packer Pump Tests

Packer pump tests are targeted at specific intervals of the borehole and are generally longer-duration and better controlled tests of hydraulic properties than drill stem pump tests. These tests are not conducted through the drill stem or during drilling, but are generally done after the borehole is completed. The equipment to support these tests consists of one or more inflatable packers to seal the annular space between the drill string and the borehole wall, a screen in the interval to be measured, lines and pump to inflate and/or deflate the packer, a sampling pump, flow meters, and associated pressure gauges. Because packers can be deflated, moved to other locations in the borehole, and re-inflated they provide a convenient means for determining the vertical distribution of water quality and hydraulic conductivity.

The operation of various packer testing consists of measuring the rate of flow and/or pressure build-up/decay in the test interval over a period of time. Water may be injected at a constant rate, as a pulse, or as a slug to determine the formation transmissivity and storage coefficient from which permeability and porosity can be derived. In deep boreholes the measuring of the upper end of transmissivity may be constrained by the hydraulics of the injection system (rate and pressure output limit of pump, supply line (friction losses), water availability, etc.). It is important to determine what the expected testing range of the zones of interest will be so equipment can be properly sized.

Three packer testing methods are commonly used:

1) Injection (Lujeon) Tests: Water is injected at specific pressure levels and the resulting pressure is recorded when the flow has reached a quasi-steady state condition.

2) Discharge Tests: The decay in formation pressure is recorded after an equilibration period.

3) Shut-In Recovery Tests: Shut-In recovery tests are usually run in conjunction with a discharge test. The shut-in pressure build-up over time is monitored and recorded against the elapsed time since the discharge test, and the time since the recovery test was started.

There are a number of considerations associated with packer inflation that require special attention when applied to the depths associated with the deep borehole. These relate to the method used to inflate the packer and the proper sizing of lines and pumps. The packer inflation pressure must be sufficient to expand the packer gland against the borehole wall and it must overcome hydrostatic pressure at depth. Therefore, the inflation pressure required will vary significantly over the 5000 m of depth associated with the deep borehole.

There are some operational considerations for packers. Packer glands are made of rubber materials that can be damaged if they scrape against sharp portions of the borehole wall. The thermal limits on these rubbers are generally below 120°C. Leakage, if it occurs, will compromise the measurements. Leakage may occur at the packer-wall interface or in the supply lines. The potential for leakage increases with depth because of the increased pressures required and is exacerbated in tighter formations. If packers are overinflated they can burst or damage the borehole. For the deep borehole application the thermal limits pose no restriction unless it might be used in combination with electrical heater tests. The other operational issues can be minimized by careful testing procedures.

3.3.4 Vertical Dipole Tracer Testing

Vertical dipole tracer testing consists of injecting a chemical tracer solution in a packed off interval of the borehole and recirculation pumping from another interval in which the tracer concentration is measured (Sanford et al., 2002; Chen et al., 2011). Solute transport occurs vertically through the rock mass between the injection interval and the pumping interval and around the intervening packer interval in the borehole, as shown in Figure 3-2. *In situ* transport properties of the rock mass are determined from the breakthrough curve of the tracer in the pumped interval. This tracer testing method has the advantage of using a single borehole, versus at least two wells required in traditional cross-hole testing. This is particularly advantageous in the case of a very deep borehole as in the deep borehole disposal system. The vertical dipole tracer testing method also interrogates the solute transport characteristics of the borehole disturbed zone immediately adjacent to the packed borehole, which would be a potential pathway for the vertical migration of radionuclides from the disposal zone.

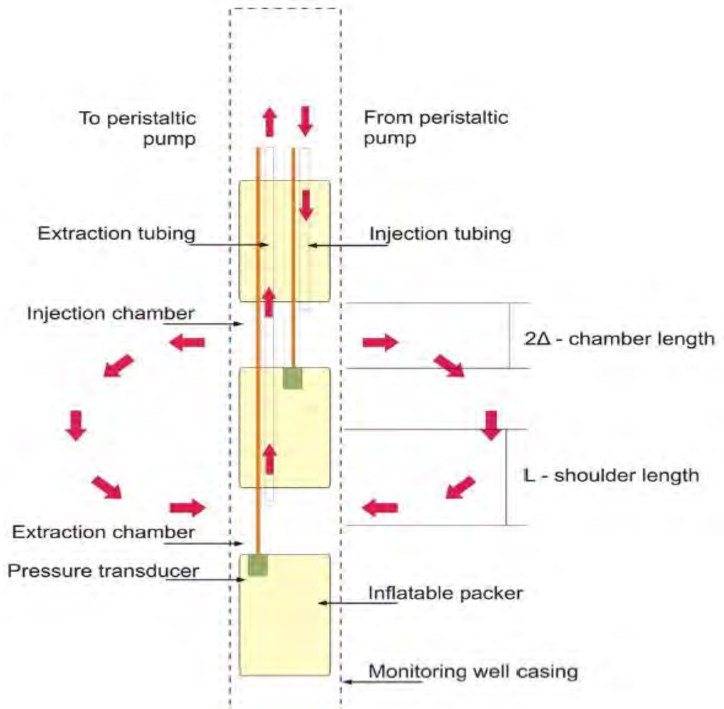


Figure 3-2. Schematic Diagram of the Vertical Dipole Tracer Test Configuration (from Roos 2009).

Parameters related to the groundwater transport of radionuclides in fractured crystalline host rock that could be derived from the vertical dipole tracer testing include flow porosity, dispersivity, sorption coefficient, and matrix diffusion rate. Multiple tracers with contrasting values of molecular diffusion coefficient and sorption coefficient can provide stronger evidence of matrix diffusion and better constrained values of transport parameters in the modeling analysis of the tracer test results (Reimus and Callahan, 2007; Sanford et al., 2002).

Vertical dipole tracer testing would be used in the characterization of a deep borehole disposal system in the following ways:

- Estimate the radionuclide transport characteristics of the host rock and borehole disturbed zone. Performance assessment modeling of radionuclide transport requires site-specific transport parameter values. *In situ* transport properties measured using tracer testing augment laboratory measurements of radionuclide transport parameters by providing data at a larger scale that is more representative of radionuclide migration from the disposal zone.

- Support the conceptual model of radionuclide transport in fractured crystalline host rock. Tracer testing provides support for key radionuclide transport processes, such as sorption and matrix diffusion, that are relevant to radionuclide migration.

3.3.5 Push-Pull Tracer Testing

Push-pull tracer testing (also referred to as single-well-injection-withdrawal tests) is a single-borehole method that consists of injecting tracer solution into the host rock and then pumping groundwater from the same packed interval of the borehole as shown in Figure 3-3. A rest period between injection and withdrawal may be included in the test to allow the tracer plume to drift under ambient flow conditions.

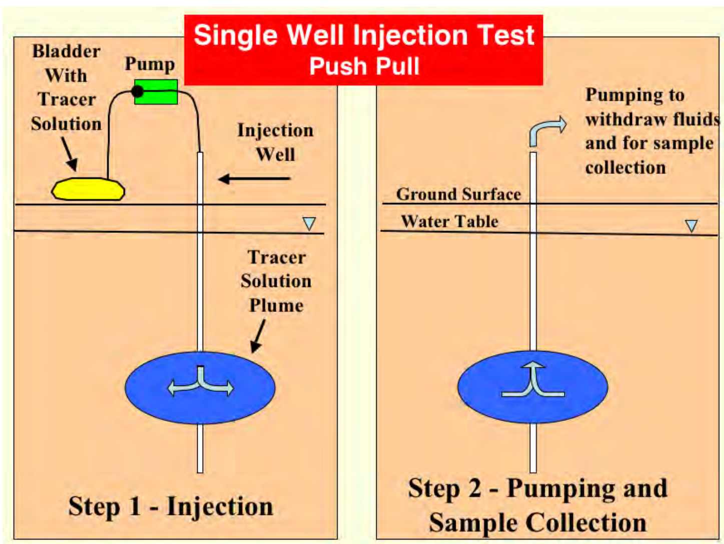


Figure 3-3. Schematic Diagram of a Push-Pull Tracer Test Configuration.

Analysis of the tracer withdrawal breakthrough curves provides information on dispersivity, matrix diffusion, reaction rates in reactive tracers, and ambient groundwater flow rates if a rest period is included in the test. As with the vertical dipole tracer test, using multiple tracers with contrasting values of molecular diffusion coefficient can better constrain the effects of matrix diffusion in the medium. For push-pull tracer tests in porous media without a rest period, the tracer follows approximately the same pathway back during the withdrawal phase that it followed into the rock formation during the injection phase. The shape of the withdrawal breakthrough curve is governed by small-scale, local dispersivity in this case (Guven et al., 1985). For tests in fractured porous media, tracer mass exchange between groundwater in the mobile and immobile regimes via matrix diffusion plays an important role in tracer recovery (Meigs and Beauheim 2001). A multi-rate model of matrix diffusion, related to the heterogeneous size of matrix blocks, is required to explain the tracer breakthrough curve in many systems (e.g., Haggerty et al., 2001). Interpretation of push-pull tracer test results may be complicated by the overlapping effects of dispersive and diffusive processes in highly heterogeneous fractured rocks (Neretnieks 2007). Push-pull tracer testing with a rest period can be used to estimate the ambient groundwater flux in the medium in addition to the tracer transport parameters (Leap and Kaplan 1988).

Push-pull tracer testing would be used in the characterization of a deep borehole disposal system in the following ways:

- Estimate the radionuclide transport parameters of dispersivity and matrix diffusion in the host rock and borehole disturbed zone. *In situ* transport properties from tracer testing augment laboratory measurements of radionuclide transport parameters by providing data at a larger scale that is more representative of radionuclide migration from the disposal zone.

- Support the conceptual model of radionuclide transport in fractured crystalline host rock. Tracer testing provides support for key radionuclide transport processes, such as matrix diffusion, that are relevant to radionuclide migration.

- Estimate the ambient groundwater specific discharge in the host rock.

3.4 Stress/Pressure Conditions and Borehole Stability

Stress conditions and the differential in horizontal stress, in particular, are important at the depths of DBD with regard to mechanical behavior of the host rock surrounding the borehole and to the stability of the borehole. These conditions are potentially relevant to the disturbed rock zone, long-term isolation of radionuclides, tectonic stability of the site, and successful construction of the completed, cased borehole.

3.4.1 Borehole Caliper Log

Borehole caliper logging is conducted to measure the condition of a borehole, indicating irregularities in the borehole wall, such as breakouts, cave-ins or swelling. The calipers, which can be mechanical or sonic, measure the diameter of the borehole. A multifinger caliper measures several diameters on the same horizontal plane simultaneously, thus measuring the irregularity of the borehole.

Borehole caliper logging would be useful for deep borehole disposal in order to determine the integrity of the well, where casing or cementation is needed and possibly identifying larger fractures. The orientations and extent of borehole breakouts and tension fractures provide information on the direction of the maximum and minimum principal horizontal stress and some indication of the difference in the magnitudes of these stresses.

3.4.2 Dipole Shear-Wave Velocity Log

Dipole shear-wave velocity logging measures the velocity of shear waves in the borehole wall as a function of azimuthal direction. Anisotropy in the shear-wave velocity is a function of differential horizontal stress, rock fabric orientation (e.g., bedding or foliation), and fracture orientations. Microfractures in the rock that are oriented in the direction of maximum horizontal compressive stress tend to be more open than microfractures that are parallel to the minimum horizontal stress. Consequently shear wave velocity tends to be higher in the direction of maximum horizontal stress than in the direction of minimum horizontal stress. Interpretation of the anisotropic shear-wave velocity log can provide an estimate of the directions of maximum and minimum in situ horizontal stress as a function of depth, even in the absence of macroscopic indicators such as borehole breakouts and drilling-induced fractures.

Dipole shear-wave velocity logging would be used in the characterization of a deep borehole disposal system in the following way:

- Estimate the directions of *in situ* maximum and minimum horizontal stresses, and their difference in magnitude. Anisotropy in horizontal stress has implications for borehole stability and the extent of the disturbed rock zone around the borehole. In addition, differential horizontal stress may give geological evidence regarding the tectonic history and structural stability of the site.

3.5 Geochemical Environment

The chemical and isotopic composition of deep groundwater helps establish groundwater age and chemical speciation. These in turn are used to constrain the degree of borehole fluid contact with higher aquifers, the potential for canister corrosion, scaling and chemical transport.

3.5.1 Fluid Samples from Packer Testing

In situ fluid samples will be obtained through packer pump tests, drill stem pump tests, and key first-strike water occurrences encountered while drilling. Special care will be taken to obtain representative groundwater samples that are not contaminated by drilling fluids.

Major ion groundwater chemistry (pH, Ca^{+2}, Mg^{+2}, Na^{+}, SO_4^{-2}, HCO_3^{-}, Cl^{-}) will be measured and used to help constrain the history and evolution of the groundwater, the mineral and gas phases likely to be in equilibrium with it, and its potential reactivity. Measured groundwater chemistry will also be used as input into geochemical equilibrium models that estimate the potential for mineral scale formation, the stability of seals and backfill materials, and the solubility and sorption of radionuclides. Additional effort will be made to accurately measure the partial pressure of H_2 gas in order to estimate the *in situ* redox state of deep borehole fluids.

Salinity profiles constructed from groundwater chemistry data will be used to estimate the resistance to upward vertical groundwater flow by salinity stratification and to assess potential overpressured conditions. Groundwater salinity measurements will also be used to constrain the potential for colloid-facilitated transport.

Environmental and isotopic tracers will be analyzed to build models of groundwater provenance, groundwater residence times, flow rates through the system, and the interaction of deep groundwater flow with the shallow hydrosphere. Fracture fluids will be sampled for stable isotopes of water (δD, $\delta^{18}O$), dissolved noble gas isotopic composition, ^{36}Cl and ^{129}I concentrations. Core samples will be taken to determine pore fluid helium isotopic concentrations and the helium neon and argon isotopic compositions of mineral and fluid inclusions. Special sampling considerations, such as maintaining pressurization, are required to obtain representative fluid samples for dissolved gas tracers.

3.6 Thermal Effects

Temperature and temperature gradient data are important for determining the physical conditions at depth and the potential for future exploitation of geothermal resources at the site. In addition, high-resolution temperature logging in combination with fracture locations is used to identify and quantify zones of groundwater inflow and outflow in the borehole. Electrical heater testing provides information on the thermal properties of the host rock and maximum projected temperatures of waste canisters. These data are relevant to the intermediate- and long-term isolation of radionuclides in the disposal system.

3.6.1 Temperature Log

Temperature logging is a commonly used geophysical measurement that records the temperature of the fluids within the borehole as a function of depth. Temperature data are usually acquired after drilling has been completed by running the logging tool into and out of the borehole; however, continuous measurements during drilling are also possible. Temperature logs are also recorded as a function of time after drilling and casing have been completed in order to correct temperatures that have been perturbed by the drilling process. Distributed temperature sensing systems have more recently been developed and used in wells to simultaneously measure temperature over the length of the fiber optic cable permanently deployed in the borehole (e.g., Selker et al., 2006; Freifeld and Finsterle 2010).

Temperature logs in boreholes are used to characterize subsurface conditions for a number of purposes in petroleum production, groundwater studies, geothermal exploration, and other geoscientific studies. Temperature data are used to calculate fluid viscosity and density, apply thermal corrections to other geophysical logs, assess geological basin hydrodynamics, model hydrocarbon maturation, identify zones of fluid inflow, and detect zones of potential overpressure in petroleum engineering. In groundwater studies temperature logs are used to identify zones of inflow and outflow from the wellbore, particularly in fractured media, to determine intra-well flow, and to delineate patterns of vertical flow in regional groundwater flow systems. Temperature logs are used in geothermal exploration and production to delineate high-temperature resources, calculate energy content of the system, estimate *in situ* thermal conductivity of the rock, and identify productive fracture zones. Borehole temperature logging is also used to estimate geothermal heat flux, to infer paleoclimatological conditions, and to study tectonic and volcanic systems.

Temperature logging would be used in the characterization of a deep borehole disposal system in the following ways:

- Determine temperature conditions to calculate engineering material properties such as fluid density, fluid viscosity, and metal strength. Other geophysical logs must be corrected for variations in temperature with depth. Hydrostatic pressure and fluid potential must be corrected for variations in fluid density resulting from differences in temperature. The performance of various tools and engineering operations may be affected or limited by high temperatures.

- Determination of the geothermal gradient and the potential for geothermal resource development. Potential future development of the host rock as a geothermal resource would be a human intrusion event that could seriously compromise the isolation of waste disposal system. Temperature and geothermal gradient measurements would be used to rule out the location as a site for future geothermal resource development.

- Identification of zones of fluid inflow and outflow from the borehole and regions of upward or downward flow within the wellbore. High-resolution temperature logging, when used in conjunction with fracture imaging methods such as FMI logs (see Section 3.2.1), can be a sensitive tool for identifying transmissive fractures and fracture zones. Zones of groundwater inflow and outflow can be used to infer the direction of the vertical hydraulic gradient. Figure 3-4 shows an example deep borehole temperature log and the calculated values of heat flux that are used to identify zones of vertical groundwater flow in the fractured rock system (Mottaghy et al., 2005). The distributed thermal perturbation sensor method has been used to make quantitative estimates of flow rates in fractures near the borehole at high spatial resolution using transient temperature data (Friefeld et al., 2006). Borehole locations of more transmissive fractures would be used for collecting groundwater samples and packer hydraulic testing.

- Potential inferences about regional groundwater flow. Perturbations of the geothermal gradient from vertical groundwater flow can be used to infer the magnitude, extent, and depth of regional groundwater flow, if the site is located in an area of significant upward or downward flow. These inferences would be used to rule out upward fluid potential due to regional groundwater flow patterns.

- Potential inferences about paleoclimatic conditions. Long-term changes in average surface temperature result in perturbations of the deep geothermal gradient and can be used to determine the climatic history of the site. Future variations in climate that could be inferred from paleoclimatic conditions would likely have no impact on performance of the deep borehole disposal system, with the possible exception of potential continental glaciations at some locations.

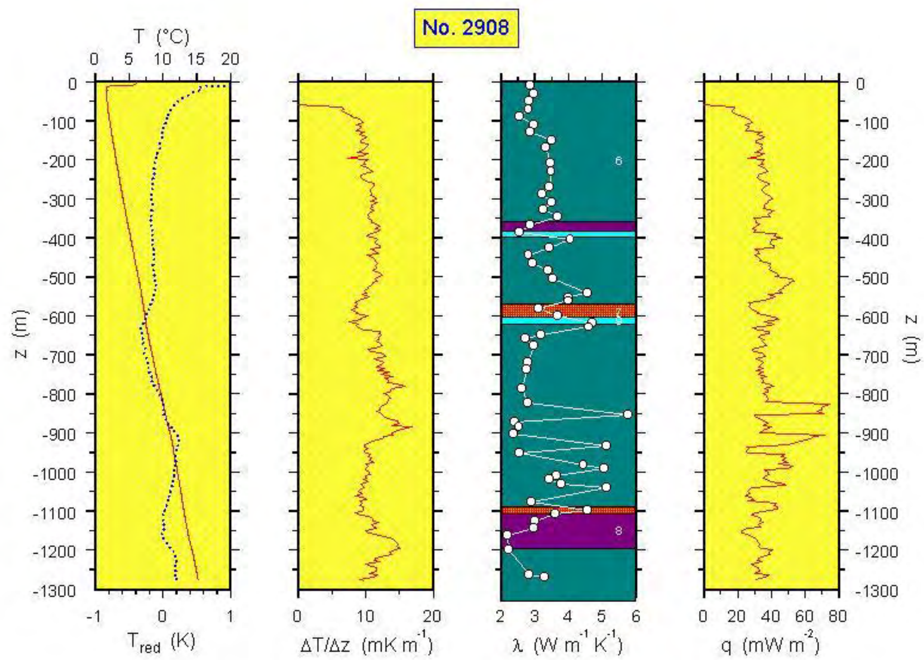


Figure 3-4. Example Borehole Temperature Log with Plots of Vertical Temperature Gradient, Measured Values of Thermal Conductivity, and Calculated Heat Flux. (Source: http://www.geophysik.rwth-aachen.de/Forschung/Geothermik/kola/kola-1.htm#CONTENT).

3.6.2 Waste Canister Mockup Electrical Heater Test

A borehole heater test would simulate the effects of heat generated by a waste canister emplaced in the host rock. A mockup of a disposal canister containing an electrical heater would be emplaced in a manner similar to waste canisters, including emplacement mud, perforated casing, and borehole seals. Temperatures, fluid pressures, and mechanical strain would be monitored in the disposal canister zone. Chemical tracers could also be added to the canister or disposal mud and monitored for potential migration past the borehole seals.

Waste canister mockup electrical heater testing would be used in the characterization of a deep borehole disposal system in the following ways:

- Estimate the bulk thermal conductivity of the host rock
- Estimate the bulk coefficient of thermal expansion of the host rock
- Provide validation of thermal-hydrologic-mechanical modeling of the system

3.7 Coupled Thermal-Hydrologic-Chemical-Mechanical Behavior

Coupled thermal-hydrologic-chemical-mechanical processes are potentially important to the temperature and pressure conditions of waste canisters, thermally driven groundwater flow, borehole stability, and long-term seals performance. These processes will be addressed through modeling and mockup electrical heater testing.

Coupled processes relevant to disposal system performance and waste isolation would be evaluated primarily by experimental results of the waste canister mockup electrical heater test and the modeling of these results. Pre-testing simulations would be used in designing the test and to evaluate predictive model validation. Modeling predictions would include temperatures, fluid pressure, axial and longitudinal strain, and solute transport from the test interval, as functions of time during the test. Predictions of corrosion of the mockup heater canister would also be made using chemical modeling of corrosion. Simulated mineralogical changes in the host rock of the borehole walls would also be compared to post-test sampling.

3.8 Engineered Material Performance

Parallel above-ground laboratory testing will establish the behavior of engineered materials under conditions simulating the temperature, pressure, and chemical conditions in the borehole. Waste canister corrosion, bentonite alteration, cement degradation, and seals breakdown are the critical unknowns that will be analyzed through a combination of laboratory testing, chemical equilibrium modeling and kinetic analysis.

Figure 3-5 shows the major components of borehole seals to be cement and bentonite. In addition, above-ground testing will examine alternative borehole sealing approaches.

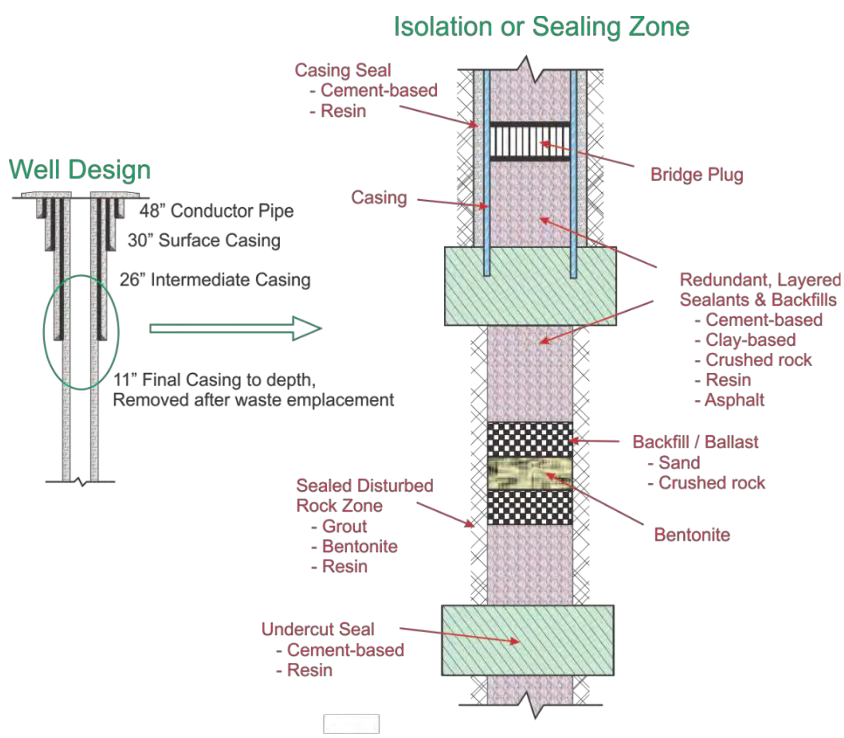


Figure 3-5. Schematic of Borehole Seals Components (from Herrick et al., 2011).

3.8.1 Waste Form

The waste form used during actual disposal of nuclear waste in a deep borehole will be 316 stainless steel drill casing. Although no credit for waste form integrity will be taken in the performance assessment of a deep borehole disposal site, understanding the corrosion of the stainless steel under borehole conditions is important for establishing the local redox state of borehole fluids and radionuclide solubility, the potential generation of hydrogen gas, and the identity of corrosion products that might sorb radionuclides.

Synthetic deep borehole test fluids will be developed that match the major element chemistry of downhole fluids described in Section 3.5. To quantify corrosion rates, and possibly hydrogen generation coupon corrosion tests will be run under ambient borehole conditions using the test fluids under the range of temperatures expected at depth. Post-test coupon surface analyses will be performed to identify corrosion products, for example magnetite and other spinels, and nickel and chromium oxides. The fluid compositions and corrosion product data will be used to verify/refine existing equilibrium and kinetic models of steel corrosion under borehole conditions. In particular, the experimental information will be used to refine the thermodynamic solubility products of the solids produced during corrosion. Measured corrosion product abundances and specific volumes will be used as input into models that predict the evolution of waste form porosity over time.

The corrosion products that form – metal oxides and spinels – will be tested for their ability to sorb anionic radionuclides, in particular ^{129}I. This will involve K_d and surface complexation–based sorption measurements done in synthetic borehole solutions at the temperatures of interest using synthetic steel corrosion product assemblages produced by accelerated corrosion of finely ground steel at high temperatures.

Hydrogen gas generation will be measured in the corrosion experiments and used to develop a preliminary kinetic model of hydrogen evolution and transport in the borehole.

3.8.2 Bentonite Alteration

The potential for long-term chemical alteration to decrease the capacity of emplaced bentonite to self-seal will be measured at the surface, but under ambient borehole conditions. Bentonite is an effective sealing material, and will be an integral component to deep borehole disposal, because of its low permeability and its high swelling pressure under confined conditions. Also, because of high surface areas and high cation exchange capacity, bentonites sorb many cationic radionuclides. Bentonites can also be chemically engineered to sorb anionic radionuclides such as ^{129}I, an important dose driver. To verify the sealing properties of bentonite over the long-term, the ability of borehole conditions to collapse the bentonite structure and to alter it to less expansive clays will be measured.

Bentonite shrinks in contact with Ca-rich and/or high ionic strength solutions, such as should be present at depth in a borehole. It is therefore important to establish the nature and extent of bentonite shrinkage as a function of temperature (depth), Na/Ca ratio, and salinity. The effect of high pH on bentonite must also be measured because borehole bentonite seals will occasionally encounter hyperalkaline (pH > 10), high Ca leachate from cement. Bentonite structural collapse occurs rapidly. Short-term bentonite volume changes due to fluid interaction will be measured using synthetic deep borehole fluids identified in Section 3.5 under the temperatures likely to prevail in the borehole. High pH cement-influenced fluids will also be tested for their effect on bentonite expansion. Volume changes and before and after fluid compositions will be used to develop mechanistic surface-complexation based models of bentonite expansion/contraction.

Over longer periods of time bentonite maybe thermodynamically favored to react to form mixed layer illite-smectites, non-expandable illites and zeolites. Long-term bentonite alteration to illite and/or mixed layer clays will be measured using accelerated testing at high temperatures.

Synthetic borehole fluids, as well as high pH cement-influenced fluids, will be combined with bentonite and over time their reaction tracked by monitoring changes in fluid chemistry and in the solid. The measured reaction trajectories will then be used to calibrate a thermokinetic model of bentonite transformation for use in subsequent performance assessment calculations. Specifically, the potential change in bentonite volume will be linked to increased permeability.

The bentonite degradation experiments will be designed to build a thermokinetic model that anticipates any change in bentonite volume, and swelling pressure, as a function of time and fluid chemistry. A sub-goal of this model will be to predict the nature and extent of bentonite-cement interaction over the time in the borehole. Presently it is difficult to predict the extent of bentonite reaction, hence its effect on bentonite seal performance, because of uncertainty in the kinetics of the individual phases. This is particularly true of cement-bentonite interaction.

3.8.3 Cement Degradation

An experimentally-based model of long-term cement stability is needed because cement will be relied upon to bond the casing to the rock, and to anchor bridge plugs. The modes and rates of cement degradation under borehole conditions are therefore important both for operation of the demonstration hole, and for understanding performance of a disposal hole. Hydrated cements contain phases that are out of chemical equilibrium with their environment and likely to chemically alter. The solid phases that form in concrete include portlandite, amorphous calcium-silicate-hydrate (CSH), ettringite, and silica. With time and exposure to water the assemblage will alter to more stable and more crystalline calcite and other minerals, though the chemical makeup of the final assemblage, the time required to reach it, and the transition assemblages that precede it, cannot be predicted with great accuracy.

Batch and column testing of cement assemblages will be done using synthetic borehole fluids (built from data described in Section 3.5) to establish mineralogic changes over time, their volume change, and the evolution of fluid chemistry. Rates will also be measured at higher than borehole temperatures to accelerate reaction and make otherwise slow reactions experimentally accessible. Experimental variables will be cement composition, temperature, input fluid composition, fluid/solid ratio, and time.

The principal outputs of the cement degradation testing will be

1. Clearer identification of solid cement phases and their appearance over time, and
2. Quantitative kinetic expressions (rate constants, dependencies, activation energies) for reaction of cement phases

These two outputs will be used to construct the larger meta-model for predicting long-term cement alteration in boreholes, and specifically the change in cement volume over time.

3.8.4 Alternative Borehole Seals

An alternative method of sealing the borehole in which a volume of crystalline rock is melted and recrystallized in a process of “rock welding” is possible, but has not been implemented or tested at the field scale. This borehole sealing method is similar to the waste encapsulation approach proposed by Gibb (1999) and Gibb et al. (2008b); however, it would be applied in the seal zone above the waste disposal zone. Heat for melting the rock surrounding the borehole would be supplied by an electrical heater, instead of decay heat, as proposed in the waste encapsulation approach.

The basic concept of sealing by rock welding is to fill a portion of the borehole below the seal with crushed host rock, insert a sacrificial electrical heater, backfill with more crushed rock, run the heater until a melt chamber is created, and then incrementally reduce the heating to control the rate of crystallization by the melt. A granitic melt would be generated by heating the system to about 800 ºC for a period of about 30 days. Recrystallization to a medium-grained granite would be achieved by reducing the electrical heating such that the melt cools at a rate of less than about 0.1 ºC/hr to a temperature of about 560 ºC (Gibb and Atrill, 2003), which would require about 100 days. The electrical heater cables would then be cut and removed from the borehole and overlying seals would be emplaced.

The rock welding method of sealing the borehole has several potential advantages over standard borehole seals. The melted and recrystallized sealing material would have the same chemical and mineralogical composition as the host rock, resulting in a seal that is in thermodynamic equilibrium with the surrounding rock and ambient physical conditions. This equilibrium state would ensure long-term chemical and mineralogical stability of the seal. Melting in the rock welding methods would extend beyond the damaged rock zone created by drilling the borehole and would seal any enhanced permeability in the volume surrounding the borehole. The recrystallized rock melt would also seal natural fractures near the borehole.

RD&D activities for the rock welding sealing concept include further testing at the small, intermediate, and field scales. In addition, modeling of the melting and recrystallization of the seal system is needed, including thermal-mechanical effects, is needed prior to full-scale implementation. Deployment of the method requires development and testing of an electrical heater and electrical cables that are robust and durable enough to function at high temperatures and pressures for the period of time required for rock melting and crystallization. Uncertainties exist about the formation of cooling fractures within the rock weld seal and the permeability of such fractures. Field-scale testing of this sealing method would include hydraulic testing of the seal after cooling.

3.9 Long-Term Monitoring

Long term monitoring of the demonstration deep borehole is not needed as no radiologic materials will be emplaced in it and no materials of any kind requiring monitoring will remain after the demonstration is completed. As discussed in Section 10, one of the potential uses for the borehole after the demonstration is as an underground research and testing facility. Activities to be conducted in this research facility either during the demonstration or afterwards may include testing of methods for characterization and long term monitoring. These activities can be demonstrated to provide proof of concept applicable to future disposal of wastes in deep boreholes at other locations of similar design and geology. As part of the prioritization of science and engineering activities during the initial phase of the demonstration project, these activities will be examined for their potential application to support long term monitoring and post-closure performance confirmation relevant to future deep borehole disposal.

Long-term monitoring of DBD will be addressed using surface-based and subsurface-based methods. Thermal, chemical, hydrologic, and mechanical evolution of the disposal system would be amenable to a long-term monitoring and safety assurance program.

3.10 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 2009, Section 4.3) that criticality may be excluded at the stage of development of FEPS for DBD. The 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.

3.10.1 Operational Criticality Safety Assurance

Because the demonstration project does not include use of fissile material, there are no criticality safety issues associated with planning, permitting or executing the demonstration project.

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.

3.10.2 Post Emplacement Criticality Safety Assurance

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. An interesting bound used in industrial practice is the minimum criticality safe diameter for an infinite cylinder of uranium and water (at the current maximum fuel enrichment of 5%). If the emplacement borehole is smaller than this bounding case, then criticality assurance may be argued „*a priori*" based on simple physics. However, depending on neutron reflection assumptions, the theoretical minimum diameter is in the range of 30 and 40 cm (LANL 1986). Given a proposed borehole diameter in the 30-50 cm range, the possibility of criticality at the extreme of most optimal conditions may not quite be excluded. Therefore, criticality exclusion may rely on one or more DBD design or site features that preclude criticality in the borehole diameter selected. These features could include

- Credit for the burn-up of fissile material during reactor operation
- Container design, including engineered material and/or internal packing material that limits achievable concentrations, excludes moderating water, restricts material re-distribution or absorbs neutrons
- Borehole design and emplacement details such as grout or other borehole packing that excludes water, restricts material re-distribution or absorbs neutrons
- Emplacement geology, such as composition of groundwater that absorbs neutrons or limits concentrations of fissile material

Analysis during the RD&D program 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. Any site characteristic data needs that are identified will be added to the demonstration and testing program.

4. ENGINEERING THRUST

The engineering thrust of the DBD RD&D roadmap presented in this section is focused on the conceptual design, analysis, and demonstration of key components of borehole drilling, borehole construction, waste canisters, handling, emplacement, and borehole sealing operations.

Drilling a deep borehole such as proposed for DBD is challenging from the standpoint of both engineering and cost. Planning for drilling a deep demonstration borehole will concentrate on using existing technology, insuring technical success and achieving these aims within budget. Although the objectives of depth and completion diameter are not beyond existing drilling capabilities, experience in drilling a hole that incorporates all of the objectives is very limited. Figure 4-1 presents a summary of the depth versus diameter boreholes that have been constructed in practice. The main conclusion is that drilling the required depth of 5 km and a waste disposal zone diameter of 0.43 m (17") proposed for a DBD demonstration would be a significant challenge and just outside the envelope of past experience.

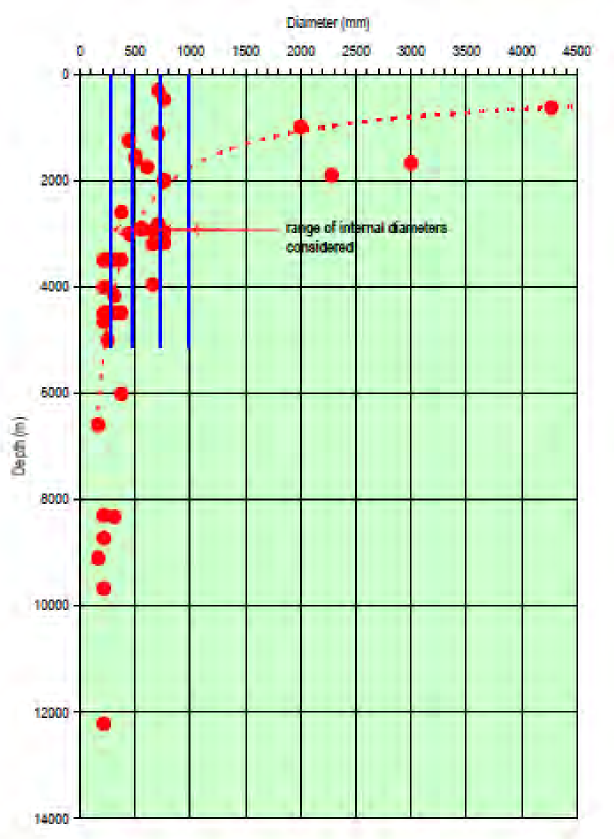


Figure 4-1. Relationship between Depth and Diameter Generated by Actual Practice (from Beswick, 2008).

A review of past experience in drilling deep, large holes in crystalline rock is a necessary starting point for this plan (Beswick 2008). Holes of 5,000 m and greater are commonly drilled in petroleum exploration; however, these boreholes are drilled in sedimentary rock with completion diameters much less than the 17" (0.43 m) proposed for DBD. Holes with depth greater than

5,000 m in crystalline rock have generally been drilled for scientific purposes, and again, the completion diameters are generally less than that proposed for DBD. Geothermal boreholes are often drilled in crystalline rock at large diameter to accommodate high production volumes; however, they are generally in the range of 2000 to 3000 m depth. Deep holes in crystalline rock would include Kola Superdeep Borehole, Russia (12,262 m); German Continental Deep Drilling Program (KTB) hole in Germany (9,101 m); and the Gravberg-1 borehole in Sweden (6,700 m). The KTB hole set 13-3/8" casing in a 14-3/4" hole to a depth of 6,000 m, and is perhaps the closest analog to the demonstration hole proposed here. Information is also available from the Hot Dry Rock project in New Mexico and the British Hot Dry Rock project at Rosemanous. To our knowledge, the largest diameter and most productive geothermal borehole (~50 MWe) is Vonderahe-1 at the Salton Sea geothermal field in California. It has 24" casing set in a 32" hole to 620 m and is completed 14-3/4" open hole to 1,684 m (A. Schreiner, personal communication). Ikeuchi et al., (1996) document one of the world‟s hottest boreholes that was completed in granite at a temperature of ~500^o C. Recently, extensive planning was done to drill an 8-1/2" borehole to a depth of 4,500 m in Iceland. The well (IDDP-1) was drilling at 12-1/4" when it intersected rhyolite magma at a depth of 2104 m and temperature of 1050^o C (Holmgeirsson et al., 2010). The well was completed at that depth and is now one of the world‟s most prolific geothermal wells (>30 MWe).

Although several of the deepest holes were drilled for scientific purposes, they also had significant technology development aspects. Both the KTB and Kola holes utilized rigs specifically constructed for drilling those holes. The derricks were fixed and enclosed. At the KTB site, technological developments included computer controls and automated pipe handling (iron roughnecks). Mobile rigs with similar technology are now available, and these improvements greatly increase the speed and safety of drilling.

In summary, the technology exists to drill deep, large diameter holes in crystalline rock. However, there is not a great deal of experience in drilling these holes. Technological improvements will ultimately be required to routinely drill boreholes for deep borehole disposal at reasonable cost if DBD is to become a practical solution to the nuclear waste management problem.

4.1 Reference Design for Demonstration

Selection of the reference design presented in this roadmap is based on the following prioritized list of subjective criteria (Arnold et al., 2011): (1) engineering and operational feasibility, (2) safety and engineering assurance, (3) simplicity, and (4) cost and efficiency. Although the reference design for a DBD system presented in Arnold et al., (2011) is conceived for full-scale disposal activities and may differ in some specifics from the borehole for the DBD demonstration project, it provides a reasonable basis for planning the demonstration project borehole.

The feasibility assessment assumes currently available drilling and borehole construction technology. The reference design also favors the use of readily available materials, such as standard borehole casing and canister connections. Although specially built engineering systems will be required for some components of the deep borehole disposal system (e.g., for transport and insertion of waste canisters at the top of the borehole), the engineering challenges are similar to those associated with emplacement of waste in mined repositories and can be overcome.

4.1.1 Borehole Requirements

Technical requirements of the reference design include

- Borehole is drilled and completed to a depth of about 5,000 m with the waste disposal zone located between 3,000 and 5,000 m depth in crystalline rock.
- Borehole and casing system must have sufficient stability and durability to provide a high level of assurance that waste canisters can be emplaced at the desired depth, with minimal probability of canisters becoming stuck during emplacement.
- Borehole and casing must have sufficiently large diameter to accommodate emplacement of test canisters.
- Deviation of the borehole from its designed trajectory must be controlled such that the distance between any two boreholes is greater than 50 m at a bottom depth of 5,000 m. Modeling has shown the thermal interference between disposal boreholes is relatively small for spacing of greater than 50 m. Drilling of multiple boreholes in an array must preclude the possibility of intercepting another borehole in which waste has already been emplaced. The spacing of waste disposal intervals at sites with multiple boreholes must meet thermal management requirements for disposal.
- Borehole and casing system must be designed such that casing can be removed from intervals where borehole seals are to be set. Optimal performance of borehole seals requires direct contact between seals and borehole wall.
- Casing and grout in the waste disposal zone must allow thermal expansion of fluid and flow into surrounding host rock to avoid overpressuring of fluid surrounding waste canisters.
- Drilling and borehole construction must be conducted to allow characterization of host rock in the waste disposal zone prior to waste emplacement.
- Borehole and casing system must have sufficient stability and durability to allow retrieval of waste canisters during the operational period, if necessary. The operational period is defined as the time until all borehole seals are emplaced and surface abandonment of the borehole is completed.

4.1.2 Borehole Design

A schematic of the demonstration borehole reference design is shown in Figure 4-2. The borehole is designed from the bottom up to the surface casing (whose maximum depth is limited by the depth that can be safely drilled without a blowout preventer); that is, the expected depth and diameter of the waste emplacement zone will determine the borehole geometry and casing program and most of the drilling equipment requirements will follow from those criteria. Casing is discussed further in Section 4.3.

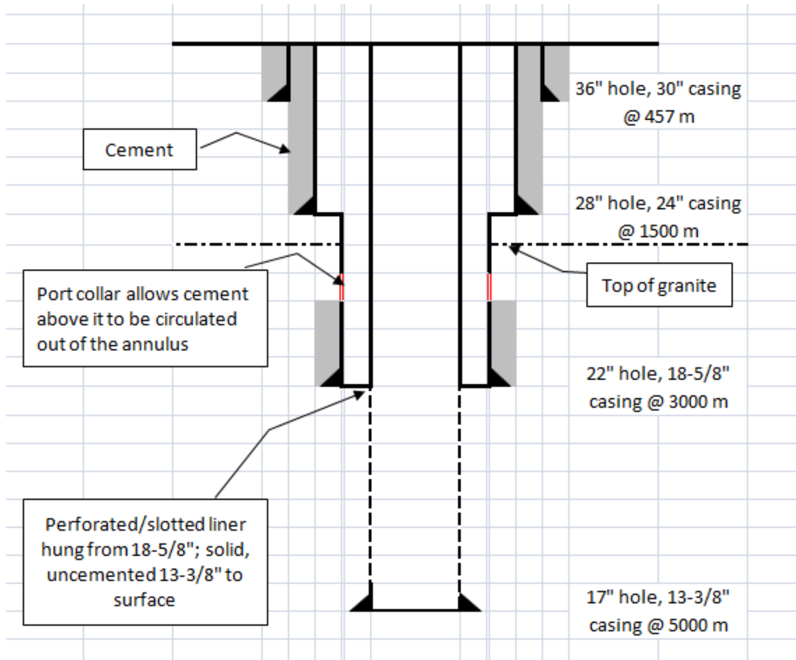


Figure 4-2. Reference Borehole Design (from Arnold et al., 2011).

4.1.3 Drilling Technology

Borehole design is based on the criterion that drilling should be done with currently available technology. The depth of the hole is not exceptional, as projects in Australia (Beardsmore 2007), France (Baumgartner et al., 2007), and the United States (Duchane and Brown 2002) have reached 4.5 – 5 km depths in granite, although the diameters of those holes were less than required here. Boreholes to the same depths with the 17" (0.43 m) bottom-hole diameter of the reference design in this report should be feasible; there are no known technical issues that present unreasonable barriers to drilling to this diameter at depth. Current geothermal practice is relevant because geothermal resources are usually found in hard, igneous rock and because the flow rates in geothermal production require large-diameter holes. Given that comparison, the drilling will most likely be done with a large, but conventional, drill rig using a rotary pipe and hard-formation, tungsten-carbide insert, journal bearing, roller-cone bits or possibly a down-hole turbine with diamond-impregnated bits. The choice between these two methods, and the selection of specific bits and operating parameters (rotary speed, hydraulics, and bit weight), will be driven by the rock properties in a given location.

For a full-scale demonstration it will be preferable to use a drilling rig and associated equipment suitable for both drilling the borehole as well as emplacing the test canisters to avoid having to deploy a separate rig and equipment. Key criteria for selecting a suitable rig in addition to depth, hole diameter, and rock type include the weight of the drill string, drill assembly, and casing that would be installed. Oil-field drilling rigs are available up to 4000HP size with lifting capacities up to 900 metric tons (Beswick 2008). These rigs should be suitable for drilling a DBD borehole of 0.43 m (17") in diameter to depths of 5 km.

The demonstration objective is to drill a large diameter hole to a depth of 5,000 m, installation of a liner to depth and subsequent deployment of test containers. Drilling in crystalline rock will be slow, with penetration rates possibly as low as 1 m/hr, and bit life will be limited, which implies frequent trips for bit replacement. These conditions, coupled with the large diameters and site-specific drilling factors, mean that well costs will be not only high, but unpredictable, especially for the first hole in a particular location.

Successfully emplacing test canisters in the emplacement zone will require a straight borehole with as little deviation from vertical as possible. A borehole that meets deviation constraints is required to allow canisters to be inserted into the borehole without obstruction. Directional control during drilling is going to be critical to avoid dog legs that would decrease the probability that a hole can be completed to the programmed depth. Keeping a hole straight will require surveying at regular intervals, and perhaps the regular application of down-hole motors. A straight hole is also necessary to control the distance between waste disposal zones in adjacent boreholes in anticipated disposal borehole arrays.

4.2 Borehole Logging

The logging industry is very sophisticated due to the common application of techniques by the petroleum industry. Borehole logging provides critical geological and geophysical information, and an extensive program has been outlined in Arnold et al. (2011). Logging while the drilling operation is underway, or Measurements While Drilling (MWD) technology, allows collection of subsurface data in real time. This capability is important for the active management of the drilling activity. In addition to MWD, open-hole logging should be scheduled to precede casing points in the borehole. A preliminary list of proposed logging and testing for the demonstration project that must be accommodated during drilling and borehole completion is presented in Table 4-1.

Table 4-1. Borehole Logging and Testing.

Borehole Logging or Testing Procedure	Interval or Frequency	Purpose of Logging or Testing
Directional Control	Entire borehole	Regular measurements of borehole azimuth and inclination are necessary to assure that the hole is kept within design limits.
Borehole Imaging – Borehole Geometry	Entire borehole	Sonic and electrical borehole imaging tools are run in open hole, and should be part of the evaluation at each casing point. These instruments can determine the stress orientation (breakouts), bedding orientation and fracture location and orientation.
Borehole caliper log	Entire borehole	Locate borehole breakouts, assess borehole stability and clearance for setting casing
Gamma ray log	Entire borehole	Identify lithology
Resistivity log	Entire borehole	Identify lithology
Spontaneous potential log	Entire borehole	Identify lithology
Temperature log	Entire borehole	Determine geothermal gradient, locate groundwater inflow and outflow
Neutron porosity log	Entire borehole	Determine porosity
Formation micro imager log	Entire borehole in initial borehole, waste disposal zone in subsequent boreholes	Determine location, orientation, spacing, and aperture of fractures, determine orientation of bedding and foliation
Anisotropic shear wave velocity log	Entire borehole	Estimate anisotropy in horizontal stress
Coring	20 m core every 500 m depth or major change in lithology	Obtain rock core for mineralogical, petrophysical, geochemical, mechanical, thermal, and hydrological testing
Drill cuttings log – lithology and sampling	Entire borehole	Identify lithology while drilling, obtain continuous samples for petrologic and geochemical testing
Drill stem test – shut-in pressure and fluid sampling	One every 1,000 m depth	Determine vertical hydraulic gradient, obtain groundwater samples for salinity and geochemical testing
Drill stem test – pump test	One every 500 m depth in waste disposal zone	Determine bulk permeability and storage coefficient of host rock

4.3 Borehole Construction

The borehole construction phase can be addressed in terms of a) site selection and characterization, b) planning and budgeting, c) procurement of supplies and services, and d) the implementation or drilling phase. The construction of the borehole will be the most critical component for the demonstration project, and it is also the component that is the most expensive and has the highest technical risk. A successful demonstration will require a high level of technical supervision at all phases of borehole construction phase.

Site Selection and Characterization. The geology of the DBD demonstration site (site selection) and the design and construction of the borehole go hand in hand. Without a specific site, we will consider the generic borehole design presented in Section 4.1.2 and Arnold et al. (2011) to represent the base line. From the borehole construction standpoint, the site selection will be critical in assuring successful technical and budgetary completion of the DBD demonstration. Discussion of other factors in site selection for the DBD demonstration project (e.g., topographic relief, tectonic activity, and volcanism) is presented in Section 8. The ideal site will have the following geological characteristics.

- The overlying sedimentary section will be flat-lying and present no drilling issues such as high-permeability zones (lost circulation), contained hydrocarbons or other difficult drilling environments such as swelling clays, other lithologies that are hard to drill such as chert or quartzite or overpressured fluids.
- The temperature gradient in the area will be low. Since the average continental gradient is about 30^{o} C/km, it is anticipated that the bottom-hole temperature at 5 km will approach 150^{o} C. Temperature influences the operational life of down-hole tools as well as mud and cement requirements.
- The area will have low differential stress. High differential stress will result in breakouts and resultant borehole ellipticity. In addition, drilling in a high-stress environment will result in the drill bit kicking off in the direction of the least principal horizontal stress.
- The crystalline rocks that will serve as the host for the demonstration project should be as homogeneous as possible. The foliation in crystalline rocks such as schist and gneiss will tend to steer the bit perpendicular to the foliation. Fractures will have the same effect and can also serve as zones of circulation loss during drilling and the migration of formation fluids during the disposal phase.
- The site will be located in an area where oil-field drilling and services companies are close. Logistical considerations, such as the availability of services and supplies and trucking distances will have an important influence on cost.

Once a site is selected, the more detailed planning can move forward. This section will specifically discuss drilling issues, but planning for permitting and regulation, site acquisition or leasing, and public relations can also move forward once the location is determined.

Planning and Budgeting. A more detailed plan and budget for the drilling operations can move forward following site selection. At that point, the variances with respect to the scenario of Arnold et al. (2011) will be evaluated. A Drilling Cost Estimate will be sought and prepared by an experienced drilling engineer. This activity is influenced by the objectives of the project and also the engineer‟s knowledge of industry equipment availability and costs. Drilling costs will fluctuate according to demand, but a detailed drilling plan and cost estimate will provide funding agencies with an order of magnitude cost estimate. Note that contingency costs of 30% or more may be appropriate at this stage of the process.

Procurement of Supplies and Services. Once funding is secured, services can be procured. It is common within the drilling industry to utilize an IADC (International Association of Drilling Contractors) day work contract with a drilling company. However, it is also common for other services and supplies (casing, logging, cement services and mud) to be procured separate from the actual drilling contract. As discussed below, Quality Assurance and Quality Control are important aspects of this phase of the project. Specifications should be rigorous and verification is required when supplies and equipment are received at the drill site.

Drilling Phase. The drilling phase will be managed by a Company Man, the authorized representative of the contracting entity. This person will have responsibility for the construction of the borehole, the budget and the control of the individual service and equipment suppliers.

In the following sections, some of the more important components of the drilling phase of the DBD demonstration are outlined.

4.3.1 Casing

The casing has a number of functions in this demonstration project. Ultimately, it provides the enclosure for the test canisters and the pathway for their emplacement and retrieval (if necessary). Casing protects the borehole from collapse and sloughing of the borehole wall. Casing is also used to control pressure and guard against blow out of the borehole in case high pressure fluids or gases are encountered during the drilling process.

Given that the borehole must accommodate waste canisters with 10.75 inches (0.27 m) outside diameter and couplings between them with 11.75 inches (0.30 m) OD, for the reference design presented in Arnold et al., (2011), over a depth interval from approximately 3000 to 5000 m, then the principal criteria for casing design (in addition to those in Section 4.1.1) are borehole control and casing strength. Borehole control considerations are generally addressed by using standard blow-out prevention equipment (BOPE) on the surface casing and all subsequent casing strings, while casing strength issues are controlled primarily by collapse pressure requirements. Design considerations for each interval are discussed in more detail below. A summary of casing properties is shown in Table 4-2. Note that the casing program will not be completely defined until a demonstration site has been selected. A schematic view of the borehole completion is shown in Figure 4-3.

Conductor (40”, 1.0 m casing in 48”, 1.2 m hole; not shown in schematic): The conductor is usually line pipe set to a depth of 50 to 100 feet (15 to 30 m) and cemented in place. It provides a flow conduit and prevents surface rubble from falling in the hole while drilling for the surface casing. This pipe is often set by a separate contractor as part of the site preparation and is not part of the drilling operation carried out by the principal drilling contractor.

Surface casing(30”, 0.76 m casing in 36”, 0.91 m hole): Maximum depth of the surface casing is controlled by requirements on BOPE (that is, how deep will regulatory agencies allow drilling without well control). This casing material is standard, minimum-property pipe weighing approximately 235 lb/ft (350 kg/m) and with a tensile yield strength of 56,000 psi (390 MPa). These properties give ample strength for the casing to support its own weight hanging in the hole, and to support an external pressure of 772 psi (5.32 MPa). Using a pore pressure gradient of 0.433 psi/ft (0.0098 MPa/m), the external pressure differential on an empty pipe would be 649 psi (4.47 MPa), so collapse is not a problem. This casing is cemented to surface and will have BOPE installed after cementing.

Intermediate 1(24”, 0.61 m casing in 28”, 0.71 m hole): This casing will be made of higher strength (125,000 psi, 862 MPa) material because of collapse requirements. It runs from the surface to approximately 1500 m, and is cemented full-length. Its collapse capability is 1170 psi (8.07 MPa) but external pressure at 1500 m would be 2131 psi (14.7 MPa), so the pipe cannot be allowed to be empty (this would be unlikely in any event). Fluid level must be maintained at or above 690 m below surface.

Intermediate 2(18.63”, 0.47 m casing in 22”, 0.56 m hole): This liner (also 125,000 psi, 862 MPa tensile yield) is hung from the bottom of the Intermediate 1 liner and runs to approximately 3000 m. Approximately 160 m above the bottom of the liner will be a “port collar”, which is a device that can be opened to create a passage from the inside of the casing to the annulus. Because the upper section of this casing must be removed to emplace seals, the upper section cannot be cemented, so after displacing cement up the annulus to a point above the port collar, it will be opened and the cement above circulated out with drilling fluid. This liner also has collapse capability less than pore pressure at depth, so it cannot be allowed to be empty – fluid level must be maintained at or above 1,530 m below surface.

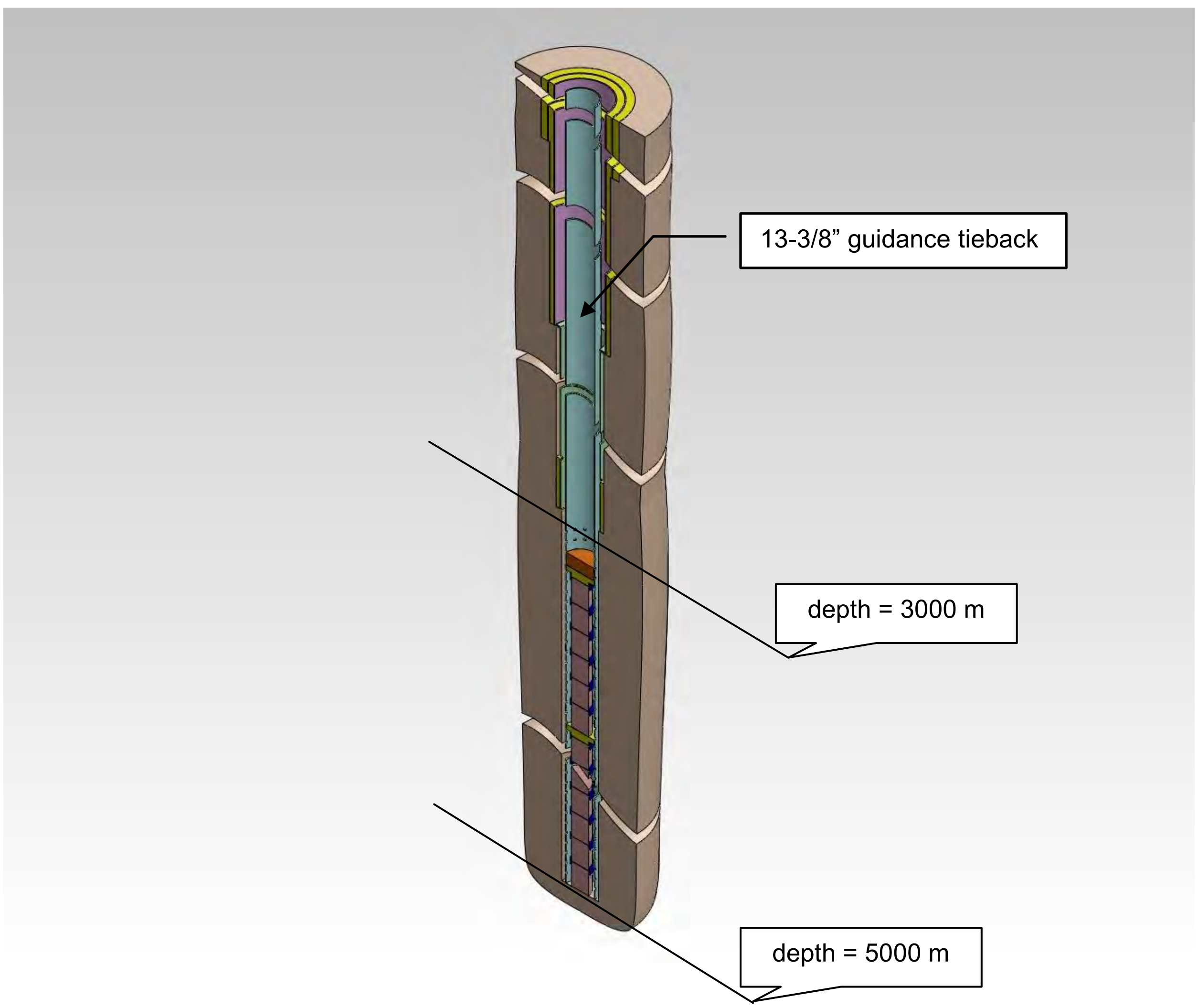


Figure 4-3. Reference Disposal Borehole Design (from Arnold et al., 2011).

Guidance liner(13.38”, 0.34 m casing in 17”, 0.43 m hole): This liner hangs from the bottom of the Intermediate 2 liner and runs to the bottom of the disposal zone at approximately 5,000 m. It will be slotted or perforated to allow pressure build-up caused by canister heat to bleed off into the formation. This also means that the liner will not see any differential collapse pressure, so its only strength requirement is to support its own weight while hanging in the hole.

Guidance tieback(13.38”, 0.34 m casing in 18.63”, 0.47 m casing): This casing runs from surface to the liner hanger in the bottom of Intermediate 2, so that there will be a smooth, constant-diameter path for the canisters as they are emplaced in the disposal zone. This casing will be completely removed after all canisters are emplaced, so it is neither cemented nor sealed at the bottom, and will not see any collapse pressure. The bottom of this casing will fit into a receptacle in the liner hanger that will assure a smooth transition into the liner but will allow the casing to expand and contract in length as temperature changes.

Table 4-2. Borehole Casing Specifications.

Interval	OD (inches)	Wall Thickness (inches)	Drift Diameter (inches)	Weight, (lb/ft)	Tensile Strength (psi)
Surface	30	0.75	28.0	235	56,000
Intermediate 1	24	0.688	22.437	174	125,000
Intermediate 2	18.63	0.693	17.052	136	125,000
Guidance liner	13.38	0.380	12.459	54.5	56,000
Guidance tieback	13.38	0.380	12.459	54.5	56,000

4.3.2 Cementing

Cementing operations are a critical part of insuring the integrity of casing strings. In addition, cementing is also used to seal permeable zones and fractures when mud and lost circulation material (LCM) has not been successful. The DBD demonstration borehole presents both depth and temperature challenges to successful cement procedures. Lost circulation zones should be sealed as drilling progresses or they will result in incomplete cementing of casing. This could cause failure of the casing as the temperature of the borehole increases under the disposal scenario.

A cementing contractor will be part of the procurement stage. The contractor will be able to provide the required mixing and pumping equipment as well as a cement product that is properly mixed for the individual requirements.

4.3.3 Bottom Hole Assemblies

Bottom Hole Assemblies (BHAs) include the drill bit, reamers and stabilizers and drill collars. Down hole motors (mud motors) are also included if they are used. This assembly is responsible for cutting the hole, keeping it in gauge, giving the drilling string stiffness to keep the hole straight, and increasing the weight on bit (WOB). The drilling bit must be properly selected to efficiently crush the rock. Large diameter bits that will efficiently penetrate crystalline rock probably represent one of the greatest challenges in this project.

4.3.4 Fluid Circulation

The fluid circulation system is composed of pumps, mud and equipment for the removal of cuttings from the circulating mud.

Mud is a general term for the fluid circulated during the drilling process. Its purposes are to cool and lubricate the bit, remove cuttings from the borehole and condition the hole to prevent sloughing and/or lost circulation. Mud often has a significant impact on the cost of the borehole, particularly when the borehole is large diameter and has lost circulation.

From a practical standpoint, the drilling of the DBD demonstration borehole is going to require a great deal of water. The most efficient way to provide this water is to access a water source with a water well in the sedimentary section overlying the crystalline bedrock.

4.3.5 Monitoring

Monitoring technology can be designed into the demonstration. This may include a separate liner outside the casing or a fiber optic cable cemented with the string. A fiber optic cable is used to monitor the temperature of the borehole and could monitor heat buildup following canister emplacement.

Another approach to monitoring that would be particularly useful in the construction of a DBD demonstration borehole is to drill a slim hole specifically for the installation of monitoring equipment. This option could allow permanent installation of sensors to measure temperature and radioactivity along with pore fluid sampling capabilities.

4.4 Test Canisters

This section discusses the engineering analysis and testing associated with the design and testing of test canisters. Actual disposal canisters would have to meet mechanical design requirements for loading, welding, transportation, surface handling, and borehole emplacement under normal operating conditions. The test canister will be designed to be representative of an actual disposal canister and will meet key requirements of the disposal canister. In addition, testing will be conducted to demonstrate test canister performance under representative accident conditions, such as dropped canisters and canisters stuck in the borehole.

4.4.1 Test Canister Design Requirements

This section describes the requirements for the demonstration test canister design. The test canister will be designed to some of the key requirements as the actual disposal canister. These requirements will include requirements for key phases of surface operations, canister emplacement in the DBD system, and down-hole integrity until seals are emplaced.

Test canisters will be designed to test key design requirements of the actual waste disposal canister, with emphasis on characteristics of the waste canisters that are important to postclosure safety and preclosure down-hole operational safety. Engineering analysis and testing of the waste canisters relevant to other preclosure safety and operational assurance issues will not be addressed through detailed testing in the borehole demonstration project, but are described in general terms in this section.

Technical requirements of the waste canister design include

- Waste canister design must provide a high level of assurance that no leakage of radioactive materials will occur during handling and emplacement of the waste canisters. Welding and sealing of canisters must prevent release of radionuclides in solid, liquid, or gaseous state.
- Waste canisters must maintain structural integrity during loading, transportation, and handling prior to emplacement.
- Waste canisters must maintain structural integrity during emplacement, sealing, and abandonment of the borehole disposal system. Waste canister design must provide a high level of assurance that the canisters can withstand fluid pressures, mechanical loads, and temperatures during emplacement and the remainder of the operational phase.
- Waste canisters must have an integrated system for connection to other waste canisters and to drill pipe for lowering to the disposal zone as a string of canisters. Connections must have sufficient strength to withstand mechanical loads during and after emplacement, and for potential retrieval during the operational phase.
- Internal length of the waste canister must be sufficient to accommodate most intact PWR fuel rods. Waste canister should have a minimum internal length of 4.2 m.
- Waste canisters should retain their integrity as long as practical. However, the deep borehole disposal concept does not rely on the waste canisters as a significant barrier to radionuclide release beyond the operational period.
- Design, handling, and emplacement of waste canisters must preclude any possibility of nuclear criticality.

The test canister design requirements include the following characteristics that will be assessed in the engineering thrust of the demonstration project:

- Test canisters will maintain structural integrity during loading, transportation, and handling prior to emplacement testing.
- Test canisters must maintain structural integrity during down-hole testing. Test canister design will assure that the canisters can withstand fluid pressures, mechanical loads, and temperatures without leakage into or out of the test canister during emplacement and retrieval from the test borehole.
- Test canisters must have an integrated system for connection to other test canisters and to drill pipe for lowering to the disposal zone as a string of canisters. Connections must have sufficient strength to withstand mechanical loads during and after emplacement, and for retrieval from the test borehole.
- Internal length of the test canister must be sufficient to accommodate most intact PWR fuel rods. Test canister should have a minimum internal length of 4.2 m.

Hydrostatic fluid pressure on test canisters will be a function of depth and the fluid density within the borehole. Fluid density will be a function of salinity and temperature, which will also vary with depth. High salinity brines are expected to occur in the host rock at the depths of deep borehole demonstration project, but fluid composition within the cased borehole could be controlled to a certain extent during test canister emplacement. The fluid pressure design requirement is conservatively based on an assumed salinity profile varying from fresh water at the surface to a density of 1.1 x fresh water density at a depth of 500 m and varying from 1.1 x fresh water density at 500 m depth to 1.3 x fresh water density at a depth of 5000 m. The assumed temperature gradient is 25 ºC/km. The resulting fluid pressure at the bottom of the borehole is about 57 MPa (8250 psi) and this pressure is used as the test canister design requirement.

The nominal mechanical load requirement for test canisters is based on the assumption that the loaded waste canisters will be emplaced in strings of 40 canisters (approximately 200 m intervals). The maximum compressive force on the bottom canister in the string after emplacement will be equal to the maximum tensile force on the uppermost canister in the string while being lowered into the borehole. The mechanical load design requirement is based on a preliminary canister design in which each canister was assumed be loaded with 421 PWR fuel rods with a weight of 2.39 kg/fuel pin (calculated from data for reference nuclear fuel assemblies in U.S. DOE 1997). The approximate total weight of the canisters and waste for 40 canisters is 69,400 kg (153,000 lbs). The reference canister design in Arnold et al. (2011) contains fewer fuel rods than used to estimate the weight given above, so the actual weight of the canister string would be less than this. Buoyancy in the fluid within the borehole is conservatively disregarded in this design requirement. Forces associated with the potential retrieval of waste canisters during the operational phase must be considered in the safety margin relative to this design requirement.

4.4.2 Test Canister Conceptual Design

The conceptual test canister design will be presented in this section and is based on the reference design presented in Arnold et al. (2011). The test canister design will be relatively simple and use materials and components available in the petroleum and geothermal industries. Drawings of the design and specifications including canister dimensions, welds, and materials will be specified as part of the demonstration project.

The reference test canister is designed to withstand hydrostatic pressure in the borehole without internal mechanical support. Canister wall thickness to withstand a maximum hydrostatic pressure of 8250 psi (57 MPa) is calculated based on American Petroleum Institute (API) 5CT specifications for K55 seamless pipe and a safety factor of 1.2. Standard manufacturing tolerances for the wall thickness of API 5CT steel tubing is ± 12.5 % and collapse strengths are calculated in the minimum thickness within this tolerance. A higher level of confidence in waste canister integrity could be achieved if tubing manufactured to tighter tolerances than the API standard were used to construct the canisters. Waste canisters with a higher tolerance for wall thickness would also help insure that the maximum number of fuel rods could be packed into each canister.

The reduction in yield strength with increasing temperature has been estimated from various sources. American Society of Mechanical Engineers (ASME) recommended design factors from boiler and pressure vessel code for carbon and low alloy steels at 300 ºC indicate a factor of 0.78. Various manufacturers provide estimates of this design factor. Tenaris reported an average number to use of 0.86 for their 55,000 psi (380 MPa) yield strength casing. Grant Pridco reported 0.74 and Hunting 0.82 for their 80,000 psi (550 MPa) yield strength casing. Canister wall thickness design is based on a retained yield strength factor of 0.82 at 300 °C and 0.90 at 160 °C. Manufacturers can be required to run yield strength tests at elevated temperatures as an acceptance criterion for the material used in the canisters. The resulting test canister dimensions have an outside diameter of 10.75 inches, inside diameter of 8.33 inches, and wall thickness of 1.21 inches.

Connections between test canisters consist of “premium” threaded coupled connections with an outside diameter of 11.75 inches (0.30 m) and 5 threads per inch. A custom design for these connections with a wall thickness of 1.21 inches (3.07 cm) would be required to match the tubing used in the test canister design. Data on existing connections with smaller wall thickness made from L80 grade steel have a coupled minimum yield strength of 80,000 psi (550 MPa).

The top of the assembled test canisters would have a J-slot safety joint screwed into the uppermost test canister. The safety joint is an assembly that is easy to release once the canister string is on the bottom of the test emplacement zone; allows for reengagement when retrieval is necessary. There are a number of slightly different designs, depending on the manufacturer, but all operate in a similar manner.

The test canisters will be sealed by welding plugs below and above the test canister contents. Test canister contents will consist of ballast material to match the weight of fuel rods in the waste canisters. Test canisters will also contain experimental packets that could measure deformation of the canister walls, temperature history, pressure history, and evidence of test canister leakage.

The test canisters will easily withstand the mechanical compressive and tensile mechanical loads from overlying canisters and from the weight of the canister string during test emplacement. With a nominal wall thickness of 1.21 inches (3.07 cm) the test canister walls have a cross-sectional area of 36.265 square inches (234 square cm). The resulting stress from an overlying (or underlying) weight of a 200-m string of canisters of 153,000 pounds (69,400 kg) is about 4,220 psi (29.1 MPa). This mechanical stress is much less than the thermally degraded yield strength of 55,000 psi (380 MPa) steel, resulting in a safety factor of greater than 10 for these mechanical loads.

4.4.3 Demonstration Canister Testing

This section describes the types of tests that will be conducted to evaluate key aspects of test canister performance. Demonstration canister tests will be conducted to verify canister integrity under mechanical stresses from hydrostatic pressures, temperatures, and mechanical loading downhole. In addition, operations associated with connecting canisters to the drill string and disconnection at waste disposal depths, along with retrieval of test canisters will be verified.

Test canisters will be assembled as a string at the borehole collar, lowered to disposal depths, disengaged from the drill string, left in place for some period of time, reengaged to the drill string, and removed from the borehole. Assembling the test canister string, lowering to disposal depths, and disengaging from the drill string will demonstrate the operational ability to emplace waste canisters and the design requirement of connecting canisters. Test canisters will be left in place in a configuration representative of a disposal borehole (i.e., canisters surrounded by bentonite mud) to expose them to ambient temperature, pressure, and hydrochemical conditions. Recording sensors in test canisters will record the temperature and deformation history for the validation of engineering analyses of canister strength and deformation. Reengaging and removing test canisters will demonstrate the ability of operational retrieval. Test canisters will be analyzed for corrosion rate, weld integrity, and potential leakage after they are removed from the borehole to verify canister integrity requirements.

4.4.4 Additional Canister Testing for a Disposal Program

Additional canister testing beyond the scope of the demonstration project will eventually be required if the DBD program were to be implemented for disposal of SNF and HLW. Such testing would be conducted on the finalized waste canister design and as part of routine quality assurance procedures during disposal operations. Such testing is described in general, conceptual terms in this section.

Waste canister testing prior to loading with waste would verify the dimensions of the canister and yield strength of materials used in their construction. Canister wall thickness would be measured to verify a manufacturing tolerance of ± 6 %. Integrity of threads for connections would be inspected and verified. Yield strengths of steel canister walls and connections would be tested at elevated temperatures to verify that design requirements had been met.

The canisters will be sealed by welding plugs below and above the waste. The bottom plug could be welded in place before the fuel rods are loaded into the canister and the connection threads are cut into the canister. The top plug would have to be robotically welded in place after the waste has been loaded into the canister. If welding of the top plug is conducted before the connection threads are cut in the top of the canister, then the upper threads would have to be cut robotically in a shielded environment. If the upper threads are cut before loading waste and welding of the upper plug, then the weld would have to be far enough from the threads to prevent distortion of the threads. RD&D activities would be required to develop the engineering technology for robotic welding.

Drop testing of a mock-up of the loaded waste canister would be conducted to demonstrate the ability of the waste canister design to withstand possible accidents during handling and emplacement. The loaded waste canister design should not leak after a potential fall from raising the shipping cask to a vertical position prior to rail transference to the borehole. Nor should a loaded waste canister leak if it strikes the bottom of the borehole at terminal velocity after the accidental release of a canister string in the borehole fluid.

4.5 Canister Loading Operations

Several operational aspects of waste canister loading require elaboration through analysis and design. These operations include fuel rod consolidation, loading of fuel rods into canisters, and canister sealing. Although these operations will not be physically demonstrated, the conceptual operational and engineering aspects of these operations will be examined and developed as part of the DBD demonstration project. These operations are discussed in this section of the report.

4.5.1 Used Fuel Loading Operations

The disposal system in the reference design in Arnold et al. (2011) is based on the disassembly of used PWR nuclear fuel assemblies at the reactor sites (or at a centralized facility) and loading of individual fuel rods in the waste canisters. Although this procedure entails greater cost and effort in the loading of the waste canisters, it allows for a smaller diameter waste canister, a smaller diameter borehole, and greater operational assurance for the construction of the borehole to the required depth. The higher density of used fuel in the waste canisters also results in fewer total waste canisters, fewer boreholes, and lower transportation, drilling and operational costs. Fuel consolidation technology and costs have been analyzed in previous studies that are summarized in Gibbs (2010). Results of these studies indicate that dismantling assemblies and consolidating of fuel rods is technically feasible, costs are reasonable, and that the costs of consolidation would be offset by savings in number of canisters and drilling costs for deep borehole disposal. Individual fuel rods can be removed from most PWR fuel assemblies and many reactor sites have existing facilities that could be adapted for the disassembly of fuel assemblies in fuel storage pools. Additional reactor site facilities would likely be required for the sealing, shielding, welding and handling of the loaded waste canisters. However, the engineering for such potentially portable facilities should be relatively straightforward, given the modest size of the waste canisters.

Waste canisters are also designed for the disposal of vitrified DOE defense high-level waste or of vitrified waste from the reprocessing of commercial spent nuclear fuel. Vitrified high-level waste could be poured as molten glass into a thin-walled steel container, which could then be placed into the waste canister.

Although demonstration of fuel assembly consolidation is not planned for this project nor is it thought to be necessary because of prior evaluations of this process, demonstration of waste canister loading could be accomplished using unirradiated fuel assemblies that could be safely handled in an unshielded facility. Engineering design of the fuel rod consolidation and canister loading facility would involve design of the remote handling or robotic components of the system. Such design could be based on similar existing facilities, such as the pilot waste conditioning plant in Gorleben, Germany.

4.5.2 Canister Welding Demonstration

Actual waste canisters would be sealed by welding plugs below and above the waste. The bottom plug could be welded in place before the fuel rods are loaded into the canister and the connection threads are cut into the canister. The top plug would have to be robotically welded in place after the waste has been loaded into the canister.

Although demonstration of canister welding is not planned for this project, demonstration of waste canister welding operations could be accomplished in a straightforward manner for the bottom plug in the canister, which can be done before waste loading. Engineering design of the robotic welding procedure for the upper plug in a shielded facility could be based in part on similar facilities for sealing vitrified HLW canisters. Welding of sealing plugs in the canister would be inspected using x-ray imaging following waste loading. During operations surface samples of the loaded waste canisters would be tested for any radiological contamination.

4.6 Waste Handling

Several operational aspects of waste handling will require elaboration through analysis and design. While radioactive waste will not be part of the demonstration project, operational procedures for shielded transference of loaded waste canisters to shipping casks, from shipping casks, positioning over the borehole collar, and insertion in the borehole are required for a licensed “production” facility. Although the waste handling operations will not be physically demonstrated, the conceptual operational and engineering aspects of waste handling will be examined and developed as part of the DBD demonstration project. Waste handling processes are discussed in this section.

4.6.1 Canister Transference to Shipping Cask

The safety of a loaded waste canister during transport would need to be evaluated. Loaded waste canisters would be transported to the deep borehole drill site by tractor trailer using transportation casks similar to existing designs for the shipping of SNF. Such casks provide shielding to workers and the public during transport, and protect the fuel from release in the event of an accident. The safety of these cask models would need to be reevaluated for the somewhat greater weight and radioactive inventory of the loaded waste canisters, relative to that of a single PWR fuel assembly for which these shipping casks were designed. A single DBD reference canister could be shipped at one time in these casks. These cask models may have to be remodeled or redesigned to allow rotation to a vertical orientation, positioning over the borehole, and attachment of the waste canister to the drill string for emplacement in the borehole.

4.6.2 Canister Transference to Borehole

Surface handling of the loaded waste canisters at an actual disposal site would be conducted in a manner similar to that described in Woodward and Clyde Consultants (1983). The Woodward and Clyde system calls for rotation of the shipping cask to a vertical position from the tractor trailer adjacent to the emplacement rig onto a rail transporter. The cask containing the loaded waste canister would then be moved along a short rail system into an enclosed area beneath the elevated drill floor of the rig. Remotely operated equipment would open the upper cover of the shipping cask, the drill pipe would be attached to the top of the canister, the canister would be lifted, the lower cover of the shipping cask would be opened, the canister would be lowered into shielded basement below the rail transporter, and the canister would be attached to the underlying waste canister that has been locked into place at the borehole collar in the basement. The underlying waste canister would then be unlocked at the borehole collar, the waste canister string would be lowered by one canister length, and the new canister would be locked at the borehole collar. The drill pipe would then be unscrewed from the top of the canister, raised above the drill floor, the empty shipping cask would be moved away from the rig, and the process would be repeated for the next waste canister. All operations at unshielded locations would be performed remotely and monitored by video links.

The Woodward and Clyde Consultants (1983) waste handling system calls for use of a standard drill rig to drill and construct the borehole, and a separate specially designed emplacement rig for emplacing the waste canisters and performing borehole plugging and sealing operations. This strategy has the advantage of freeing up the drill rig for drilling and construction of the next borehole at the same site, while waste is simultaneously being emplaced by the emplacement rig. It has the disadvantage of requiring the capital investment in a specialized, dedicated emplacement rig that probably lacks the full capability and capacities of a deep drill rig. A deep drill rig probably would be better equipped to deal with unplanned events, such as a lodged waste canister string. Alternatively, it may be more effective to modify an existing deep drill rig to drill the borehole and to emplace the waste and perform borehole sealing and plugging operations.

4.7 Waste Emplacement

Some aspects of waste emplacement operations, including assembly of the test canister string, lowering the string in the borehole, and disengaging the test canister string, will be addressed in the test canister demonstration discussed in Section 4.4. Several additional operational aspects of actual waste canister emplacement in the borehole disposal system will require elaboration through further analysis and design during the DBD demonstration project. These additional operational aspects are discussed in this section and include assembly of an actual waste canister string using remote handling methods, insertion of the borehole string in the emplacement grout, and setting bridge plugs and cement plugs to support overlying waste canisters.

4.7.1 Waste Canister String Demonstration

This section describes the operations that would be demonstrated for attaching strings of test canisters together and lowering into the borehole. Test canisters would be emplaced in the disposal zone of the borehole in strings of 40 canisters, with a total length of about 200 m, depending on the test canister design.

Test canisters would be emplaced in the emplacement zone of the borehole in strings of 40 canisters, with a total length of about 192 m, based on the test canister design presented in Arnold et al. (2011). Each test canister string would be lowered to the emplacement zone and would rest on the bottom of the borehole in the case of first string or on the bridge plug and cement emplaced above the previous test canister string for subsequent canister strings. The test canister string would then be disengaged from the drill pipe using the J-slot assembly. A bridge plug and cement would be set above the test canister string prior to the emplacement of the next test canister string.

One issue of concern that would not be addressed in the test canister string demonstration described above for non-heat generating test canisters is the maximum temperature rating for commercially available bridge plugs and the temperature increases that may arise from the radioactive waste in an actual disposal implementation. Several standard designs for bridge plugs that would fit the 13-3/8 inch (0.34 m) casing in the disposal zone are rated up to 400 ºF (204 ºC). This maximum temperature rating is sufficient for close proximity to the representative spent nuclear fuel analyzed in Brady et al. (2009) and the low-temperature canister design. However, this maximum temperature rating for bridge plugs could be exceeded within one year near actual waste canisters that contain the higher heat output vitrified HLW. This problem will be addressed by evaluating the feasibility of implementing a waste loading strategy that places the higher heat output waste canisters in the middle of canister strings. This strategy would increase the distance between the hotter waste canisters and the bridge plugs, protecting them from exceeding their maximum temperature rating.

4.7.2 Emplacement Grout Demonstration

A synthetic oil base mud containing bentonite will be used in the canister emplacement zone during test canister emplacement. Although the test canisters will not be cemented in place, the high concentration of bentonite in the mud will provide some degree of grouting around the canisters over time. The emplacement mud will also provide lubrication to assure emplacement at the desired depth and facilitate operational retrieval of the canisters. This section describes the operations and processes that will demonstrate the emplacement of grout in the canister emplacement zone.

4.7.3 Setting Bridge Plugs

The primary function of the bridge plug is to provide a base upon which the thicker cement plug can be emplaced. Together the bridge plug and cement plug must support the weight of the overlying test canister string. This section describes the operations and processes for demonstrating the emplacement of a bridge plug and cement plug in a deep borehole.

Each test canister string will be separated by a bridge plug and overlying cement plug. The cement plug would also invade the annulus between the perforated casing liner and the borehole wall, and provide a barrier to fluid migration within this annulus between test canister string intervals. Due to incompatibility between the oil base mud and cement, any oil base mud in the borehole above the bridge plug will be flushed out prior to setting the cement plug.

Bonding recommendations are made on the basis of the compressive strength of the set cement and on the assumption that the material satisfying the strength requirements will also provide an adequate bond. In a borehole, the shear bond is typically used to determine the weight of pipe the cement can support. The shear bond force divided by the cement/casing contact area yields the shear bond stress. Smith (1989) presents a relationship for the support capacity of the cement sheath outside a casing to support the weight of the casing:

$$F = 0.969\,(S_c)(d_p)(h_c)$$

where F is the force or load to break cement bond (pounds), S_c is the compressive strength of the cement (psi), d_p is the casing diameter (inches), and $h_c$is the height of cement column (feet). The typical strength of a Class H cement at 15,000 ft (4570 m) depth is conservatively taken as 4000 psi for the anticipated temperatures and pressures (Smith 1989, Table 4.8). Using an inside diameter of the casing of 12.459 inches (0.316 m) and the weight of the overlying canister string of 153,000 lbs (69,400 kg), the length of the cement plug required is about 3.2 ft (0.98 m). The bond properties of the cement to the casing are highly dependent on the cement job, age of casing, surface finish of casing, amount of time the cement has had to cure, and the type of fluid in the borehole amongst other possible factors. Taking these unknown factors into consideration and the desire to infiltrate and form a barrier in the annulus between the casing and the borehole wall, a cement plug of 10 m is recommended.

Numerous bridge plug types are commercially available for use in the test canister emplacement procedure. Both mechanical and inflatable designs are available. Some inflatable, packer-style bridge plugs can be filled with cement for permanent installation. Two example bridge plugs are: 1) Weatherford PBP bridge plug and 2) TechTool high-pressure bridge plug. Both of these designs are rated for temperatures up to 400 ºF (204 ºC) and for a casing size of 13⅜ inches (0.34 m).

4.7.4 Operational Radiological Monitoring

While radioactive materials will not be part of the DBD demonstration project, they are for a “production” disposal facility and monitoring ability requires demonstration for later phases of the program. Operational safety for waste emplacement would be assured through routine monitoring and planning for potential unexpected conditions or events.

Radiological monitoring would include dosimeters for all workers and visitors on site and during transportation of waste canisters. Equipment would be routinely sampled and monitored for radioactive contamination using standard radiation safety procedures. Real time monitoring of radiation levels in working areas of the drill rig would be conducted and connected to an alarm system during waste emplacement operations.

Fluids circulated in the borehole would need to be continuously monitored for radiation levels and periodically sampled for analysis of radionuclide concentrations. Design of monitoring equipment and operational procedures for radiological protection during drilling operations may be readily adapted from drilling experience at the Nevada Test Site, in which drilling was done into contaminated underground nuclear testing sites. Detection of excessive radiation in the borehole fluid would cause immediate suspension of waste emplacement. In addition, storage capacity for contaminated fluids would be part of the rig design and actions would be taken to securely store any contaminated fluids produced at the surface.

4.8 Seal Design and Closure

Although the demonstration borehole will not be permanently sealed, considerable effort will go into designing, downhole emplacement, and downhole testing of seals. The integrity of each constructed seal will be tested, and then will be drilled through to keep the borehole open.

Candidate seal designs will be developed for downhole testing. It is particularly important to test seal emplacement feasibility and seal integrity at depths greater than 2 km. Seal materials will include cement and bentonite and potential alternative sealing using the rock welding approach (see Section 3.8.4). Above-ground testing of long-term cement and bentonite degradation is described in Sections 3.8.2 and 3.8.3. Emplacement approaches are described below.

4.8.1 Seal Emplacement Operations

While the plugging of boreholes with clay and cement seal materials is routine in the construction, geotechnical, and water well industries, plugging must be demonstrated successfully at the much greater depths of deep boreholes. Candidate methods for emplacing bentonite and cement are described below.

4.8.1.1 Bentonite Emplacement

A widely accepted method of sealing shallow holes is to use a grout pump to carefully pump bentonite slurries downhole. Alternatively, bentonite chips or pellets can be dropped, usually via a tremie pipe, into holes containing standing water, providing a relatively low permeability seal.

Methods that will be demonstrated for placing clay plugs at depth include container, pellet, and perforated tube methods.

1. *The Container Method*. In the container method, a highly compacted plug segment is confined in a sealed container until it reaches its destination in the borehole. Either a ram in the container or the drill string can be used to push the plug out through a lid at the end of the container. The plug segment will rest on the previously placed clay core or concrete plug and be hydrated from every side swelling from the outside in based on the clays water uptake rate at the emplaced condition. The advantages to the method are that no clay is lost to erosion during the placement phase and high clay densities can be obtained on placement of the plug.
2. *The Pellet Method*. The pellet method utilizes either commercially available clay pellets or sorted bits from crushed highly compacted blocks. The suggested method to place pellet plugs is very similar to that of the container method: fill a sealed transfer bucket with dry pellets, lower the bucket to the desired position, and push the pellets out with a ram or the drill rod. The advantage of this method is that it utilizes commercially available clay pellets and the pellets hydrate more quickly. The disadvantage is that the clay density is much lower than either of the two alternatives.

3. *The Perforated Tube Method.* This technique was originally developed during the international Stripa project in Sweden. The plugs consist of perforated tubes containing tightly fitting blocks of highly compacted clay. The plug is lowered in the hole and left there. Clay swells on contact with water through the perforations of the tube, contacts the walls of the borehole and encases the tube. Copper is recommended for the tubing material due to its chemical stability and that its impact on smectite clay is negligible. The advantage is that high saturated densities for the clay are attainable. The disadvantage is that if the plug is not placed at the seal location quickly enough during the placement operations, the clay will begin to hydrate and swell. This could cause resistance to insertion of the plug, possibly even resulting in a stuck plug. It is inevitable that erosion of the clay will occur and that will lower the initial density of the clay.

4.8.1.2 Cement Emplacement

The following cement plug emplacement approaches will be tested:

1. *Balanced Plug Method.*The balanced plug method involves pumping a desired quantity of cement slurry through a drillpipe or other tubing until the cement level outside the drillpipe/tubing is equal to that inside. The pipe or tubing is then pulled out slowly from the slurry leaving the plug in place. The method is simple and requires no special equipment other than a cementing service unit. The characteristics of the mud are very important in the balancing of a cement plug in a well, particularly the ability to circulate freely during placement.

2. *Cement Squeeze Method.* The cement squeeze method is often used to isolate wellbore intervals or to cement fractures to obtain static equilibrium. The cement squeeze method involves pumping slurry to the desired interval through a drillpipe or other tubing. Sufficient hydraulic pressure is applied to the slurry so that the slurry begins to dehydrate and is no longer flowable and a filter cake forms at the plug edges. The cement becomes a barrier that prevents fluid movement. A cement squeeze job is either a bradenhead squeeze or packer squeeze. A bradenhead squeeze is a relatively low-pressure cement squeeze job in which the cement is pumped down a tubing string or drillstring (workstring). The drillstring is positioned just above the zone to be squeezed. The drillstring casing head (“bradenhead”) annulus is closed. Pressure is applied through the workstring to squeeze cement into position. A packer squeeze is a relatively high-pressure cement squeeze job. A packer is used to seal the workstring annulus above the zone to be squeezed. The cement is pumped down the drillstring, and pressure is applied.

3. *Dump Bailer Method.* Typically, the dump bailer method is used for placing cement on platforms formed by previous plugging operations or on mechanical isolation tools. The method is usually used at shallow depths; but with the formulation of retarded setting cementing compositions, it has been used to depths exceeding 3.5 km (12,000 ft). The dump bailer containing a measured quantity of cement is lowered into the well on a wireline. The bailer is opened on impact with the previously placed structure or by electric activation and is raised to release the cement slurry at this location. The method has certain advantages in that the tool is run on wireline and the depth of the cement plug is easily controlled. The cost of a dump bailer job is usually

low compared with one using conventional pumping equipment. Two disadvantages of the method are that mud can contaminate the cement unless the hole is circulated before dumping and there is a limit to the quantity of slurry that can be placed per run, and an initial set may be required before the next run can be made.

4. *The Two-Plug Method.* In the two-plug method, top and bottom tubing plugs are run to isolate the cement slurry from the well fluids and displacement fluids on top of the previous plug or a bridge plug set at depth. A special baffle tool is run on the bottom of the string and placed at the depth desired for the bottom of the cement plug. This tool permits the bottom tubing plug to pass through and out of the tubing. Cement is then pumped out of the string and begins to fill the annulus. The top tubing plug, following the cement, is caught in the plug-catcher tool and causes a sharp rise in the surface pressure, which indicates that the plug has landed. The latching device holds the top tubing plug to help prevent cement from backing up into the string, but permits reverse circulation. This design allows the string to be pulled up after cement placement to "cut off" the cement plug at the desired depth by establishing reverse circulation through the plug catcher; thus excess cement is allowed to be reversed up and out of the tubing. The string is then pulled, leaving a cement plug that should last indefinitely and provide good, hard support for any subsequent operation. Advantages of the two-plug method are that (1) it minimizes the likelihood of overdisplacing the cement; (2) it forms a tight, hard cement structure; and (3) it permits establishing the top of the plug. The two-plug method of plugging is preferred to the balanced method.
5. *Mechanical Plugs.* Mechanical isolation tools such as bridge plugs, cement retainers, and permanent packers are used to isolate sections of the wellbore. These maybe set at prescribed depths by wireline, tubing, workstring, or drill pipe. Cement caps are then placed on top of the plug to provide a secondary seal.

4.8.2 Seal Integrity Testing

As-built measurements of the seal system performance will be done, including

- Material testing of as-emplaced materials (can include standard strength/permeability tests of cast cement samples, remolded clays, etc.) (e.g., API, 1990)
- In situ strength tests – commonly accomplished by applying vertical loads via the drill rig itself, or via application of a packer pressure system if the overall formation permeability is low.
- In situ permeability testing – using a packer system, apply pressure above a seal system component and monitor pressure decay to determine system permeability.

4.9 Operational Retrievability

Retrievability during the waste canister emplacement processes is a consideration in the safe operation of a DBD facility and certain elements of operational retrieval require demonstration during the DBD demonstration project. Care is exercised in the design of the borehole to minimize the likelihood of a stuck waste canister during emplacement. These borehole design considerations and requirements are identified and discussed. In an operating facility if an unexpected situation arises where a waste canister becomes stuck during emplacement, retrieval will need to be conducted or a decision made to abandon the borehole and move to another borehole in the field. The demonstration of the retrieval operation is developed and described in this section.

One unplanned scenario of concern would be that a canister string becomes lodged in the borehole at some depth shallower than the disposal zone. A number of measures in the reference design and operations make this scenario highly unlikely. The borehole will be fully cased from the surface to the bottom during waste emplacement operations. The casing will be surveyed using a caliper tool prior to waste emplacement to detect deviations in inside diameter, bending, shearing, or any other obstructions that could cause the waste string to become lodged. A guide shoe with rounded nose will be on the first canister in the string. The formation testing prior to waste emplacement will provide information concerning the potential for rock breakout during operations potentially compromising the casing. Additional assurance could be achieved by using a disposable caliper tool that would be attached below the lowermost waste canister in the string. This tool would send real-time measurements of the casing inside dimensions to operators via telemetry. Lowering of the drill string would be stopped if a potential obstruction is encountered ahead of the waste canister string, preventing it from becoming stuck.

If a waste canister string becomes lodged in the borehole, considerable force could be applied by the drill rig to pull, push, or rotate the canister string, based on the strength of the waste canisters and the connections between them. If the waste canister string cannot be dislodged, then a bridge plug and cement plug could be set above the canister string. Waste emplacement could continue if the lodged waste canister string is located in the waste disposal zone. If the waste canister string is lodged in the liner casing above the waste disposal zone, then it would be possible to extract the liner from the borehole, pulling the lodged canister string up with the liner. This method of retrieval would require a drill rig capable of lifting the combined weight of the liner and the lodged canister string. Furthermore, the liner casing would have to be of sufficient strength to support the weight of itself and the lodged canister string during the extraction process. The borehole would be grouted, sealed, and abandoned if the waste canister string is lodged above the disposal zone and cannot be retrieved. Other retrieval methods, such as mining from the surface, may be possible for a waste canister string that is lodged at a very shallow depth.

Retrieval of test canisters during the DBD demonstration project would be conducted as described in Section 4.4.3. This part of the canister testing would serve as a demonstration of retrieval for canisters that are not stuck in the borehole. A demonstration of retrieval of stuck waste canisters is beyond the scope of the DBD demonstration project and would have to be addressed in later phases of the disposal program through further analysis or, potentially, by downhole testing.

5. IDENTIFICATION & PRIORITIZATION OF RESEARCH AND DEVELOPMENT NEEDS

This section describes the systematic approach that will be used to identify and prioritize RD&D science and engineering needs during the demonstration phase of the DBD concept. An example implementation of the approach is presented. The complete prioritization will occur in an early phase of the demonstration. This approach is similar to the systems engineering approach developed previously for the Used Fuel Disposition (UFD) Campaign R&D Roadmap (U.S. DOE 2011). For this roadmap the initial identification and prioritization of RD&D needs will rely on existing qualitative and quantitative information and consider both pre- and postclosure.

5.1 Systematic Approach

At a high level the systematic approach described herein involves ranking of candidate science and engineering activities against multiple metrics and combining these multiple rankings into an overall priority score using objective functions and a set of weighting factors on the individual metric components.

The approach will utilize qualitative and quantitative analyses and leverage existing information from multiple sources. The approach will utilize an adaption of the classical "performance assessment methodology" (Bonano et al., 2010) to supplement the qualitative analyses supporting the evaluation of the science and engineering activities. The steps in the approach include

- Identify potential RD&D needs (information needs and knowledge gaps) (Section 5.2)
- Characterize the RD&D needs to support prioritization (Section 5.3)
- Prioritize RD&D needs based on an established methodology (Section 5.3)

Each of these steps is described below.

5.2 Identification of Potential RD&D Needs

The identification step involves the following three activities:

1. Identify objectives of the deep borehole disposal demonstration (Section 5.2.1)
2. Identify the relevant features, events, and process associated with deep borehole disposal (Section 3.1)
3. Identify potential science and engineering activities needed for the demonstration (Section 5.2.2)

5.2.1 Objectives of the DBD Demonstration

The project objectives are presented in Section 2.2. The two high-level objectives focused on science and engineering activities are refined to establish the objectives of the identification and prioritization activity as follows:

1. Identify and prioritize science and engineering activities that directly support site selection for the demonstration.

2. Identify and prioritize science and engineering activities that directly support the drilling and completion of a deep borehole.
3. Identify and prioritize science and engineering activities that require evaluation and verification during the demonstration.
4. Identify science and engineering gaps associated with the demonstration.

5.2.2 Identification and Characterization of Science and Engineering Activities

As presented in Section 3.1, the FEPs identified as relevant to DBD are used to inform and identify areas where science thrust and characterization activities can contribute to a successful demonstration. The engineering thrust activities of potential relevance for evaluation and prioritization are identified using previously developed information generated in Brady et al 2009 and Arnold et al 2011 and references therein. This information is supplemented with expert judgment, as well as the UFD R&D Road Map (U.S. DOE 2011). Table B-1 of Appendix B summarizes the potential science and engineering activities that support the deep borehole demonstration. Detailed discussions of these activities were presented in Sections 3 and 4. They are organized here according to those activities supporting demonstration site selection, borehole drilling and completion, and postclosure.

Summaries of the different types of activities are provided below.

5.2.2.1 Direct Support of Demonstration Site Selection

These activities are primarily science activities that provide technical information to assist in the selection of a site for the deep borehole demonstration. From a technical perspective the focus is on obtaining a site where there is a high confidence of successfully demonstrating the deep borehole concept and its supporting technical basis. There are non-technical factors that also must be considered when siting the deep borehole demonstration and these factors are discussed in Section 8.

5.2.2.2 Direct Support of Drilling for the Demonstration

These activities are primarily engineering activities that are potentially required to "get a hole in the ground." The borehole reference design presented in Section 4.1.2 has been designed so that borehole construction has a high probability of success given today‟s technology, as well as having size and depth to meet reasonable waste form and disposal needs. While the deep borehole demonstration is not intended to be a "drilling research" program, a borehole of this size and depth has never been constructed and does challenge the technology envelope as discussed in Section 4. The activities supporting drilling for the demonstration fall into the areas of drilling technology, borehole logging, borehole construction (casing, liner, cementing), operational, and borehole monitoring. These activities are described in Section 4, with some of the supporting drilling science activities described in Section 3.

5.2.2.3 Postclosure Activities Requiring Evaluation and Verification in the Demonstration

These are science and engineering activities that may require verification of proof of concept during the demonstration in order to identify and address technical gaps associated with potential future disposal. Postclosure activities comprise a significant portion of the activities that need to be demonstrated. Subsets of these activities also support demonstration site selection and drilling. Details of post closure science and engineering activities were presented in Sections 3 and 4, respectively, and fall into the following areas:

- Geology (Section 3.2)
- Hydrogeology (Section 3.3)
- Stress/Pressure Conditions and Borehole Stability (Section 3.4)
- Geochemical Environment (Section 3.5)
- Thermal Effects (Section 3.6)
- Engineered Material Performance (Sections 3.8 and 4.8)
- Waste Form Performance (Section 3.8)
- Long-Term Monitoring (Section 3.9)
- Nuclear Criticality (Section 3.10)
- System and Sub-system Modeling (Section 6)
- Canister Emplacement and Operational Retrieval (Sections 4.7 and 4.9)
- Fuel Assembly Consolidation (Section 4.5)

5.3 Evaluation and Prioritization of RD&D Activities

The next step is to evaluate and prioritize each of the potential science and engineering activities with respect to a set of metrics. Example metrics are identified in Section 5.3.1. Evaluation and prioritization will occur during the initial phase of the demonstration. (See schedule in Section 9.5.) The process used, and an example of its use, are presented in this roadmap. Prioritization of activities is organized around those supporting demonstration site selection, borehole drilling and completion, preclosure, and postclosure.

An example of the evaluation and prioritization process of the potential science and engineering activities identified in Section 5.3.2 is conducted in the section for a subset of the science activities. This is intended only to demonstrate the prioritization process and the results of this example can be expected to change when the more comprehensive evaluation is conducted in the initial phase of the demonstration. Example results are presented in a summary table of ranking for each metric and the cumulative. The evaluation and prioritization is conducted in three steps:

- Identify metrics and characteristics of the science and engineering activities to support prioritization.(Section 5.3.1).
- Evaluate the science and engineering activities for demonstration in the context of the established metrics. (Section 5.3.2).
- Determine objective functions and tally combined ranking (Section 5.3.3).

5.3.1 Identification of Metrics

The identification of metrics for evaluating and prioritizing potential science and engineering activities relevant to deep borehole demonstration is the first step. Because of the desire to simplify metric scoring and the qualitative nature of available information, the use of expert judgment is required and the assessment is somewhat subjective. There are three basic types of metrics:

- *Natural metrics* are those that can be physically measured and that directly determine the degree to which an objective is met. (e.g., Importance to PA, FEP Relevancy).
- *Constructed metrics* are generally those used to measure an objective that does not have a simple physical meaning or that encompasses several aspects of a decision problem. Constructed metric often require a conversion of the metric scale into some other units that can be combined with the other metrics. (e.g., Maturity, Redundancy).
- *Proxy metrics* are the final, and least desirable, type of metric considered. This metric type indirectly measures the achievement of the objective, when a direct natural (or constructed) metric cannot easily be assessed. (e.g., Value of Information).

There are some qualities of metrics that are desirable for a reproducible, transparent, and high-quality screening analysis. A basic set of metric qualities has been given by Keeney and Gregory (2005) as unambiguous, comprehensive, direct, operational, and understandable. Additionally, Keeney and Raiffa (1993) describe important qualities for *sets* of metrics: complete, minimal, non-redundant, and operational.

An example of metrics selection is conducted. These metrics will be revisited when a prioritization of higher pedigree is conducted in the initial phase of the demonstration project. In the example presented herein, six metrics are identified that are used to evaluate the importance of a sub-set of the science activities relevant to the deep borehole demonstration. Table 5-1 identifies these metrics and the scoring associated with each metric. In general a low, medium, and high score results in a lowering, no change, or raising of the priority. Each of the metrics is described following the table.

These metrics will be revisited and possibly changed when the evaluation is conducted during the demonstration. Additionally, it is likely that the metrics associated with engineering activities may differ from those associated with the science activities. If this is the case separate evaluations and prioritization of sciences and engineering activities will be required.

Table 5-1. Example Metrics and Scoring for Prioritizing Science Activities.

Metrics	**Low Score**	**Moderate Score**	**High Score**
Maturity	Not Established	Moderately Established	Well Established
Redundancy	Highly Redundant	Moderately Redundant	Limited Redundancy
FEP Relevancy	Number of FEPs addressed: That is, the number of FEPs for which the activity provides information are counted. Once this exercise is completed bin ranges will be selected to represent low, moderate, and high scores.		
Uncertainty Reduction/Importance to PA	Low Reduction Low Importance	Moderate Reduction Moderate Importance	Large Reduction Large Importance
Value of Information	Limited Value	Moderate Value	High Value
Cost	High Cost	Moderate Cost	Low Cost

Note: Low Score: Lowers priority
Moderate Score: Neutral priority
High Score: Raises priority

Maturity: A considerable amount of work has been completed both in the U.S. and other countries on many, if not all, of the RD&D activities under consideration. This body of work can be used to determine the current level of understanding, or maturity with respect to deep borehole demonstration and to identify information gaps.

The following guidelines are used to help evaluate the maturity scoring of the activities as either "not established," "moderately established," or "well established":

- Not Established: Includes
  - Fundamental Gaps in Method: The representation of the activity (conceptual and/or mathematical, experimental) is lacking
  - Fundamental Data Needs: the activity requires data or parameters that is lacking
- Moderately Established: Includes
  - Improved Representation: The activity may be technically defensible, but for application to the deep borehole addition proof of concept would be beneficial
  - Improved Confidence: The activity (both method and any supporting data) exist or are readily obtainable and is technically defensible but there is not widely-agreed upon confidence concerning the activity‟s use in a deep borehole environment
  - Improved Defensibility: Related to confidence, but focuses on improving the activities technical basis, and defensibility, with respect to the deep borehole environment
- Well Established: Includes
  - Well Understood – The representation of the activity is well developed, has a strong technical basis, and is defensible.

Redundancy: Some of the RD&D activities are redundant in that they provide the same or very similar information. Many activities also address the same FEPs. The following is used to help evaluate the redundancy scoring of the activities as either "highly redundant," "limited redundancy," or "no redundancy." The scoring for each activity is determined by the number of FEPs that overlap with other activities. Because some activities address more FEPs than others (FEPs relevancy), the score is normalized to the number of FEPs the activity addresses. The result is then binned into three ranges: limited redundancy (< 2), moderately redundant (>2 but <4), highly redundant (>=4).

FEP Relevancy: Most of the RD&D activities directly support FEPs evaluation by providing information needed to either defensively exclude a FEP from further consideration in a safety assessment or in providing information needed to include a FEP in the safety assessment. The scoring is determined by identifying the number of FEPs an activity supports. Scoring is binned into three ranges: Low (1 to 4, inclusive), Medium (5 to 8, inclusive), and High (>8).

Uncertainty Reduction/Importance to PA: As used here uncertainty reduction is related to importance of the RD&D activity to the safety assessment. System and sub-system sensitivity analyses evaluate the sensitivity of parameters described with uncertain values or distributions of values to performance or safety metrics. Existing system and sub-system analyses of deep borehole disposal will be used to evaluate uncertainty reduction scoring of the activities as either "low reduction/importance," "moderate reduction/importance," or "large reduction/importance." This metric is the only metric that utilizes quantitative information and results from modeling studies.

Value of Information: This metric supplements the information obtained from the FEP Relevancy and Uncertainty/Importance to performance assessment (PA) metrics; value scoring this metric is very subjective.

Cost: The cost metric only plays a role when there are multiple RD&D activities capable of providing the same or very similar information and at the same level of confidence. As such, this metric will not enter into the objective function which combines the weighted scores of the other metrics. It will be used as an activity "tie-breaker." Cost scoring of the activities is either "high cost," "moderate cost," or "low cost."

A numerical score is assigned to the qualitative scores for each of the immediately preceding three metrics. The numerical score ranges from 1 to 9, inclusive with low, medium, and high scores being assigned values of 2, 5, and 8, respectively. For redundancy these scores are reversed since low redundancy tends toward a higher priority.

5.3.2 Evaluation of Science and Engineering Activities Supporting Deep Borehole Disposal Demonstration

In the next step, each of the activities is evaluated against the selected metrics. An example of this evaluation is presented in Table 5-2 for a sub-set of the potential science activities. Additionally, the combined score shows an example of using the objective function defined in Section 5.3.3. A more detailed and comprehensive evaluation of all the science and engineering activities relevant to the deep borehole demonstration will be conducted in the initial phase of the demonstration project.

Table 5-2. Example Evaluation and Prioritization of Potential Science Activities.

Activity	Maturity	Redundancy	FEPs Relevancy	Uncertainty Reduction/PA Importance	Value of Information	Combined
3D Seismic Imaging	High	High	6 - Medium	Medium	High	5.6
Borehole Caliper Log	High	Medium	1 - Low	Low	Medium	3.65
Borehole Gravity Log	Medium	Low	2 - Low	Low	Low	3.05
Dipole Shear-Wave Velocity Log	High	High	3 - Low	Medium	Medium	5
Downhaul Force Mechanical Testing	Medium	High	5 - Medium	Medium	High	6.05
Drill Cuttings	High	Medium	8 - Medium	Medium	High	5.6
Drill Stem Pump Tests	High	Medium	10 - High	Medium	Medium	5.6
Drill Stem Tests of Shut-In Pressure	High	High	11 - High	High	High	6.5
Electrical Resistivity Profile	High	Medium	6 - Medium	Medium	Low	4.25

Fluid Pressure Drawdown Test of Effective Permeability	High	High	2 - Low	Medium	High	5.3
Fluid Samples from Packer Testing	High	High	49 - High	High	High	8
Formation Micro Imager Log	High	High	12 - High	Medium	Medium	6.35
Gamma Ray Log	High	Medium	4 - Low	Low	Low	2.6
Gravity and Magnetic Surveys	High	Medium	3 - Low	Low	Medium	2.9
Intermittent Coring	High	High	8 - Medium	High	High	6.2
Neutron Porosity Log	High	Medium	4 - Low	Medium	Medium	3.5
Packer Pump Tests	High	High	13 - High	High	High	6.5
Push-Pull Tracer Testing	Medium	Medium	1 - Low	Medium	Medium	3.2
Resistivity Log (Borehole Based)	High	Medium	11 – High	Low	Low	5.45
Spontaneous Potential Log	High	Low	1 – Low	Low	Low	2.6
Surface Geological Mapping	High	Medium	2 – Low	Low	Medium	3.65
Temperature Log	High	High	12 – High	Medium	High	5.9
Vertical Dipole Tracer Testing	Low	High	2 – Low	High	High	3.8
Waste Canister Mockup Electrical Heater Test	Low	Low	1 - Low	High	High	5.3

5.3.3 Scoring and Prioritization

To prioritize science and engineering activities, the results of the individual metrics must be combined to provide a composite value (e.g., the score in the last column of Table 5-2). A weighting function (also called a value or utility function) is employed to achieve this value roll up. In the example presented in Table 5-2 the weighting function is simply the linear combination of a weight times the score for each metrics to be included. That is, the weights on each metric are assigned the same weight. In the absence of further information this is a reasonable implementation.

The composite score for an activity is given by:

$$CS = \sum_{i}^{N_m} W_i S_i$$

where *CS* is the composite score for an activity, N_m is the number of metrics considered, W_i is the weighting value assigned to the i^{th} metric, and S_i is the activity score for the i^{th} metric.

Alternately, the weights of the metrics can be developed by the same technical experts who developed the metrics, since they best understand the relative importance of each. Various weighting formulations can be used to evaluate the sensitivity of the prioritization to the selection of the metric weights.

If different metrics are used, Engineering and Science activities will be scored and prioritized separately. The total weight of all metrics for science (and possibly separately for engineering) is 1. In the example prioritization for the science activities the following weights have been assigned to the metrics in this evaluation:

1) Maturity: 0.1
2) Redundancy: 0.25
3) FEP Relevancy: 0.35
4) Uncertainty Reduction/PA Importance: 0.2
5) Value of Information: 0.1

These will be revisited and adjusted during the demonstration and weights for combining the metric scores for the engineering activities will be developed. The logic for this initial selection of metric weights is as follows:

Maturity: Maturity is weighted lower than the average of the other metrics because application of some of the activities relevant to deep borehole disposal challenge current technology or have not been applied in this area.

Redundancy: Redundancy is weighted higher than the average of the other metrics because unless there are additional and compelling reasons, it is not necessary to have multiple activities that accomplish the same purpose.

FEP Relevancy: FEP relevancy is weighted the highest among the metrics because this metric is an indicator of the degree to which a particular activity supports the technical basis of deep borehole disposal.

Uncertainty Reduction/PA Importance: Normally, importance to performance assessments through sensitivity analyses would be given a higher weighting. Because results and analyses conducted to date are limited and are not comprehensive its weight has been limited to the average across the metrics.

Value of Information: The value of information is given a lower than average weighting because it is not entirely independent of the other metrics.

6. DEMONSTRATION OF SAFETY

The approach to prioritizing activities described above will be informed by analysis and insights gained from existing and new safety analyses. This section addresses those aspects of the DBD demonstration that require verification and proof of concept for assuring safety of potential future disposal.

6.1 Postclosure Safety

Postclosure science activities and FEPs that are important to demonstrating the postclosure safety of the deep borehole disposal concept were identified in the UFD R&D Road Map (U.S. DOE 2011). In addition, several preliminary analyses on long-term performance of DBD were conducted in Brady et al. (2009); Herrick et al. (2011); Clayton et al. (2011); and Vaughn et al. (2012b). In these analyses, uncertainties in parameters were characterized and propagated through system and sub-system models. Sensitivity analyses on the uncertainty results can be used to inform the prioritization of science and engineering activities that would benefit from demonstration. In addition, FEPs were evaluated for relevancy to Deep Borehole Disposal (Brady et al., 2009) and these are provided in Table A-1 of Appendix A. Several characterization methods have been associated with these FEPs (Arnold et al., 2011 and Vaughn et al., 2012a). The results of these previous studies are summarized in this section.

6.1.1 UFD R&D Road Map

In the UFD R&D Road Map postclosure science activities and FEPs that are important to the deep borehole disposal concept were identified considering the objectives of containment, limiting releases, and defense in depth. The relative priority of activities was judged against a set of metrics that included importance to the safety case, adequacy and state of the art of current information, and length of time to complete the activity. The first two are particularly relevant to the Deep Borehole Road Map. Table 6-1 presents a summary of the UFD R&D Road Map evaluations.

In addition, the UFD R&D Road Map identified multi-borehole analyses and thermal management considerations as areas requiring further understanding associated with deep borehole disposal.

For deep borehole disposal, simulation of multi-borehole arrays should be undertaken for a system consisting of 10 to 100 individual boreholes. Such investigations could evaluate the potential for communication between boreholes, thermal or hydrologic interactions, and large-scale responses to borehole arrays. Performance assessments are needed to establish a better sense of the potential performance variability that might be expected in multiple implementations of borehole disposal fields.

Assuming that young, heat-generating wastes must be either stored or disposed directly, there is a need to understand the general thermal considerations for siting and screening. Work is needed to define metrics representing thermal management, e.g., host rock thermal conductivity, solubility vs. temperature, and other geologic sensitivities to elevated temperature, and thermal limits, etc.

Table 6-1. UFD R&D Road Map Priorities for DBD.

Disposal System Component	Importance	Information Available
Engineered Disturbed Zone	Medium	Insufficient
Basement Rock Properties	High	Partially Sufficient
Other Rock Properties	Medium	Partially Sufficient
Flow and Transport Pathways and Properties	High	Partially Sufficient
Basement Rock Fracture and Stress Characterization	High	Insufficient
Mechanical Processes and Properties	Low	Partially Sufficient
Hydrologic Processes and Properties	High	Partially Sufficient
Chemical Processes and Properties	Medium	Insufficient
Natural System Radionuclide Transport	Medium	Partially Sufficient
Biologic Processes and Properties	Low	Partially Sufficient
Thermal Processes and Properties	High	Partially Sufficient
Nuclear Criticality	Low	Sufficient
Gas Sources and Effects	Low	Sufficient

The UFD R&D Road Map also evaluated the importance of a number of cross cutting areas for generic disposal that also have relevance to deep borehole disposal. These are presented in Table 6-2.

Table 6-2. Synopsis of the Results of Cross-Cutting R&D Issues.

DESIGN CONCEPT DEVELOPMENT	High
DISPOSAL SYSTEM MODELING	High
OPERATIONS-RELATED RESEARCH AND TECHNOLOGY DEVELOPMENT	Low
KNOWLEDGE MANAGEMENT	Medium
SITE SCREENING AND SELECTION TOOLS	Medium
EXPERIMENTAL AND ANALYTICAL TECHNIQUES FOR SITE CHARACTERIZATION	Medium
UNDERGROUND RESEARCH LABORATORIES	Medium
RESEARCH AND DEVELOPMENT CAPABILITIES EVALUATION	Medium

The UFD R&D Road Map also evaluated the importance of FEPs to deep borehole disposal. These are presented in Appendix C, Tables C-1 and C-2. Table C-1 is an evaluation of the importance of deep borehole natural system FEPs and Table C-2 is an evaluation of the importance of deep borehole engineered system FEPs. The evaluations are expressed using low, medium, and high importance rankings.

The UFD Road Map (U.S. DOE 2011) also summarizes the ranking of FEPs with respect to the importance to a safety case for generic disposal as a numerical priority value. This priority value used 2 metrics, 3 safety case components, and 4 decision points. The portion of this table relevant to deep borehole disposal is extracted and reproduced as Table 6-2.

In producing the results of the UFD Road Map, the importance of a FEP to the safety case is a function of its importance to each of the three components of the safety case importance to safety assessment, importance to design, construction & operations, importance to overall confidence in the safety case. FEPs were assigned a value of 0 to 3 with higher values being more important. A weighted sum of the across the three components is used. Additionally, importance for each component was identified for each of 4 decision points: Site Screening, Site Selection, Site Characterization, and Site Suitability, if applicable. A weighted sum of the across the 4 decision points is used. The overall FEP priority for each decision point and component was a function of two metrics, the importance of the information and the adequacy of information currently available. The overall FEP priority reported is the weighted sum of the priority of the FEP at each decision point.

Table 6-3. FEP Importance to Deep Borehole Disposal Safety Case by Priority.

UFD FEP	Priority
2.2.01.01 - Evolution of EDZ - Deep Boreholes	6.13
2.2.09.01 - Chemical Characteristics of Groundwater in Host Rock - Deep Boreholes	5.86
2.2.09.02 - Chemical Characteristics of Groundwater in Other Geologic Units (Non-Host-Rock) - Confining Units - Aquifers - Deep Boreholes	5.86
2.2.09.05 - Radionuclide Speciation and Solubility in Host Rock - Deep Boreholes	5.86
2.2.09.06 - Radionuclide Speciation and Solubility in Other Geologic Units (Non-Host-Rock) - Deep Boreholes	5.86
2.2.09.03 - Chemical Interactions and Evolution of Groundwater in Host Rock - Deep Boreholes	5.40
2.2.09.04 - Chemical Interactions and Evolution of Groundwater in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers - Deep Boreholes	5.40
2.2.02.01 - Stratigraphy and Properties of Host Rock - Deep Boreholes	3.74
2.2.05.01 - Fractures - Host Rock - Other Geologic Units - Deep Boreholes	3.65
2.2.08.01 - Flow Through the Host Rock - Deep Boreholes	3.65

2.2.08.02 - Flow Through the Other Geologic Units - Confining Units - Aquifers - Deep Boreholes	3.65
2.2.08.06 - Flow Through EDZ - Deep Boreholes	3.65
2.2.11.04 - Thermal Effects on Chemistry and Microbial Activity in Geosphere - Deep Boreholes	3.55
2.2.11.06 - Thermal-Mechanical Effects on Geosphere - Deep Boreholes	3.40
2.2.11.07 - Thermal-Chemical Alteration of Geosphere - Deep Boreholes	3.40
2.2.08.04 - Effects of Repository Excavation on Flow Through the Host Rock - Deep Boreholes	3.23
2.2.11.01 - Thermal Effects on Flow in Geosphere - Repository-Induced - Natural Geothermal - Deep Boreholes	3.10
2.2.11.02 - Thermally-Driven Flow (Convection) in Geosphere - Deep Boreholes	3.10
2.2.08.07 - Mineralogic Dehydration - Deep Boreholes	2.82
2.2.09.51 - Advection of Dissolved Radionuclides in Host Rock - Deep Boreholes	2.53
2.2.03.01 - Stratigraphy and Properties of Other Geologic Units (Non-Host-Rock) - Deep Boreholes	2.46
2.2.05.03 - Alteration and Evolution of Geosphere Flow Pathways - Host Rock - Other Geologic Units - Deep Boreholes	2.46
2.2.11.03 - Thermally-Driven Buoyant Flow / Heat Pipes in Geosphere - Deep Boreholes	2.46
2.2.09.52 - Advection of Dissolved Radionuclides in Other Geologic Units (Non-Host-Rock) - Confining Units - Aquifers - Deep Boreholes	2.40
2.2.09.53 - Diffusion of Dissolved Radionuclides in Host Rock - Deep Boreholes	2.40
2.2.09.54 - Diffusion of Dissolved Radionuclides in Other Geologic Units (Non-Host-Rock) - Confining Units - Aquifers - Deep Boreholes	2.40
2.2.09.55 - Sorption of Dissolved Radionuclides in Host Rock - Deep Boreholes	2.40
2.2.09.56 - Sorption of Dissolved Radionuclides in Other Geologic Units (Non-Host-Rock) - Confining Units - Aquifers - Deep Boreholes	2.40
2.2.09.57 - Complexation in Host Rock - Deep Boreholes	2.40
2.2.09.58 - Complexation in Other Geologic Units (Non-Host-Rock) - Deep Boreholes	2.40
2.2.09.61 - Radionuclide Transport Through EDZ - Deep Boreholes	2.40

2.2.09.64 - Radionuclide Release from Host Rock - Dissolved - Colloidal - Gas Phase - Deep Boreholes	2.40
2.2.09.65 - Radionuclide Release from Other Geologic Units - Dissolved - Colloidal - Gas Phase - Deep Boreholes	2.40
2.2.09.59 - Colloidal Transport in Host Rock - Deep Boreholes	2.22
2.2.09.60 - Colloidal Transport in Other Geologic Units (Non-Host-Rock) - Confining units - Aquifers - Deep Boreholes	2.22
2.2.09.62 - Dilution of Radionuclides in Groundwater - Host Rock - Other Geologic Units - Deep Boreholes	2.10
2.2.09.63 - Dilution of Radionuclides with Stable Isotopes - Host Rock - Other Geologic Units - Deep Boreholes	2.10
2.2.07.01 - Mechanical Effects on Host Rock - Deep Boreholes	1.63
2.2.07.02 - Mechanical Effects on Other Geologic Units - Deep Boreholes	1.32
2.2.10.01 - Microbial Activity in Host Rock - Deep Boreholes	1.32
2.2.10.02 - Microbial Activity in Other Geologic Units (Non-Host-Rock) - Deep Boreholes	1.32
2.2.12.02 - Effects of Gas on Flow Through the Geosphere - Deep Boreholes	0.95
2.2.12.03 - Gas Transport in Geosphere - Deep Boreholes	0.73
2.2.11.05 - Thermal Effects on Transport in Geosphere - Deep Boreholes	0.00
2.2.12.01 - Gas Generation in Geosphere - Deep Boreholes	0.00

Some high-level conclusions from the UFD R&D Roadmap, relevant to the deep borehole demonstration activities are

1) The information of Table 6-3 and the tables of Appendix C are useful for informing the prioritization of postclosure activities supporting the deep borehole demonstration and will be used for this prioritization during the initial phase of the demonstration.

2) Activities of High importance include

    - Those supporting conceptual design and the deep borehole system model
    - Basement Rock Properties Evaluation including Fracture, and Stress
    - Hydrologic Processes and Properties
    - Transport Properties Evaluation
    - Thermal Processes and Properties

3) Activities of Moderate importance include
    - EDZ Properties (more recent assessments indicate that this is of high importance)
    - Chemical Processes and Properties
4) Activities of Low importance include
    - Nuclear Criticality
    - Gas Sources and Effects
    - Biologic Processes and Properties

The UFD R & D Road Map is in the process of being revised, so the above evaluation may change.

6.1.2 Existing Postclosure Analyses in Support of Activity Prioritization

This section presents a synthesis of the existing deep borehole disposal postclosure safety assessments and sensitivity analyses that provide risk based information in support of the prioritization. These analyses were conducted by Brady et al., 2009; Herrick et al., 2011; and Vaughn et al., 2012b). Current analyses have been limited to undisturbed (in the absence of external events) performance.

6.1.2.1 Deep Borehole Disposal of High-Level Radioactive Waste (Brady et al., 2009)

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. These DB-PA results are based on several bounding and conservative assumptions, such as: all waste is assumed to instantly degrade and dissolve inside the waste canisters; all waste is assumed to be PWR assemblies; no credit is taken for sorption or decay along the saturated zone transport pathway from the sealed borehole to the withdrawal well assumed to take 8,000 years.

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. **Medium** 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 both the full-system performance of multi-borehole arrays should be undertaken, consistent with an assumption that a regional borehole disposal facility could entail an array of 10-100 individual boreholes.
    a. **Moderate** PA metric rating for Science activities: Multi-well Hydraulic Testing, Cross-hole Tomography, Multi-Borehole Modeling.

6.1.2.2 Deep Borehole Seals (Herrick et al., 2011)

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. The objective of this analysis was to determine the maximum effective permeability of the borehole seals and the surrounding disturbed rock zone (DRZ) that would result in an allowable level of risk, as estimated by radiological dose. 5 cases were evaluated.

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 activities
3) Seal permeabilities on the order of 10^{-16} m^2 are sufficient to limit releases and integrity is a dominate driver for releases to AE
    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

6.1.2.3 Generic Disposal System Modeling Fiscal Year 2011 Progress Report (Clayton et al., 2011)

A preliminary safety assessment and some supporting system and sub-system sensitivity analyses of deep borehole disposal were conducted. 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 process-level results and coupled to the system model.

Conclusions from the Clayton et al., 2011 analyses relevant to prioritization of deep borehole demonstration activities, the following can be learned:

1) Diffusion dominates transports in the base case while advection dominants 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 dose 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
    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 for 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.

6.1.2.4 Draft Generic Deep Geologic Disposal Safety Case (Vaughn et al., 2012b)

A preliminary safety assessment and some supporting system and sub-system sensitivity analyses of deep borehole disposal were conducted in Vaughn et al., 2012b. In these analyses, a set of "one-off," *ceirtus paribus,* simulations were performed where selected parameter were varied while holding all others at baseline values.

The following observations from the Vaughn et al., 2012b 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 EA
    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

7. LEGAL AND REGULATORY FRAMEWORK

Legal and regulatory issues and requirements will be addressed for the DBD demonstration project during the site selection process. This will allow specific state and local requirements to be evaluated and managed. The legal and regulatory framework for DBD disposal of SNF and HLW will be addressed in subsequent work.

7.1 Demonstration

Regulatory preparations will be initiated at the start of the site selection process and continued through the technical planning and drilling of the demonstration borehole. The regulatory environment is different in different states and for Federal versus private land. Experience has shown that acquiring permits often results in project delays and is responsible for changes in borehole design. Since the demonstration borehole will be unique, in terms of both size and purpose, it is important that regulatory agencies be presented with realistic plans that take into account existing regulations. There is a possibility in unique situations such as that presented by a DBD demonstration project that regulators may be overly cautious.

7.1.1 Local, State, and Federal Permits

These permits will vary by location, but it is important to define the operator of the demonstration borehole who will be the responsible party. Permitting may require the posting of bonds.

7.1.2 Drilling Permits

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.

7.1.3 Air Quality Permits

Air quality permits may be required for the drilling operation since this represents a point source for emissions. Some states are much more restrictive than others and may require Tier 3 engines on the rig and associated power units meet strict emission guidelines.

7.1.4 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‟s division of water rights.

7.2 National Environmental Policy Act Compliance

As a Federally funded project, compliance with the National Environmental Policy Act (NEPA) is a requirement. Some uncertainty exists regarding the level of effort required to comply. It appears unlikely that a categorical exclusion would be granted. The project scope and duration is not of a magnitude that would generally require an Environmental Impact Statement, so for our planning purpose we have included time and money to perform an Environmental Assessment. In the near future we will complete an Environmental Checklist and discuss our findings with the

Sandia Site Office, NEPA Compliance Officer. This discussion will allow us to finalize our NEPA compliance strategy.

8. SITE SELECTION/DEMONSTRATION PROJECT

This section discusses the RD&D data gaps associated with choosing the location for a DBD demonstration project and the eventual selection of a site for deployment of the DBD system. The focus will be on a process that locates the demonstration borehole at a site that is representative of the geology and other characteristics in which future DBD might be carried out. Selection guidelines are aimed at avoiding locations with potentially unfavorable conditions for DBD, such as overpressured conditions or high geothermal gradient. In addition to the technical siting factors, this section also discusses the socio-political factors and public outreach program that are relevant to successfully siting and implementing the DBD demonstration project.

8.1 Siting Process

The demonstration project team will develop a siting process that embraces the principles outlined in the Blue Ribbon Commission on America‟s Nuclear Future recommendations. Even though this demonstration project will not involve nuclear waste, we believe the siting principles should be utilized to the greatest extent practical to maximize the success of the project. These principles include

- Consent-based - in the sense that affected communities have an opportunity to decide whether to accept facility siting decisions and retain significant local control.
- Transparent - in the sense that all stakeholders have an opportunity to understand key decisions and engage the process in a meaningful way.
- Phased - in the sense that key decisions are revisited and modified as necessary along the way rather than being pre-determined.
- Adaptive - in the sense that process itself is flexible and produces decisions that are responsive to new information and new technical, social, or political developments.
- Standards-and science-based - in the sense that the public can have confidence that all facilities meet rigorous, objective, and consistently-applied standards of safety and environmental protection.
- Governed by partnership arrangements or legally-enforceable agreements between the implementing organization and host states, tribes, and local communities.
- Representative Site – that the selected site or sites be representative in terms of features, events, and processes important to disposal.

The recommended approach for identifying the location of the DBD demonstration project includes the following steps. Existing data will be analyzed by the project team to determine several regional or sub-regional areas that exhibit technical characteristics that are favorable to DBD, in terms of the science thrust and the engineering thrust of the RD&D demonstration plan, as described in Section 8.2. Potential stakeholders in the scientific and drilling engineering communities will be engaged in assessing the viability of pursuing the DBD demonstration project in different geographic areas. Such stakeholders may include regional university faculty, state geological surveys, and regional drilling and service contractors. State and local stakeholders in the political and economic arena will be engaged in determining the social viability of the demonstration project after a supporting consensus has been formed by the scientific and engineering communities. Selection of a specific site for the potential DBD demonstration project would consider a number of factors, including land ownership, permitting issues, local availability of supporting services, proximity to project participants, and potential importance and/or impacts to natural resources. Surface-based characterization methods would be used at a specific site prior to a go/no go decision on the drilling for the demonstration project.

Site selection for a deep borehole disposal site would be a more complex process than the siting process for the DBD demonstration project for a number of reasons. Actual disposal of nuclear waste would likely be much more controversial activity from a social and political perspective than the DBD demonstration project. In this sense, site selection for DBD program would involve a more extensive stakeholder outreach program and more complex political engagement than locating the DBD demonstration project. Site selection for a DBD facility would also involve consideration of waste transportation costs and infrastructure, which could vary considerably depending on the disposal site location relative to waste storage or nuclear power plant locations. A DBD facility would also require a larger site and a longer-term commitment than the DBD demonstration project, which would be important considerations in the site selection process.

8.2 Site Selection Guidelines

As part of the science and engineering thrust of this project, a set of basic initial technical siting guidelines will be established to ensure successful deep borehole disposal. These guidelines will focus on technical elements that are representative of potential future sites for DBD and conditions favorable for waste disposal in the deep subsurface.

8.2.1 Technical Guidelines Related to the Science Thrust

This section discusses factors related to the science thrust that could be evaluated prior to drilling regarding suitability and representativeness of the demonstration site, based on regional geological and hydrological data. Emphasis will be placed on evaluating characteristics that, if present, would be unfavorable to long-term safety of DBD. Although actual waste disposal is not a part of the demonstration project, RD&D activities should be conducted at a site that has characteristics representative of and consistent with implementation and safety of the DBD concept. This provides some assurance that what is learned during the demonstration project is transferrable to other similar locations favorable to DBD. Factors discussed include depth to crystalline basement rocks, deep groundwater circulation, tectonically unstable conditions, overpressured fluids at depth, major faults, volcanism, high geothermal heat flow, and potential for economically valuable mineral deposits.

Technical factors in the science thrust that are potentially important to waste isolation in the DBD concept and to the successful implementation of the DBD demonstration project include

- Depth to crystalline basement
- Crystalline basement lithology
- Basement geological structural complexity
- Topographic relief within 100 to 200 km of site
- Geothermal gradient
- Geothermal heat flux

- Petroleum exploration and production
- Mineral resources
- Tectonic activity and seismicity
- Faults
- Volcanism

A depth of less than 2,000 m to the crystalline basement allows for a 2,000 m disposal zone and a 1,000 m thick seal zone in the crystalline basement for the DBD demonstration project borehole (see, for example, Figure 2 in Brady et al., 2009). These conditions are consistent with the DBD concept. Areas with regional geological structural complexity, particularly in the western U.S., have a higher uncertainty in the depth to crystalline basement at some specific locations. Such structural complexity is also broadly associated with geologically recent tectonic activity, seismicity, and higher topographic relief. Crystalline basement lithology is variable, but broad patterns of age and rock type have been identified for Precambrian terrain that is covered by Phanerozoic-age sedimentary rocks. Granite or granitic gneissic rocks are preferred for the DBD concept. Major structural features, faults, and formerly tectonically active zones, such as the Precambrian-age midcontinent rift (Ojakangas et al., 2001), are generally potentially unfavorable for DBD because of possible enhanced crustal-scale permeability and non-crystalline rock types in the Precambrian basement.

Vertical and horizontal groundwater hydraulic gradients in the deep subsurface are generally related to regional variations in topographic elevation. Topographically driven groundwater flow can extend to great depths and long distances under some hydrogeological conditions, leading to overpressured conditions and the potential for upward flow in regional discharge areas. Proximity to significant variations in topographic elevation (i.e., slope) is a generally unfavorable condition for DBD and for the deep borehole demonstration project, although deep groundwater can be isolated and stagnant in some hydrogeologic settings, in spite of topographic effects.

High geothermal heat flow is related to the potential for deep geothermal energy development and possible human intrusion by drilling into the crystalline basement. High geothermal heat flow may also be related to the potential for overpressured conditions at depth and upward hydraulic gradients. Because of these factors areas with high geothermal heat flow are considered generally unfavorable for the DBD demonstration project.

The potential for human intrusion at a site would be unfavorable for DBD and waste isolation. Exploration for petroleum resources would be limited to sedimentary rocks overlying the crystalline basement, with the potential exception of locations where Precambrian rocks have been thrust over the sedimentary section. Extensive development of petroleum resources in sedimentary rocks overlying the crystalline basement might impact the release of radionuclides from DBD in some scenarios. Mineral resources at the depths of DBD in the crystalline basement are generally beyond the reach of current mineral exploration activities; however, exceptional cases of such resources potentially could be economically exploited at depths of several thousand meters. Information on the potential for mineral resources that would be useful in the DBD demonstration project site selection generally does not exist. Surface-based geophysical methods might provide indications of potential mineral resources in some cases, but are unlikely to do so.

High seismic hazard would present somewhat higher risks during drilling and waste emplacement operations; however, these risks could be mitigated through engineering solutions. Seismic hazard is a very general indicator of tectonic activity, risk of borehole shearing by fault movement, and geological structural complexity. Additionally, because emplaced waste packages are highly confined by the borehole walls, they would not be expected to be subject to displacement and damage during seismic events. Faulting and potential for volcanism can be assessed from surface geological mapping.

Evaluation of many of these factors can be accomplished on a preliminary, regional basis with existing data. An accurate compilation of relevant data can be made using a geographical information system (GIS) database, and such activities are underway as part of the UFD Campaign efforts in assessing regional geology for alternative disposal system concepts.

8.2.2 Technical Guidelines Related to the Engineering Thrust

The DBD demonstration borehole should be located in an area where the geology and drilling environment are well known. The geology will influence the casing and drilling programs. Past drilling experience will assist in identifying drilling issues that are the sources of uncertainty and cost. To reduce operational cost, the proximity to drilling equipment and supplies will be a consideration for site selection. Previous drilling history for an area will allow definition of casing points, identification of potential drilling problem zones, evaluation of potential overpressures, and occurrences of hydrocarbons.

It is anticipated that additional geophysical surveys may be required prior to selecting a location for the DBD demonstration project. Seismic reflection can be used to determine the stratigraphy and in particular the depth to crystalline basement. It should also be used to verify the absence of faults. The sedimentary cover should be relatively flat to aid in keeping the borehole vertical. Seismic monitoring should be conducted prior to drilling to provide a baseline and verify the absence of seismic activity. From an operational standpoint, an area with a moderate climate should be selected. From a postclosure safety standpoint this is not a significant consideration.

On deep scientific drilling projects, pilot holes are often drilled to evaluate the geologic environment and drilling conditions in advance of a more expensive large diameter hole. The technology is available to continuously core the isolation zone (Nielson 2001). This type of drilling provides continuous samples that can be subjected to petrologic and physical property determinations. These boreholes can also be instrumented for long term monitoring of temperature and fluids.

8.3 Stakeholder Outreach

Experience indicates that project success is strongly influenced by stakeholder participation. This section of the report identifies and evaluates the appropriate involvement of all the stakeholder groups during the development of the project. In addition, it is expected that the process of construction and post-construction phases of the project will have a significant stakeholder/public access component. Much of the stakeholder outreach implementation will be covered by the Communication Management Plan covered in the Business Management section of this plan.

The general strategy for siting the DBD demonstration project is a staged and adaptive approach. The strategy also seeks to obtain input from multiple interested parties, with the ultimate goal of achieving support from key stakeholders. A process similar to that used in selecting sites for deep scientific drilling projects would be employed.

The first step in the siting process for the demonstration project would be regional evaluations of relevant guidelines, as described in Section 8.2. From these evaluations several candidate regional or sub-regional areas could be identified for further consideration. Communication with potentially interested stakeholders in the area of scientific investigations, such as regional universities and state geological surveys would be initiated to assess receptiveness to participating in the DBD demonstration project. In addition, opinions on siting from the much broader international deep scientific drilling community would be sought. Engagement with regional drilling and services companies would be used to alert private industry to the nature of a demonstration project and to gather information on the local availability of such resources. Outreach to state and local political entities would be initiated in favorable regional or sub-regional areas, ideally with the support of scientific investigations and business stakeholders. Such outreach would seek to communicate the nature, scope, and benefits of the DBD demonstration project, including uses of the facility after completion of the demonstration, and to solicit feedback on the political and social viability of the project in a given area.

9. BUSINESS MANAGEMENT

A sound business management plan (Project Management Plan/Project Execution Plan) will be prepared for this project. The Plan will be an evolving document that describes the key elements of our business planning, outlining the processes, skills, tools and techniques we will implement to ensure the success of this project. We anticipate that after the DOE formally declares the activity a "project," under the requirements of DOE O 413, "Program and Project Management for the Acquisition of Capital Assets," a Project Execution Plan will be prepared.

9.1 Project Team and Organizational Structure

The project team will comprise various organizations from National Laboratories, industry and academia. International collaborations will also be important. Under the authority of the Department of Energy, Sandia National Laboratories will be the lead organization and it will be supported by individuals from other organizations that have people with the needed skills for the particular activity to be managed and/or performed. Appropriate people will be identified and roles and responsibilities will be clearly assigned to ensure successful completion of the project.

The organizational structure of the DBD Project Team will reflect the three major functional components of the demonstration project: (1) drilling and construction, (2) scientific investigations, and (3) engineering demonstration. These components will be well integrated and frequent interactions will be held to manage and resolve potential conflicts among these groups during the demonstration project. A formalized structure and process will be established for communication, coordination and prioritization of activities among these components.

9.2 Project Execution and Management Plan

When appropriate, in accordance with DOE O 413, a Project Execution/Project Management Plan will be prepared to document the actions and processes necessary to define, prepare, integrate, and coordinate all project activities and plans. The plan will define how the project is executed, monitored and controlled, and completed. The project team will direct the performance of the planned project activities, and manage the various technical and organizational interfaces that exist within the project. It will include the coordination of all elements of drilling, logging, testing, and engineering involved in the project.

9.3 Work Breakdown Structure

As shown in Appendix D, a high-level, work breakdown structure (WBS) has been prepared to subdivide the project deliverables and project work into smaller, more manageable components. As greater detail is established for the project, the WBS will be modified to add additional levels of detail. All the planned work will be contained within the WBS components, and the lowest level of the WBS will be designated as work packages and encompass and define the total scope of work for the project.

9.4 Cost Management

The Project Cost Management will be included in the Project Execution Plan and it will be refined as the project evolves. When the project is fully defined the total project cost will be the aggregation of the estimated costs of individual activities or work packages and this estimate will establish an authorized cost baseline or budget. The project cost will be monitored at the work package level through-out the project life and required changes will be managed to control the cost baseline. The preliminary cost estimate for this project is $75M, as shown in Appendix E. This estimate will be refined as more project details are known.

9.5 Project Schedule

The project schedule is presented in Appendix F. This schedule assumes an October 1, 2012 start and will be modified, as appropriate, when DOE funding profile and authorization is received. As the project evolves greater detail will be added with specific planned start and finish dates for all project activities (the lowest level of the WBS) and milestones. An approved project schedule will serve as a baseline to track progress and it will be maintained through-out the project as work progresses.

9.6 Communications Management

A Communication Management Plan will be prepared, in conjunction with the Project Execution Plan and Site Selection, to include the processes required for ensuring timely and appropriate generation, collection, distribution, storage, retrieval, and ultimate disposition of project information. Effective communication will create a bridge between diverse stakeholders involved in the project, connecting various cultural and organizational backgrounds, different levels of expertise, and various perspectives and interests in the project execution or outcome.

9.7 Project Risk Assessment

Drilling has some risk largely because of unknown conditions in the subsurface. Drilling plans deal with risk by applying contingency factors to different budget components. Risk is also mitigated by employing experienced personnel and assuring that the best expertise is present during critical activities in the borehole construction process.

As part of the Project Execution Plan, the project team will include a risk management section, which will include the processes of conducting risk management planning, identification, analysis, response planning, monitoring and control. The objectives of Project Risk Management will be to increase the probability and impact of positive events, and decrease the probability and impact of negative events in the project.

9.8 Quality Assurance

Work performed under this Plan is subject to the quality assurance (QA) and quality control (QC) programs and requirements of DOE Orders. The demonstration project for DBD will generate a considerable amount of data and probably a large volume of samples. The technical and scientific conclusions of the project will be based on this information. Appropriate quality assurance procedures for analysis and documentation are essential and will be followed. In addition, protocols for collection and storage of data and samples must be established before the project gets underway. An important part of a QA/QC program also concerns the drilling equipment and supplies that are used on the project. Specifications should be carefully set during the planning and procurement process. An inspection program must insure that the supplies and components received achieve the required standards.

10. LONG-TERM USE AND MAINTENANCE

The details of long-term use and maintenance of the facility will be evaluated as the project is sited and developed. Since the demonstration will result in a significant investment and will result in a potentially valuable facility, it is important to consider potential long-term uses of the facility. The potential for long term use depends on a number of factors, especially the end state of the facility at the conclusion of the demonstration:

- If seals testing must be demonstrated in the deep borehole, this will involve emplacement of materials and sealing of at least a portion of the borehole. If and how this is done may compromise the most potentially useful and valuable asset of the demonstration: the deep borehole itself.
- The condition of the surface including the deposition of the drill cuttings will require restoration, which must be identified along with how that restoration can contribute to end use.
- The end state of the surface and subsurface components of the various characterization techniques requiring testing during the demonstration needs to be described. These are potentially valuable assets contributing to the usefulness of the facility after demonstration.
- The fate of the drilling rig and specialized waste canister emplacement rig (if needed) will need to be decided upon and may contribute to the long-term usefulness of the facility.
- The surface support facilities including utility services also contributes to long-term use and consideration of how these can be adapted to support long-term use will be required.

There are a number of possibilities with respect to long-term facility use. Because of multiple uncertainties (e.g., end-state uncertainties, political and regulatory at this time, etc.), it is prudent to evaluate a suite of options during the demonstration process rather than focus on a single expected path forward for future use. Possible use options after the demonstration will be identified, evaluated, and included in the planning process.

The likely spectrum of options will be bound by (1) closure, restoration, and walk away option and (2) long-term use as a RD&D “underground” laboratory for geosciences, hydrology, and other sciences.

11. SUMMARY

A successful DBD demonstration project will increase the disposal options available to the United States. Deep Borehole Disposal of HLW and SNF is a potentially robust disposal option which offers cost-effective disposal and other advantages over repository disposal but still remains unconfirmed, unlike disposal in geologic repositories. This roadmap establishes the technical and programmatic basis for fielding a full-scale DBD project. The roadmap includes identification of science and engineering needs and gaps, use of risk informed methods, regulatory and legal considerations for establishing the demonstration, site selection for the demonstration, deep borehole construction, demonstration of surrogate waste emplacement operations, , costs, schedule, and the necessary business management functions.

The science and engineering needs and gaps associated with the DBD project are discussed and a risk informed approach is developed that will be used to prioritize those needs and gaps during the early phase of the demonstration. A comprehensive RD&D effort over 5 years and a lifetime cost of $75 million will be required to achieve the four goals of the DBD project:

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,
4) Demonstrate safety and practicality of licensing.

A top-down systems approach will be taken to identify, evaluate, and prioritize the science and engineering needs during the initial phase of the demonstration project. This systems approach will utilize Sandia National Laboratories" PA methodology beginning with an analysis of FEPs. In this approach both qualitative and quantitative information is used to provide risk-information primarily from existing FEPs analyses, system and subsystem sensitivity analyses, and preclosure and postclosure safety assessments. Given the goals and objectives of the demonstration, the approach will be conducted in the following steps:

1) Identify the relevant Features, Events, and Process associated with Deep Borehole Disposal (Section 3.1 and Tables A-1 and A-2, Appendix A)
2) Using FEPs as a guide, identify potential science and engineering activities potentially needed for the demonstration (Section 5.2.2 and Table B-1, Appendix B)
3) Identify evaluation metrics (Section 5.3.1)
4) Evaluate the science and engineering activities for demonstration in the context of the established metrics. (Section 5.3.2)
5) Determine objective functions and associated weighing factors and tally combined ranking (Section 5.3.3)

Although not formally prioritized, a number of Engineering activities are particularly important to the success of the DBD project, particularly those activities that support the drilling of a sufficiently straight and smooth borehole and the design and emplacement of surrogate waste packages. While the DBD project is not a drilling research project, the drilling of the borehole would be a significant challenge and just outside the envelope of past experience. Borehole logging activities and directional control (Section 4.2) as well as casing design and emplacement (Section 4.3) promote the successful drilling program. Seal system design using risk information and its implementation (Section 4.8) are crucial to the isolation of disposed materials. Finally waste package design, testing, and emplacement are important operational needs requiring demonstration under the unique conditions characteristic of Deep Borehole Disposal (Section 4.4).

A technical evaluation of existing and available boreholes within the US will be conducted in an early phase of the demonstration to further study the issues related to DBD. This evaluation will examine lessons learned about deep drilling, mechanical and geologic media issues, and hydrologic and gaseous transport issues that would arise in the field for the DBD concept. This evaluation will provide both statistical and geologic media specific information for guiding the DBD demonstration project, if implemented. Identification of important factors determined to be important for successful implementation of a DBD demonstration will continually be updated with the acquisition of data from existing deep boreholes configurations and operations, and a GIS database. This activity will leverage and be integrated with UFD Campaign efforts, e.g., assessing regional geology for alternative disposal system concepts.

Finally, it is anticipated that the DBD project will provide input to nuclear waste disposal regulators and policymakers. Implementation of DBD will require new regulations and the form of these regulations could be informed by the RD&D roadmap by providing the technical rationale for engineering design and scientific investigations. In addition, the list of activities and the cost estimates in this report provide policymakers with information on the resource commitments and budget necessary to field the DBD demonstration project.

12. REFERENCES

American Petroleum Institute (API). 1990. *Specification for Materials and Testing for Well Cements*. API Spec 10, 5th edition. July 1, 1990. Dallas, Texas.

Anderson, V. K. 2004. *An Evaluation of the Feasibility of Disposal of Nuclear Waste in Very Deep Boreholes*. Dept. of Nuclear Engineering. Cambridge, MA: Massachusetts Institute of Technology (MIT).

Arnold, B.W., P.V. Brady, S.J. Bauer, C. Herrick, S. Pye, and J. Finger. 2011. *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste.* SAND2011-6749. Albuquerque, NM: Sandia National Laboratories.

Bates, E.A., M.J. Driscoll, and J. Buongiorno. 2011. Drop-in concept for deep borehole canister emplacement. *Proceedings of the 13th International High Level Radioactive Waste Management Conference*, *Albuquerque, New Mexico (April 10-14, 2011).* La Grange Park, IL: American Nuclear Society.

Baumgartner, J., T. Gandy, T. Hettkamp, and D. Teza. 2007. Drilling of hot and fractured granite at Soultz-sous-Forêts. *ENGINE Mid-Term Conference (January 9-12, 2007).* Potsdam: GFZ.

Beardsmore, G. 2007. The burgeoning Australian geothermal energy industry. *Geo-Heat Centre Quarterly Bulletin* **28.** Klamath Falls, OR: Oregon Institute of Technology.

Bechtel SAIC Company (BSC). 2005. *The Development of the Total System Performance Assessment-License Application Features, Events, and Processes*. TDR-WIS-MD-000003 REV 02, ACC: DOC.20050829.0004. Las Vegas, NV: Bechtel SAIC Company.

Beswick, J. 2008. *Status of Technology for Deep Borehole Disposal*. Contract No. NP 01185. EPS International.

Blue Ribbon Commission on America‟s Nuclear Future (BRC). 2012. *Report to the Secretary of Energy.* U.S. Department of Energy.

Bonano, E.J., D. Kessel, M. Marietta, P. Swift, and L. Dotson. 2010. *Performance Assessment for Radioactive Waste Management at Sandia National Laboratories: A 30-year History.* SAND2010-0807C. Albuquerque, NM: Sandia National Laboratories.

Brady, P.V., B.W. Arnold, G.A Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, and J.S. Stein. 2009. *Deep Borehole Disposal of High-Level Radioactive Waste.* SAND 2009-4401. Albuquerque, NM: Sandia National Laboratories.

Chapman, N. and F.G.F. Gibb. 2003. A truly final waste management solution – Is very deep borehole disposal a realistic option for HLW or fissile material? *Radwaste Solutions* July/August, p. 26-35.

Chen, J.-S., C.-W. Liu, Y.-C. Chan, C.-F. Ni, and K.-K. Kao. 2011. Effect of transverse dispersion on solute transport in a vertical dipole flow test with a tracer. *J. of Hydrology* **402** (3-4):206-216.

Clayton, D., G. Freeze, T. Hadgu, E. Hardin, J. Lee, J. Prouty, R. Rogers W. M. Nutt, J. Birkholzer, H.H. Liu, L. Zheng, and S. Chu. 2011. *Generic Disposal System Modeling Fiscal Year 2011 Progress Report*. SAND2011-5828P, FCRD-USED-2011-00018. U.S. Department of Energy, Used Fuel Disposition R&D Campaign.

Duchane, D., and D. Brown, 2002. Hot dry rock (HDR) geothermal energy research and development at Fenton Hill, New Mexico. *Geo-Heat Centre Quarterly Bulletin* **23.** Klamath Falls, OR: Oregon Institute of Technology.

Ferguson, K.L. 1994. *Excess Plutonium Disposition: The Deep Borehole Option (U)*. WSRC-TR-94-0266. Aiken, SC: Westinghouse Savannah River Company.

Freeze, G., P. Mariner, J.A. Blink, F.A. Caporuscio, J.E. Houseworth, and J.C. Cunnane. 2011. *Disposal System Features, Events, and Processes (FEPs) Progress Report.* SAND2011-6059P. Albuquerque, NM: Sandia National Laboratories.

Freeze, G., P. Mariner, J.E. Houseworth, and J.C. Cunnane. 2010. *Used Fuel Disposition Campaign Features, Events, and Processes (FEPs): FY10 Progress Report*. SAND2010-5902. Albuquerque, NM: Sandia National Laboratories.

Freifeld, B., C. Doughty, and S. Finsterle. 2006. *Preliminary Estimates of Specific Discharge and Transport Velocities near Borehole NC-EWDP-24PB.* Lawrence Berkeley National Laboratory.

Freifeld, B, and S. Finsterle. 2010. *Imaging Fluid Flow in Geothermal Wells Using Distributed Thermal Perturbation Sensing*. Lawrence Berkeley National Laboratory.

Gibb, F.G.F. 1999. High-temperature, very deep, geological disposal: a safer alternative for high-level radioactive waste? *Waste Management* **19,** 207-211.

Gibb, F.G.F., and P.G. Atrill. 2003. Granite recrystallisation: The key to the nuclear waste problem? *Geology* **31**, 657 – 660.

Gibb, F.G.F., N.A. McTaggart, K.P. Travis, D. Burley, and K.W. Hesketh. 2008a. High-density support matrices: Key to the deep borehole disposal of spent nuclear fuel, *J. of Nuclear Materials* **374,** 370-377.

Gibb, F.G.F., K.J. Taylor, and B.E. Burakov. 2008b. The „granite encapsulation" route to the safe disposal of Pu and other actinides. *J. of Nuclear Materials* **374,** 364-369.

Gibbs, J.S. 2010. *Feasibility of Lateral Emplacement in Very Deep Borehole Disposal of High Level Nuclear Waste*. Cambridge, MA: MIT Dept. of Nuclear Engineering.

Guven,O., R.W. Falta, F.J. Molz, and J.G. Melvillei. 1985. Analysis and interpretation of single-well tracer tests in stratified aquifers. *Water Resources Research* **21,** 676-684.

Haggerty, R., S.W. Fleming, L.C. Meigs, and S.A. McKenna. 2001. Tracer tests in a fractured dolomite. 2. Analysis of mass transfer in single-well injection-withdrawal tests. *Water Resources Research* **37,** 1129-1142.

Hansen, F.D., and C.D. Leigh. 2011. *Salt Disposal of Heat-Generating Nuclear Waste.* SAND2011-0161. Albuquerque, NM: Sandia National Laboratories.

Harrison, T. 2000. *Very Deep Borehole – Deutag's Opinion on Boring, Canister Emplacement and Retreivability.* SKB Report R-00-35. Svensk Karnbranslehantering AB.

Herrick, C., B. Arnold, T. Hadgu, R. Finley, P. Vaughn, and P. Brady. 2011. *Deep Borehole Seals*. Albuquerque, NM: Sandia National Laboratories.

Hoag, C.I. 2006. *Canister Design for Deep Borehole Disposal of Nuclear Waste*. Cambridge, MA: MIT Dept. of Nuclear Engineering.

Holmgeirsson, S., A. Gudmundsson, B. Palsson, H.A. Boasson, K. Ingasson, S. Thorhallsson. 2010. Drilling operations of the first Iceland deep drilling well (IDDP). *Proceedings of the World Geothermal Congress 2010*.

Ikeuchi, K., R. Komatsu, N. Doi, Y. Sakagawa, M. Sasaki, H. Kamenenosono, and T. Uchida. 1996. Bottom of hydrothermal convection found by temperature measurements above 500^{o} C and fluid inclusion study of WD-1 in Kakkonda geothermal field, Japan. *Geothermal Resources Council Transactions* **20,** 609-616.

Juhlin, C., and H. Sandstedt. 1989. *Storage of Nuclear Waste in Very Deep Boreholes: Feasibility Study and Assessment of Economic Potential. Part I: Geological Considerations. Part II: Overall Facility Plan and Cost Analysis*. Svensk Karnbranslehantering AB.

Keeney, R.L., and R.S. Gregory. 2005. Selecting attributes to measure the achievement of objectives. *Oper. Res.* **53**(1):1-11.

Keeney R.L., and H. Raiffa. 1993. *Decisions with Multiple Objectives*. 2nd Edition. New York: Cambridge University Press.

Lawrence Livermore National Laboratory (LLNL). 1996. *Fissile Material Disposition Program – Deep Borehole Disposal Facility PEIS Data Input Report for Direct Disposal*, Version 3.0. UCRL-LR-119481. Lawrence Livermore National Laboratory. Livermore, CA: University of California.

Leap, D.I., and P.G. Kaplan. 1988. A single-well tracing method for estimating regional advective velocity in a confined aquifer: Theory and preliminary laboratory verification. *Water Resources Research* **24**, 993-998.

Los Alamos National Laboratory (LANL). 1986. *Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu and ^{233}U.* LA-10860-MS, p. 39. Los Alamos, NM: Los Alamos National Laboratory.

Meigs, L.C., and R.L. Beauheim. 2001. Tracer tests in a fractured dolomite. 1. Experimental design and observed tracer recoveries. *Water Resources Research* **37,** 1113-1128.

Mottaghy, D., R. Schellschmidt, Y.A. Popov, C. Clauser, I.T. Kukkonen, G. Nover, S. Milanovsky, R.A. Romushkevich. 2005. New heat flow data from the immediate vicinity of the Kola superdeep borehole: Vertical variation in heat flow confirmed and attributed to advection. *Tectonophysics* **401**(1-2):119-142.

Moulton, T.A. 2008. *Parametric Study of the Total System Life Cycle Cost of an Alternate Nuclear Waste Management Strategy Using Deep Boreholes*. Cambridge, MA: MIT Dept. of Nuclear Engineering.

National Academy of Sciences (NAS). 1957. *The Disposal of Radioactive Waste on Land*. http://www.nap.edu/openbook.php?record_id=10294

Neretnieks, I. 2007. *Single well injection withdrawal tests (SWIW) in fractured rock - Some aspects on interpretation*. SKB R-07-54. Stockholm, Sweden: SvenskKärnbränslehantering AB.

Nirex. 2004. *A Review of the Deep Borehole Disposal Concept.* Report N/108. United Kingdom Nirex Limited.

Ojakangas, R.W., G.B. Morey, J.C. Green. 2001. The Mesoproterozoic Midcontinent Rift System, Lake Superior Region, U.S.A. *Sedimentary Geology* **141-142,** 421-442.

Patrick, W.C. 1986. *Spent Fuel Test – Climax: An Evaluation of the Technical Feasibility of Geologic Storage of Spent Nuclear Fuel in Granite – Final Report*. UCRL-53702. Livermore, CA: Lawrence Livermore National Laboratory.

Reimus, P.W., and T.J. Callahan. 2007. Matrix diffusion rates in fractured volcanic rocks at the Nevada Test Site: Evidence for a dominant influence of effective fracture apertures. *Water Resources Research* **43**, W07421, doi:10.1029/2006WR005746.

Roos, G.N. 2009. *Development of the Dipole Flow and Reactive Tracer Test (DFRTT) for Aquifer Parameter Estimation*. M.S. Thesis. Waterloo, Canada: University of Waterloo.

Sanford, W.E., P.G. Cook, and J.C. Dighton. 2002. Analysis of a vertical dipole tracer test in highly fractured rock. *Ground Water* **40**(5):535-542.

Selker, J.S., L. The´venaz, H. Huwald, A. Mallet, W. Luxemburg, N. van de Giesen, M. Stejskal, J. Zeman, M. Westhoff, and M.B. Parlange. 2006. Distributed fiber-optic temperature sensing for hydrologic systems. *Water Resources Research* **42**, W12202, doi:10.1029/2006WR005326.

Sizer, C.G. 2006. *Minor Actinide Waste Disposal in Deep Geological Boreholes*. Cambridge, MA: MIT Dept. of Nuclear Engineering.

Smith, D.K. 1989. *Cementing*. SPE Monograph Series, Volume 4. Richardson, Texas: Society of Petroleum Engineers.

Swedish Nuclear Fuel and Waste Management Co. (SKB). 2011. *Long-term safety for the final repository for spent nuclear fuel at Forsmark; Main report of the SR-Site project.* Swedish Nuclear Fuel and Waste Management Co. Technical Report TR-11-01, Volumes I, II and III (March 2011).

U.S. Department of Energy (U.S. DOE). 1997. *Integrated Database Report*. DOE-IDB97. Washington, DC.

U.S. Department of Energy (U.S. DOE). 2011. *Used Fuel Disposition Campaign Disposal Research and Development Roadmap.* FCR&D-USED-2011-000065. U.S. Department of Energy Used Fuel Disposition.

Vaughn, P., B.W. Arnold, S.J. Altman, P.V. Brady, and W.P. Gardner. 2012a. *Site Characterization Methodology Report*. In preparation, Albuquerque, New Mexico: Sandia National Laboratories.

Vaughn, P., M. Voegele, W.M. Nutt, G. Freeze, J. Prouty, E. Hardin, D. Sevougian, and R. Weiner. 2012b. *Draft Generic Deep Geologic Disposal Safety Case*. FCRD-UFD-2012-000146. Sandia National Laboratories.

Woodward - Clyde Consultants. 1983. *Very Deep Hole Systems Engineering Studies*. Columbus, OH: ONWI.

Appendix A. FEPS and Science Thrust Information Needs and Characterization Methods

Table A-1. Comprehensive FEPs List with likely Screening Decision, Effort to support Decision, and Supporting Characterization Needs. (Based on YMP Features, Events, and Processes List and Screening Decisions Listed by FEP Number: Sandia National Laboratories 2008, Table 7.1.).

Note: Highlighted entry indicates key FEP for Deep Borehole Disposal (Brady et al., 2009)

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
0.1.02.00.0A	Timescales of Concern	Included	Include	1	Address with other information
0.1.03.00.0A	Spatial Domain of Concern	Included	Include	1	Address with other information
0.1.09.00.0A	Regulatory Requirements and Exclusions	Included	Include	3 Regulations and laws will need to be revised	Address with other information
0.1.10.00.0A	Model and Data Issues	Included	Include	1	Address with other information
1.1.01.01.0A	Open Site Investigation Boreholes	Excluded	Exclude	1	N/A
1.1.01.01.0B	Influx Through Holes Drilled in Drift Wall or Crown	Excluded	Exclude	1	N/A
1.1.02.00.0A	Chemical Effects of Excavation and Construction in EBS	Excluded	Exclude	2	Address with other information
1.1.02.00.0B	Mechanical Effects of Excavation and Construction in EBS	Excluded	Exclude	2	Borehole caliper log, fluid pressure drawdown test of effective permeability of seals
1.1.02.01.0A	Site Flooding (During Construction and Operation)	Excluded	Exclude	1	Address with existing data and engineering mitigation
1.1.02.02.0A	Preclosure Ventilation	Included	Exclude (NA)	1	N/A
1.1.02.03.0A	Undesirable Materials Left	Excluded	Exclude	2	Address with other information
1.1.03.01.0A	Error in Waste Emplacement	Excluded	Exclude	3 Need to consider the emplacement that may get stuck halfway down. Also need to consider canisters that are crushed by overlying canisters	Address with other information
1.1.03.01.0B	Error in Backfill Emplacement	Excluded	Include	1 May be difficult to ensure that backfill is emplaced uniformly, may be simplest to include FEP and take no credit for backfill1	Address with engineering demonstration
1.1.04.01.0A	Incomplete Closure	Excluded	Exclude	2	Address with engineering demonstration
1.1.05.00.0A	Records and Markers for the Repository	Excluded	Exclude)	1	Address with other information regulatory

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
1.1.07.00.0A	Repository Design	Included	Include	1	Address with other information
1.1.08.00.0A	Inadequate Quality Control and Deviations from Design	Excluded	Exclude	1	Address with other information regulatory or low consequence
1.1.09.00.0A	*Schedule and Planning*	*Excluded*	*Exclude*	*1*	Address with other information
1.1.10.00.0A	*Administrative Control of the Repository Site*	*Excluded*	*Exclude*	*1*	Address with other information
1.1.11.00.0A	*Monitoring of the Repository*	*Excluded*	*Exclude*	*1*	Address with other information
1.1.12.01.0A	*Accidents and Unplanned Events During Construction and Operation*	*Excluded*	*Exclude*	*1*	Address with other information
1.1.13.00.0A	*Retrievability*	*Included*	*Exclude*	*2*	Address with engineering demonstration
1.2.01.01.0A	*Tectonic Activity - Large Scale*	*Excluded*	*Exclude*	*1*	Address with existing data
1.2.02.01.0A	*Fractures*	*Included*	*Include*	*2*	Formation micro imager log, temperature log,
1.2.02.02.0A	*Faults*	*Included*	*Include*	*2*	3-D seismic imaging, surface geological mapping, formation micro imager log, Electrical Resistivity (Surface Based – Large Scale)
1.2.02.03.0A	*Fault Displacement Damages EBS Components*	*Included*	*Include?*	*2* *Note—if no credit is taken for WP and WF components, all EBS FEPs are simplified to the consideration of the borehole seals*	3-D seismic imaging, surface geological mapping, formation micro imager log, Electrical Resistivity (Surface Based – Large Scale)
1.2.03.02.0A	*Seismic Ground Motion Damages EBS Components*	*Included*	*Exclude*	*2*	Address with other information
1.2.03.02.0B	*Seismic-Induced Rockfall Damages EBS Components*	*Excluded*	*Exclude*	*1*	N/A
1.2.03.02.0C	*Seismic-Induced Drift Collapse Damages EBS Components*	*Included*	*Exclude*	*1*	N/A
1.2.03.02.0D	*Seismic-Induced Drift Collapse Alters In-Drift Thermohydrology*	*Included*	*Exclude*	*1*	N/A
1.2.03.02.0E	*Seismic-Induced Drift Collapse Alters In-Drift Chemistry*	*Excluded*	*Exclude*	*1*	N/A
1.2.03.03.0A	*Seismicity Associated With Igneous Activity*	*Included*	*Exclude*	*1*	Address with other information
1.2.04.02.0A	*Igneous Activity Changes Rock Properties*	*Excluded*	*Exclude*	*2* *Need to evaluate potential for igneous activity at each site (should generically be low), also need to determine if repository*	Address with other information

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
				heat can contribute to rock melting	
1.2.04.03.0A	*Igneous Intrusion Into Repository*	*Included*	*Exclude*	*2*	Address with other information
1.2.04.04.0A	*Igneous Intrusion Interacts With EBS Components*	*Included*	*Exclude*	*2*	Address with other information
1.2.04.04.0B	*Chemical Effects of Magma and Magmatic Volatiles*	*Included*	*Exclude*	*2* *Volatiles may impact transport*	Address with other information
1.2.04.05.0A	*Magma or Pyroclastic Base Surge Transports Waste*	*Excluded*	*Exclude*	*1*	Address with other information
1.2.04.06.0A	*Eruptive Conduit to Surface Intersects Repository*	*Included*	*Exclude*	*2*	Address with other information
1.2.04.07.0A	*Ashfall*	*Included*	*Exclude*	*1*	Address with other information A
1.2.04.07.0B	*Ash Redistribution in Groundwater*	*Excluded*	*Exclude*	*1*	Address with other information
1.2.04.07.0C	*Ash Redistribution Via Soil and Sediment Transport*	*Included*	*Exclude*	*1*	Address with other information
1.2.05.00.0A	*Metamorphism*	*Excluded*	*Exclude*	*2* *Repository heat may create metamorphic conditions*	Address with other information
1.2.06.00.0A	*Hydrothermal Activity*	*Excluded*	*Exclude*	*3* *Repository heat may create local hydrothermal activity*	Address with other information
1.2.07.01.0A	*Erosion/Denudation*	*Excluded*	*Exclude*	*1*	Address with other information
1.2.07.02.0A	*Deposition*	*Excluded*	*Exclude*	*1*	Address with other information
1.2.08.00.0A	*Diagenesis*	*Excluded*	*Exclude*	*2*	Address with other information
1.2.09.00.0A	*Salt Diapirism and Dissolution*	*Excluded*	*Exclude*	*1*	Address with other information
1.2.09.01.0A	*Diapirism*	*Excluded*	*Exclude*	*2* *Need to demonstrate that repository heat will not generate local diapirism*	Address with other information
1.2.09.02.0A	*Large-Scale Dissolution*	*Excluded*	*Exclude*	*1*	Address with other information
1.2.10.01.0A	*Hydrologic Response to Seismic Activity*	*Excluded*	*Exclude*	*1*	Address with other information
1.2.10.02.0A	*Hydrologic Response to Igneous Activity*	*Excluded*	*Exclude*	*2*	Address with other information
1.3.01.00.0A	*Climate Change*	*Included*	*Exclude*	*1*	Address with other information
1.3.04.00.0A	*Periglacial Effects*	*Excluded*	*Exclude*	*1*	Address with existing data, groundwater chemistry and isotopic composition in fluid samples from packer testing
1.3.05.00.0A	*Glacial and Ice Sheet Effect*	*Excluded*	*Exclude*	*2* *Need to consider fluid pressure effects of future*	Address with existing data, groundwater chemistry and isotopic composition in fluid

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
				ice sheet loading	samples from packer testing
1.3.07.01.0A	*Water Table Decline*	*Excluded*	*Exclude*	*1*	Address with other information
1.3.07.02.0A	*Water Table Rise Affects SZ*	*Included*	*Exclude*	*1*	Address with other information
1.3.07.02.0B	*Water Table Rise Affects UZ*	*Included*	*Exclude*	*1* *All UZ FEPs are simplified*	Address with other information
1.4.01.00.0A	*Human Influences on Climate*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.01.01.0A	*Climate Modification Increases Recharge*	*Included*	*Exclude*	*1*	Address with other information
1.4.01.02.0A	*Greenhouse Gas Effects*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.01.03.0A	*Acid Rain*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.01.04.0A	*Ozone Layer Failure*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.02.01.0A	*Deliberate Human Intrusion*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.02.02.0A	*Inadvertent Human Intrusion*	*Included*	*Exclude*	*1 (requires regulatory change)*	Mineral composition of core and cuttings samples, gamma ray log, surface magnetic surveys to exclude ore deposits; temperature log to exclude geothermal resources; 3D seismic imaging to exclude overthrusting above sedimentary rocks to exclude drilling for petroleum resources; Electrical Resistivity (Surface Based – Large Scale)
1.4.02.03.0A	*Igneous Event Precedes Human Intrusion*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.02.04.0A	*Seismic Event Precedes Human Intrusion*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.03.00.0A	*Unintrusive Site Investigation*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.04.00.0A	*Drilling Activities (Human Intrusion)*	*Included*	*Exclude*	*1*	Mineral composition of core and cuttings samples, gamma ray log, surface magnetic surveys to exclude ore deposits; temperature log to exclude geothermal resources; 3D seismic imaging to exclude overthrusting above sedimentary rocks to exclude drilling for petroleum resources; Electrical Resistivity (Surface Based – Large Scale)
1.4.04.01.0A	*Effects of Drilling Intrusion*	*Included*	*Exclude*	*1*	Address with other information

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
1.4.05.00.0A	*Mining and Other Underground Activities (Human Intrusion)*	*Excluded*	*Exclude*	*1* *Includes natural resource issues*	Mineral composition of core and cuttings samples, gamma ray log, surface magnetic surveys to exclude ore deposits; Electrical Resistivity (Surface Based – Large Scale)
1.4.06.01.0A	*Altered Soil Or Surface Water Chemistry*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.07.01.0A	*Water Management Activities*	*Included*	*Exclude*	*1*	Address with existing data for characterization of the reference biosphere
1.4.07.02.0A	*Wells*	*Included*	*Exclude*	*1*	Address with existing data for characterization of the reference biosphere
1.4.07.03.0A	*Recycling of Accumulated Radionuclides from Soils to Groundwater*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.08.00.0A	*Social and Institutional Developments*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.09.00.0A	*Technological Developments*	*Excluded*	*Exclude*	*1*	Address with other information
1.4.11.00.0A	*Explosions and Crashes (Human Activities)*	*Excluded*	*Exclude*	*1*	Address with other information
1.5.01.01.0A	*Meteorite Impact*	*Excluded*	*Exclude*	*1*	Address with other information
1.5.01.02.0A	*Extraterrestrial Events*	*Excluded*	*Exclude*	*1*	Address with other information
1.5.02.00.0A	*Species Evolution*	*Excluded*	*Exclude*	*1*	Address with other information
1.5.03.01.0A	*Changes in the Earth's Magnetic Field*	*Excluded*	*Exclude*	*1*	Address with other information
1.5.03.02.0A	*Earth Tides*	*Excluded*	*Exclude*	*1*	Address with other information
2.1.01.01.0A	*Waste Inventory*	*Included*	*Include*	*1*	Address with other information
2.1.01.02.0A	Interactions Between Co-Located Waste	Excluded	Exclude	1	Address with other information
2.1.01.02.0B	Interactions Between Co-Disposed Waste	Included	Exclude	1	N/A
2.1.01.03.0A	Heterogeneity of Waste Inventory	Included	Include	1	Address with other information
2.1.01.04.0A	Repository-Scale Spatial Heterogeneity of Emplaced Waste	Included	Include	1	Address with other information
2.1.02.01.0A	DSNF Degradation (Alteration, Dissolution, and Radionuclide Release)	Included	Exclude	1	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.02.02.0A	CSNF Degradation (Alteration, Dissolution, and Radionuclide Release)	Included	Exclude	1 Assume no credit for CSNF waste form	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.02.03.0A	HLW Glass Degradation	Included	Exclude	1	Address with other

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
	(Alteration, Dissolution, and Radionuclide Release)			Assume no credit for HLW waste form	information, groundwater chemistry in fluid samples from packer testing
2.1.02.04.0A	Alpha Recoil Enhances Dissolution	Excluded	Exclude	1	Address with other information
2.1.02.05.0A	HLW Glass Cracking	Included	Exclude	1	Address with other information
2.1.02.06.0A	HLW Glass Recrystallization	Excluded	Exclude	1	Address with other information
2.1.02.07.0A	Radionuclide Release from Gap and Grain Boundaries	Included	Exclude	1	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.02.08.0A	Pyrophoricity from DSNF	Excluded	Exclude	1	Address with other information
2.1.02.09.0A	Chemical Effects of Void Space in Waste Package	Included	Exclude	1	Address with other information
2.1.02.10.0A	Organic/Cellulosic Materials in Waste	Excluded	Exclude	1	Address with other information
2.1.02.11.0A	Degradation of Cladding from Waterlogged Rods	Excluded	Exclude	1	Address with other information
2.1.02.12.0A	Degradation of Cladding Prior to Disposal	Included	Exclude	1	Address with other information
2.1.02.13.0A	General Corrosion of Cladding	Excluded	Exclude	1	Address with other information
2.1.02.14.0A	Microbially Influenced Corrosion (MIC) of Cladding	Excluded	Exclude	1	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.02.15.0A	Localized (Radiolysis Enhanced) Corrosion of Cladding	Excluded	Exclude	1	Address with other information
2.1.02.16.0A	Localized (Pitting) Corrosion of Cladding	Excluded	Exclude	1	Address with other information
2.1.02.17.0A	Localized (Crevice) Corrosion of Cladding	Excluded	Exclude	1	Address with other information
2.1.02.18.0A	Enhanced Corrosion of Cladding from Dissolved Silica	Excluded	Exclude	1	Address with other information
2.1.02.19.0A	Creep Rupture of Cladding	Excluded	Exclude	1	Address with other information
2.1.02.20.0A	Internal Pressurization of Cladding	Excluded	Exclude	1	Address with other information
2.1.02.21.0A	Stress Corrosion Cracking (SCC) of Cladding	Excluded	Exclude	1	Address with other information
2.1.02.22.0A	Hydride Cracking of Cladding	Excluded	Exclude	1	Address with other information
2.1.02.23.0A	Cladding Unzipping	Included	Exclude	1	Address with other information
2.1.02.24.0A	Mechanical Impact on Cladding	Excluded	Exclude	1	Address with other information
2.1.02.25.0A	DSNF Cladding	Excluded	Exclude	1	Address with other information
2.1.02.25.0B	Naval SNF Cladding	Included	Exclude	1	N/A, Exclude Naval SNF from

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
					analysis completely
2.1.02.26.0A	Diffusion-Controlled Cavity Growth in Cladding	Excluded	Exclude	1	Address with other information
2.1.02.27.0A	Localized (Fluoride Enhanced) Corrosion of Cladding	Excluded	Exclude	1	Address with other information
2.1.02.28.0A	Grouping of DSNF Waste Types Into Categories	Included	Exclude	1	Address with other information
2.1.02.29.0A	Flammable Gas Generation from DSNF	Excluded	7Exclude	1	Address with other information
2.1.03.01.0A	General Corrosion of Waste Packages	Included	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.01.0B	General Corrosion of Drip Shields	Included	Exclude	1	N/A, no drip- shield
2.1.03.02.0A	Stress Corrosion Cracking (SCC) of Waste Packages	Included	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.02.0B	Stress Corrosion Cracking (SCC) of Drip Shields	Excluded	Exclude	1	N/A, no drip- shield
2.1.03.03.0A	Localized Corrosion of Waste Packages	Included	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.03.0B	Localized Corrosion of Drip Shields	Excluded	Exclude	1	N/A, no drip- shield
2.1.03.04.0A	Hydride Cracking of Waste Packages	Excluded	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.04.0B	Hydride Cracking of Drip Shields	Excluded	Exclude	1	N/A, no drip- shield
2.1.03.05.0A	Microbially Influenced Corrosion (MIC) of Waste Packages	Included	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.05.0B	Microbially Influenced Corrosion (MIC) of Drip Shields	Excluded	Exclude	1	N/A, no drip- shield
2.1.03.06.0A	Internal Corrosion of Waste Packages Prior to Breach	Excluded	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.07.0A	Mechanical Impact on Waste Package	Excluded	Exclude	1 This FEP includes all damage to WPs after emplacement	N/A, Assume no flow barrier credit for WP
2.1.03.07.0B	Mechanical Impact on Drip Shield	Excluded	Exclude	1	N/A, no drip- shield
2.1.03.08.0A	Early Failure of Waste Packages	Included	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.08.0B	Early Failure of Drip Shields	Included	Exclude	1	N/A, no drip- shield
2.1.03.09.0A	Copper Corrosion in EBS	Excluded	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.10.0A	Advection of Liquids and Solids Through Cracks in the Waste Package	Excluded	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.10.0B	Advection of Liquids and Solids Through Cracks in the Drip Shield	Excluded	Exclude (NA)	1	N/A, no drip- shield
2.1.03.11.0A	Physical Form of Waste Package and Drip Shield	Included	Include	1	Address with other information
2.1.04.01.0A	Flow in the Backfill	Excluded	Include	1	Address with other

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
				Include FEPs that degrade backfill by assuming no credit due to difficulty in ensuring full emplacement	information
2.1.04.02.0A	Chemical Properties and Evolution of Backfill	Excluded	Include	1	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.04.03.0A	Erosion or Dissolution of Backfill	Excluded	Include	1	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.04.04.0A	Thermal-Mechanical Effects of Backfill	Excluded	Include	1	Address with other information
2.1.04.05.0A	Thermal-Mechanical Properties and Evolution of Backfill	Excluded	Include	1	Address with other information
2.1.04.09.0A	Radionuclide Transport in Backfill	Excluded	Exclude	1 Exclude beneficial transport effects of backfill because of difficulty in ensuring full emplacement	Address with other information
2.1.05.01.0A	Flow Through Seals (Access Ramps and Ventilation Shafts)	Excluded	Include	3	Fluid pressure drawdown test of effective permeability of seals
2.1.05.02.0A	Radionuclide Transport Through Seals	Excluded	Include	3	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.05.03.0A	Degradation of Seals	Excluded	Include	3	Address with other information
2.1.06.01.0A	Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS	Excluded	Include (Seals are EBS, so one entire release pathway to RMEI is in EBS)	3	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.06.02.0A	Mechanical Effects of Rock Reinforcement Materials in EBS	Excluded	Exclude	3 What happens to borehole seal as casing degrades?	Address with other information, anisotropic shear wave velocity log
2.1.06.04.0A	Flow Through Rock Reinforcement Materials in EBS	Excluded	Exclude	1	Address with other information
2.1.06.05.0A	Mechanical Degradation of Emplacement Pallet	Excluded	Exclude	1	N/A, no pallet
2.1.06.05.0B	Mechanical Degradation of Invert	Excluded	Exclude	1	N/A, no invert
2.1.06.05.0C	Chemical Degradation of Emplacement Pallet	Included	Exclude)	1	N/A, no pallet
2.1.06.05.0D	Chemical Degradation of	Excluded	Exclude)	1	N/A, no invert

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
	Invert				
2.1.06.06.0A	Effects of Drip Shield on Flow	Included	Exclude	1	N/A, no drip shield
2.1.06.06.0B	Oxygen Embrittlement of Drip Shields	Excluded	Exclude	1	N/A, no drip shield
2.1.06.07.0A	Chemical Effects at EBS Component Interfaces	Excluded	Include	2	Address with other information
2.1.06.07.0B	Mechanical Effects at EBS Component Interfaces	Excluded	Exclude	3	Address with other information
2.1.07.01.0A	Rockfall	Excluded	Exclude	1	Address with other information
2.1.07.02.0A	Drift Collapse	Excluded	Exclude	1 If drift = borehole, then this is a potentially significant operational FEP	Address with other information
2.1.07.04.0A	Hydrostatic Pressure on Waste Package	Excluded	Include	2	Drill stem tests of shut-in pressure
2.1.07.04.0B	Hydrostatic Pressure on Drip Shield	Excluded	Exclude	1	N/A, no drip shield
2.1.07.05.0A	Creep of Metallic Materials in the Waste Package	Excluded	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.07.05.0B	Creep of Metallic Materials in the Drip Shield	Excluded	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.07.06.0A	Floor Buckling	Excluded	Exclude	1	N/A, no floor
2.1.08.01.0A	Water Influx at the Repository	Included	Include	1	Formation micro imager log, temperature log, drill stem pump tests, packer pump tests
2.1.08.01.0B	Effects of Rapid Influx into the Repository	Excluded	Exclude	1	Address with other information
2.1.08.02.0A	Enhanced Influx at the Repository	Included	Exclude	1	Address with other information
2.1.08.03.0A	Repository Dry-Out Due to Waste Heat	Included	Include	1	Address with other information, drill stem tests of shut-in pressure
2.1.08.04.0A	Condensation Forms on Roofs of Drifts (Drift-Scale Cold Traps)	Included	Exclude	1	N/A, no roof
2.1.08.04.0B	Condensation Forms at Repository Edges (Repository-Scale Cold Traps)	Included	Exclude	1	Address with other information
2.1.08.05.0A	Flow Through Invert	Included	Exclude	1	N/A, no invert
2.1.08.06.0A	Capillary Effects (Wicking) in EBS	Included	Exclude	1	Address with other information
2.1.08.07.0A	Unsaturated Flow in the EBS	Included	Exclude	1	N/A, borehole is in saturated zone
2.1.08.09.0A	Saturated Flow in the EBS	Excluded	Include	3	Packer pump tests, drill stem pump tests, formation micro imager log, drill stem tests of shut-in pressure, temperature log
2.1.08.11.0A	Repository Resaturation Due to Waste Cooling	Included	Include	1	Address with other information

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
2.1.08.12.0A	Induced Hydrologic Changes in Invert	Excluded	Exclude (NA)	1	N/A, no invert
2.1.08.14.0A	Condensation on Underside of Drip Shield	Excluded	Exclude (NA)	1	N/A, no drip shield
2.1.08.15.0A	Consolidation of EBS Components	Excluded	Include	3	Address with other information
2.1.09.01.0A	Chemical Characteristics of Water in Drifts	Included	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.01.0B	Chemical Characteristics of Water in Waste Package	Included	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.02.0A	Chemical Interaction With Corrosion Products	Included	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.03.0A	Volume Increase of Corrosion Products Impacts Cladding	Excluded	Exclude	1	Address with other information
2.1.09.03.0B	Volume Increase of Corrosion Products Impacts Waste Package	Excluded	Exclude	1	Address with other information
2.1.09.03.0C	Volume Increase of Corrosion Products Impacts Other EBS Components	Excluded	Exclude	1	Address with other information
2.1.09.04.0A	Radionuclide Solubility, Solubility Limits, and Speciation in the Waste Form and EBS	Included	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.05.0A	Sorption of Dissolved Radionuclides in EBS	Included	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.06.0A	Reduction-Oxidation Potential in Waste Package	Included	Include	1	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.06.0B	Reduction-Oxidation Potential in Drifts	Included	Include	1	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.07.0A	Reaction Kinetics in Waste Package	Included	Exclude	2	Address with other information
2.1.09.07.0B	Reaction Kinetics in Drifts	Included	Exclude	2	Address with other information
2.1.09.08.0A	Diffusion of Dissolved Radionuclides in EBS	Included	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.08.0B	Advection of Dissolved Radionuclides in EBS	Included	Include	3	Packer pump tests, drill stem pump tests, formation micro imager log, drill stem tests of

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
					shut-in pressure, temperature log
2.1.09.09.0A	Electrochemical Effects in EBS	Excluded	Exclude	1	Address with other information
2.1.09.10.0A	Secondary Phase Effects on Dissolved Radionuclide Concentrations	Excluded	Include	2	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.11.0A	Chemical Effects of Waste-Rock Contact	Excluded	Include	2	Groundwater chemistry in fluid samples from packer testing, mineral composition of core and cuttings samples, address with other information
2.1.09.12.0A	Rind (Chemically Altered Zone) Forms in the Near-Field	Excluded	Exclude	2	Address with other information
2.1.09.13.0A	Complexation in EBS	Excluded	Exclude	2	Address with other information
2.1.09.15.0A	Formation of True (Intrinsic) Colloids in EBS	Excluded	Exclude	1	Address with other information
2.1.09.16.0A	Formation of Pseudo-Colloids (Natural) in EBS	Included	Exclude	1	Address with other information
2.1.09.17.0A	Formation of Pseudo-Colloids (Corrosion Product) in EBS	Included	Exclude	1	Address with other information
2.1.09.18.0A	Formation of Microbial Colloids in EBS	Excluded	Exclude	1	Address with other information
2.1.09.19.0A	Sorption of Colloids in EBS	Excluded	Exclude	1	Address with other information
2.1.09.19.0B	Advection of Colloids in EBS	Included	Exclude	1	Address with other information
2.1.09.20.0A	Filtration of Colloids in EBS	Excluded	Exclude	1	Address with other information
2.1.09.21.0A	Transport of Particles Larger Than Colloids in EBS	Excluded	Exclude	1	Address with other information
2.1.09.21.0B	Transport of Particles Larger Than Colloids in the SZ	Excluded	Exclude	1	Address with other information
2.1.09.21.0C	Transport of Particles Larger Than Colloids in the UZ	Excluded	Exclude	1	Address with other information
2.1.09.22.0A	Sorption of Colloids at Air-Water Interface	Excluded	Exclude	1	Address with other information
2.1.09.23.0A	Stability of Colloids in EBS	Included	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.24.0A	Diffusion of Colloids in EBS	Included	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.25.0A	Formation of Colloids (Waste-Form) By Co-Precipitation in EBS	Included	Include	?	Groundwater chemistry in fluid samples from packer testing, address with other information

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
2.1.09.26.0A	Gravitational Settling of Colloids in EBS	Excluded	Exclude	1	Address with other information
2.1.09.27.0A	Coupled Effects on Radionuclide Transport in EBS	Excluded	Include	2	Groundwater chemistry in fluid samples from packer testing, temperature log, address with other information
2.1.09.28.0A	Localized Corrosion on Waste Package Outer Surface Due to Deliquescence	Excluded	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.09.28.0B	Localized Corrosion on Drip Shield Surfaces Due to Deliquescence	Excluded	Exclude	1	N/A, no drip shield
2.1.10.01.0A	Microbial Activity in EBS	Excluded	Exclude	2	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.11.01.0A	Heat Generation in EBS	Included	Include	3	Address with other information
2.1.11.02.0A	Non-Uniform Heat Distribution in EBS	Included	Include	3	Address with other information
2.1.11.03.0A	Exothermic Reactions in the EBS	Excluded	Exclude	1	Address with other information
2.1.11.05.0A	Thermal Expansion/Stress of in-Package EBS Components	Excluded	Exclude	1	Address with other information
2.1.11.06.0A	Thermal Sensitization of Waste Packages	Excluded	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.11.06.0B	Thermal Sensitization of Drip Shields	Excluded	Exclude	1	N/A, no drip shield
2.1.11.07.0A	Thermal Expansion/Stress of in-Drift EBS Components	Excluded	Include	3 This may be where thermal-mechanical effects on the seals is captured	Address with other information
2.1.11.08.0A	Thermal Effects on Chemistry and Microbial Activity in the EBS	Included	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.11.09.0A	Thermal Effects on Flow in the EBS	Included	Include	3	Packer pump tests, drill stem pump tests, formation micro imager log, drill stem tests of shut-in pressure, temperature log
2.1.11.09.0B	Thermally-Driven Flow (Convection) in Waste Packages	Excluded	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.11.09.0C	Thermally Driven Flow (Convection) in Drifts	Included	Include	3 Drifts = boreholes with waste	Packer pump tests, drill stem pump tests, formation micro imager log, drill stem tests of shut-in pressure, temperature log
2.1.11.10.0A	Thermal Effects on Transport in EBS	Excluded	Include	3	Packer pump tests, drill stem pump tests, formation micro

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
					imager log, drill stem tests of shut-in pressure, temperature log, address with other information
2.1.12.01.0A	Gas Generation (Repository Pressurization)	Excluded	Exclude	3 Need to consider gas pressure effects on seals	Address with other information
2.1.12.02.0A	Gas Generation (He) from Waste Form Decay	Excluded	Exclude	3	Address with other information
2.1.12.03.0A	Gas Generation (H_2) from Waste Package Corrosion	Excluded	Exclude	3	Address with other information
2.1.12.04.0A	Gas Generation (CO_2, CH_4, H_2S) from Microbial Degradation	Excluded	Exclude	2	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.12.06.0A	Gas Transport in EBS	Excluded	Exclude	2	Address with other information
2.1.12.07.0A	Effects of Radioactive Gases in EBS	Excluded	Exclude	1	Address with other information
2.1.12.08.0A	Gas Explosions in EBS	Excluded	Exclude	1	Address with other information
2.1.13.01.0A	Radiolysis	Excluded	Exclude	2	Address with other information
2.1.13.02.0A	Radiation Damage in EBS	Excluded	Exclude	1	Address with other information
2.1.13.03.0A	Radiological Mutation of Microbes	Excluded	Exclude	1	Address with other information
2.1.14.15.0A	In-Package Criticality (Intact Configuration)	Excluded	Exclude	3	Address with other information
2.1.14.16.0A	In-Package Criticality (Degraded Configurations)	Excluded	Exclude	3 Criticality exclusion on Prob. of geometry? Consequence is low, but hard to quantify because of thermal effects	Address with other information
2.1.14.17.0A	Near-Field Criticality	Excluded	Exclude	2	Address with other information
2.1.14.18.0A	In-Package Criticality Resulting from a Seismic Event (Intact Configuration)	Excluded	Exclude	1	Address with other information
2.1.14.19.0A	In-Package Criticality Resulting from a Seismic Event (Degraded Configurations)	Excluded	Exclude	1	Address with other information
2.1.14.20.0A	Near-Field Criticality Resulting from a Seismic Event	Excluded	Exclude	1	Address with other information
2.1.14.21.0A	In-Package Criticality Resulting from Rockfall (Intact Configuration)	Excluded	Exclude	1	Address with other information
2.1.14.22.0A	In-Package Criticality Resulting from Rockfall (Degraded Configurations)	Excluded	Exclude	1	N/A
2.1.14.23.0A	Near-Field Criticality	Excluded	Exclude	1	N/A

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
	Resulting from Rockfall				
2.1.14.24.0A	In-Package Criticality Resulting from an Igneous Event (Intact Configuration)	Excluded	Exclude	2	Address with other information
2.1.14.25.0A	In-Package Criticality Resulting from an Igneous Event (Degraded Configurations)	Excluded	Exclude	2	Address with other information
2.1.14.26.0A	Near-Field Criticality Resulting from an Igneous Event	Excluded	Exclude	1	Address with other information
2.2.01.01.0A	Mechanical Effects of Excavation and Construction in the Near-Field	Included	Include	3 High K pathways around borehole	Anisotropic shear wave velocity log
2.2.01.01.0B	Chemical Effects of Excavation and Construction in the Near-Field	Excluded	Include	2 Altered rock properties near borehole	Groundwater chemistry in fluid samples from packer testing, address with other information
2.2.01.02.0A	Thermally-Induced Stress Changes in the Near-Field	Excluded	Include	3	Anisotropic shear wave velocity log, thermal properties of rock samples from coring
2.2.01.02.0B	Chemical Changes in the Near-Field from Backfill	Excluded	Exclude	1	Address with other information
2.2.01.03.0A	Changes In Fluid Saturations in the Excavation Disturbed Zone	Excluded	Exclude	1	Address with other information
2.2.01.04.0A	Radionuclide Solubility in the Excavation Disturbed Zone	Excluded	Include	2	Groundwater chemistry in fluid samples from packer testing, address with other information
2.2.01.05.0A	Radionuclide Transport in the Excavation Disturbed Zone	Excluded	Include	3	Groundwater chemistry in fluid samples from packer testing, intra-borehole dipole tracer testing, push-pull tracer testing, neutron porosity log, sorption properties of samples from coring and drill cuttings, address with other information
2.2.03.01.0A	Stratigraphy	Included	Include	1	3D seismic imaging, gamma ray log, resistivity log, spontaneous potential log, neutron porosity log, drill cuttings lithology log, rock cores, Electrical Resistivity (Surface Based – Large Scale)
2.2.03.02.0A	Rock Properties of Host Rock and Other Units	Included	Include	1	Neutron porosity log, borehole gravity log, formation micro imager log, drill cuttings samples, rock cores
2.2.06.01.0A	Seismic Activity Changes Porosity and Permeability of	Excluded	Exclude	1	Address with other information

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
	Rock				
2.2.06.02.0A	Seismic Activity Changes Porosity and Permeability of Faults	Excluded	Exclude	1	Address with other information
2.2.06.02.0B	Seismic Activity Changes Porosity and Permeability of Fractures	Excluded	Exclude	1	Address with other information
2.2.06.03.0A	Seismic Activity Alters Perched Water Zones	Excluded	Exclude	1	Address with other information
2.2.06.04.0A	Effects of Subsidence	Excluded	Exclude	1	Address with other information
2.2.06.05.0A	Salt Creep	Excluded	Exclude	1	N/A, no salt
2.2.07.01.0A	Locally Saturated Flow at Bedrock/Alluvium Contact	Excluded	Exclude	1	Address with other information
2.2.07.02.0A	Unsaturated Groundwater Flow in the Geosphere	Included	Exclude	1	Address with other information
2.2.07.03.0A	Capillary Rise in the UZ	Included	Exclude	1	N/A, borehole located in saturated zone
2.2.07.04.0A	Focusing of Unsaturated Flow (Fingers, Weeps)	Included	Exclude	1	N/A, borehole located in saturated zone
2.2.07.05.0A	Flow in the UZ from Episodic Infiltration	Excluded	Exclude	1	N/A, borehole located in saturated zone
2.2.07.06.0A	Episodic or Pulse Release from Repository	Excluded	Exclude	1	Address with other information
2.2.07.06.0B	Long-Term Release of Radionuclides from the Repository	Included	Include	2	Chemical and isotopic composition of groundwater samples from packer testing, address with other information
2.2.07.07.0A	Perched Water Develops	Included	Exclude	1	N/A
2.2.07.08.0A	Fracture Flow in the UZ	Included	Exclude	1	Address with other information
2.2.07.09.0A	Matrix Imbibition in the UZ	Included	Exclude	1	Address with other information
2.2.07.10.0A	Condensation Zone Forms Around Drifts	Included	Exclude	1	N/A, no open drifts
2.2.07.11.0A	Resaturation of Geosphere Dry-Out Zone	Included	Include	1	Address with other information
2.2.07.12.0A	Saturated Groundwater Flow in the Geosphere	Included	Include	3 This is one of two release pathways (EBS transport through seals is the other)	Packer pump tests, drill stem pump tests, formation micro imager log, drill stem tests of shut-in pressure, temperature log, chemical and isotopic composition of groundwater samples from packer testing
2.2.07.13.0A	Water-Conducting Features in the SZ	Included	Included	3	Formation micro imager log, temperature log
2.2.07.14.0A	Chemically-Induced Density Effects on Groundwater Flow	Excluded	Exclude	1	Address with other information
2.2.07.15.0A	Advection and Dispersion in the SZ	Included	Include	3	Packer pump tests, drill stem pump tests, formation micro imager log, drill stem tests of

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
					shut-in pressure, temperature log, intra-borehole dipole tracer testing
2.2.07.15.0B	Advection and Dispersion in the UZ	Included	Exclude	1	Address with other information
2.2.07.16.0A	Dilution of Radionuclides in Groundwater	Included	Include	1	Address with existing data for characterization of the reference biosphere
2.2.07.17.0A	Diffusion in the SZ	Included	Include	3	Diffusion properties of rock samples from coring
2.2.07.18.0A	Film Flow into the Repository	Included	Exclude	1	Address with other information
2.2.07.19.0A	Lateral Flow from Solitario Canyon Fault Enters Drifts	Included	Exclude	1	N/A, formations not present
2.2.07.20.0A	Flow Diversion Around Repository Drifts	Included	Exclude	1	N/A, drifts not present
2.2.07.21.0A	Drift Shadow Forms Below Repository	Excluded	Exclude	1	N/A, drifts not present
2.2.08.01.0A	Chemical Characteristics of Groundwater in the SZ	Included	Include	1	Chemical and isotopic composition of groundwater samples from packer testing
2.2.08.01.0B	Chemical Characteristics of Groundwater in the UZ	Included	Exclude	1	Address with other information
2.2.08.03.0A	Geochemical Interactions and Evolution in the SZ	Excluded	Include	2	Chemical and isotopic composition of groundwater samples from packer testing
2.2.08.03.0B	Geochemical Interactions and Evolution in the UZ	Excluded	Exclude	1	Address with other information
2.2.08.04.0A	Re-Dissolution of Precipitates Directs More Corrosive Fluids to Waste Packages	Excluded	Exclude	1	Address with other information
2.2.08.05.0A	Diffusion in the UZ	Excluded	Exclude	1	Address with other information
2.2.08.06.0A	Complexation in the SZ	Included	Include	?	Chemical composition of groundwater samples from packer testing
2.2.08.06.0B	Complexation in the UZ	Included	Exclude	1	Address with other information
2.2.08.07.0A	Radionuclide Solubility Limits in the SZ	Excluded	Include	2	Chemical composition of groundwater samples from packer testing
2.2.08.07.0B	Radionuclide Solubility Limits in the UZ	Excluded	Exclude	1	Address with other information
2.2.08.07.0C	Radionuclide Solubility Limits in the Biosphere	Excluded	Exclude	1	Address with other information
2.2.08.08.0A	Matrix Diffusion in the SZ	Included	Include	3	Diffusion properties of rock samples from coring, formation micro imager log
2.2.08.08.0B	Matrix Diffusion in the UZ	Included	Exclude	1	Address with other information
2.2.08.09.0A	Sorption in the SZ	Included	Include	3	Sorption properties of rock samples from drill cuttings

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
					and coring, bulk density from borehole gravity log, neutron porosity log
2.2.08.09.0B	Sorption in the UZ	Included	Exclude	1	Address with other information
2.2.08.10.0A	Colloidal Transport in the SZ	Included	Include	3	Chemical composition and colloid concentrations of groundwater samples from packer testing
2.2.08.10.0B	Colloidal Transport in the UZ	Included	Exclude	1	Address with other information
2.2.08.11.0A	Groundwater Discharge to Surface Within The Reference Biosphere	Excluded	Exclude	1	Address with other information
2.2.08.12.0A	Chemistry of Water Flowing into the Drift	Included	Include	2	Chemical composition of groundwater samples from packer testing
2.2.08.12.0B	Chemistry of Water Flowing into the Waste Package	Included	Include	2	Chemical composition of groundwater samples from packer testing
2.2.09.01.0A	Microbial Activity in the SZ	Excluded	Exclude	2	Microbiological composition of groundwater samples from packer testing
2.2.09.01.0B	Microbial Activity in the UZ	Excluded	Exclude	1	Address with other information
2.2.10.01.0A	Repository-Induced Thermal Effects on Flow in the UZ	Excluded	Exclude	1	Address with other information
2.2.10.02.0A	Thermal Convection Cell Develops in SZ	Excluded	Exclude	3	Packer pump tests, drill stem pump tests
2.2.10.03.0A	Natural Geothermal Effects on Flow in the SZ	Included	Include	2	Temperature log, packer pump tests, drill stem pump tests
2.2.10.03.0B	Natural Geothermal Effects on Flow in the UZ	Included	Exclude	1	Address with other information
2.2.10.04.0A	Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository	Excluded	Exclude	3	Formation micro imager log, thermal and mechanical properties of rock samples from coring
2.2.10.04.0B	Thermo-Mechanical Stresses Alter Characteristics of Faults Near Repository	Excluded	Exclude	3	Address with other information
2.2.10.05.0A	Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below The Repository	Excluded	Exclude	3	Address with other information
2.2.10.06.0A	Thermo-Chemical Alteration in the UZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)	Excluded	Exclude	1	Address with other information
2.2.10.07.0A	Thermo-Chemical Alteration of the Calico Hills Unit	Excluded	Exclude (NA)	1	N/A, no formation
2.2.10.08.0A	Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes,	Excluded	Exclude	3	Chemical composition of groundwater samples from packer testing

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
	Precipitation/Dissolution)				
2.2.10.09.0A	Thermo-Chemical Alteration of the Topopah Spring Basal Vitrophyre	Excluded	Exclude	1	N/A, no formation
2.2.10.10.0A	Two-Phase Buoyant Flow/Heat Pipes	Included	Exclude	1	Address with other information
2.2.10.11.0A	Natural Air Flow in the UZ	Excluded	Exclude	1	Address with other information
2.2.10.12.0A	Geosphere Dry-Out Due to Waste Heat	Included	Include	1	Address with other information
2.2.10.13.0A	Repository-Induced Thermal Effects on Flow in the SZ	Excluded	Include	3	Packer pump tests, drill stem pump tests, formation micro imager log, drill stem tests of shut-in pressure, temperature log
2.2.10.14.0A	Mineralogic Dehydration Reactions	Excluded	Exclude	3	Address with other information
2.2.11.01.0A	Gas Effects in the SZ	Excluded	Exclude	2	Address with other information
2.2.11.02.0A	Gas Effects in the UZ	Excluded	Exclude	1	Address with other information
2.2.11.03.0A	Gas Transport in Geosphere	Excluded	Exclude	1	Address with other information
2.2.12.00.0A	Undetected Features in the UZ	Excluded	Exclude	1	Address with other information
2.2.12.00.0B	Undetected Features in the SZ	Included	Include	1	3D seismic imaging; Electrical Resistivity (Surface Based – Large Scale)
2.2.14.09.0A	Far-Field Criticality	Excluded	Exclude	1	Address with other information
2.2.14.10.0A	Far-Field Criticality Resulting from a Seismic Event	Excluded	Exclude	1	Address with other information
2.2.14.11.0A	Far-Field Criticality Resulting from Rockfall	Excluded	Exclude	1	N/A
2.2.14.12.0A	Far-Field Criticality Resulting from an Igneous Event	Excluded	Exclude	1	Address with other information
2.3.01.00.0A	Topography and Morphology	Included	Exclude	1	Address with other information
2.3.02.01.0A	Soil Type	Included	Include	1 (Biosphere model inputs are all "included" assuming well water and farming)	Address with existing data
2.3.02.02.0A	Radionuclide Accumulation in Soils	Included	Include	1	Address with existing data
2.3.02.03.0A	Soil and Sediment Transport in the Biosphere	Included	Exclude	1	Address with other information
2.3.04.01.0A	Surface Water Transport and Mixing	Included	Exclude	1	Address with other information
2.3.06.00.0A	Marine Features	Excluded	Exclude	1	Address with other information
2.3.09.01.0A	Animal Burrowing/Intrusion	Excluded	Exclude	1	Address with other information
2.3.11.01.0A	Precipitation	Included	Exclude	1	Address with other information

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
2.3.11.02.0A	Surface Runoff and Evapotranspiration	Included	Exclude	1	Address with other information
2.3.11.03.0A	Infiltration and Recharge	Included	Exclude	1	Address with existing data
2.3.11.04.0A	Groundwater Discharge to Surface Outside The Reference Biosphere	Excluded	Exclude	1	Address with existing data
2.3.13.01.0A	Biosphere Characteristics	Included	Include	1 Assume well pumps from SZ at location of borehole	Address with existing data
2.3.13.02.0A	Radionuclide Alteration During Biosphere Transport	Included	Include	1	Address with existing data
2.3.13.03.0A	Effects of Repository Heat on The Biosphere	Excluded	Exclude	1	Address with other information
2.3.13.04.0A	Radionuclide Release Outside The Reference Biosphere	Excluded	Exclude	1	Address with other information
2.4.01.00.0A	Human Characteristics (Physiology, Metabolism)	Included	Include	1	Address with existing data
2.4.04.01.0A	Human Lifestyle	Included	Include	1	Address with existing data
2.4.07.00.0A	Dwellings	Included	Include	1	Address with existing data
2.4.08.00.0A	Wild and Natural Land and Water Use	Included	Include	1	Address with existing data
2.4.09.01.0A	Implementation of New Agricultural Practices Or Land Use	Excluded	Exclude	1	Address with other information
2.4.09.01.0B	Agricultural Land Use and Irrigation	Included	Include	1	Address with existing data
2.4.09.02.0A	Animal Farms and Fisheries	Included	Include	1	Address with existing data
2.4.10.00.0A	Urban and Industrial Land and Water Use	Included	Include	1	Address with existing data
3.1.01.01.0A	Radioactive Decay and Ingrowth	Included	Include	1	Address with existing data
3.2.07.01.0A	Isotopic Dilution	Excluded	Exclude	1	Address with other information
3.2.10.00.0A	Atmospheric Transport of Contaminants	Included	Exclude	1	Address with other information
3.3.01.00.0A	Contaminated Drinking Water, Foodstuffs and Drugs	Included	Include	1	Address with existing data
3.3.02.01.0A	Plant Uptake	Included	Include	1	Address with existing data
3.3.02.02.0A	Animal Uptake	Included	Include	1	Address with existing data
3.3.02.03.0A	Fish Uptake	Included	Include	1	Address with existing data
3.3.03.01.0A	Contaminated Non-Food Products and Exposure	Included	Include	1	Calculated from PA model
3.3.04.01.0A	Ingestion	Included	Include	1	Calculated from PA model
3.3.04.02.0A	Inhalation	Included	Include	1	Calculated from PA model
3.3.04.03.0A	External Exposure	Included	Include	1	Calculated from PA model
3.3.05.01.0A	Radiation Doses	Included	Include	1	Calculated from PA model
3.3.06.00.0A	Radiological Toxicity and Effects	Excluded	Exclude	1	Address with other information
3.3.06.01.0A	Repository Excavation	Excluded	Exclude	1	Address with other information
3.3.06.02.0A	Sensitization to Radiation	Excluded	Exclude	1	Address with other information
3.3.07.00.0A	Non-Radiological Toxicity	Excluded	Exclude	1	Address with other

DBD/YMP FEP Number	DBD/YMP FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort	
	and Effects				information
3.3.08.00.0A	Radon and Radon Decay Product Exposure	Included	Include	1	Calculated from PA model
Highlighted entry indicates key FEP for Deep Borehole Disposal (Brady et al., 2009)					

Table A-2. Characterization Methods supporting Deep Borehole FEPs.

Note: Highlighted entry indicates key FEP for Deep Borehole Disposal (Brady et al., 2009)

Characterization Method	Information Needed	FEP Number Addressed	FEP Title Addressed
3D Seismic Imaging Section 3.1.1	To exclude overthrusting above sedimentary rocks to exclude drilling for petroleum resources	*1.4.02.02.0A* *1.4.04.00.0A*	*- Inadvertent Human Intrusion* *- Drilling Activities (Human Intrusion)*
	Detect other features in raock and characteristics such as porosity, density, lithology, and saturation.	*2.2.12.00.0B* *1.2.02.02.0A* *1.2.02.03.0A*	*-Undetected Features in the SZ* *-Faults* *-Fault Displacement Damages EBS Components*
	Stratigraphy	*2.2.03.01.0A*	*- Stratigraphy*
Borehole Caliper Log Section 3.2.1.1	Determine integrity of borehole and identify faults intersecting borehole.	*1.1.02.00.0B*	*- Mechanical Effects of Excavation and Construction in EBS*
Borehole Gravity Log Section 3.2.1.9	Determine bulk density of rock	*2.2.08.09.0A*	*- Sorption in the SZ*
	Other	*2.2.03.02.0A*	*- Rock Properties of Host Rock and Other Units*
Dipole Shear- Wave Velocity Log Section 3.2.1.8	Estimate the directions of *in situ* maximum and minimum horizontal stresses, and their difference in magnitude. Give geological evidence regarding the tectonic history and structural stability of the site	*2.1.06.02.0A* *2.2.01.01.0A* *2.2.01.02.0A*	*- Mechanical Effects of Rock Reinforcement Materials in EBS* *- Mechanical Effects of Excavation and Construction in the Near-Field* *- Thermally-Induced Stress Changes in the Near-Field*
Downhaul Force Mechanical Testing Section 3.2.6.1	Estimate the strength of borehole seals and plugs.	*1.1.02.00.0B* *1.2.02.03.0A* *2.1.05.01.0A* *2.1.05.02.0A* *2.1.05.03.0A*	*-Mechanical Effects of Excavation and Construction* *- Fault Displacement Damages EBS Components* *- Flow Through Seals (Access Ramps and Ventilation* *- Radionuclide Transport Through Seals* *- Degradation of Seals*
Drill Cuttings Section 3.2.2.1	Stratigraphy	*2.2.03.01.0A*	*- Stratigraphy*
	Mineral composition of cuttings samples	*2.1.09.11.0A* *1.4.02.02.0A* *1.4.04.00.0A* *1.4.05.00.0A*	*- Chemical Effects of Waste-Rock Contact* *- Inadvertent Human Intrusion* *- Drilling Activities (Human Intrusion)* *- Mining and Other Underground Activities (Human Intrusion)*
	Sorption properties of samples from drill cuttings	*2.2.01.05.0A* *2.2.08.09.0A*	*- Radionuclide Transport in the Excavation Disturbed Zone* *- Sorption in the SZ*

	Other basic rock properties	*2.2.03.02.0A*	*- Rock Properties of Host Rock and Other Units*
Drill Stem Pump Tests Section 3.2.3.2	Provide formation pressure, formation permeability, and water chemistry	*2.2.10.03.0A* *2.1.08.01.0A* *2.2.07.12.0A* *2.1.08.09.0A* *2.1.09.08.0B* *2.1.11.09.0A* *2.1.11.09.0C* *2.1.11.10.0A* *2.2.10.13.0A* *2.2.07.15.0A* *2.2.10.02.0A*	*- Natural Geothermal Effects on Flow in the SZ* *- Water Influx at the Repository* *- Saturated Groundwater Flow in the Geosphere* *- Saturated Flow in the EBS* *- Advection of Dissolved Radionuclides in EBS* *- Thermal Effects on Flow in the EBS* *- Thermally Driven Flow (Convection) in Drifts* *- Thermal Effects on Transport in EBS* *- Repository-Induced Thermal Effects on Flow in the SZ* *- Advection and Dispersion in the SZ* *- Thermal Convection Cell Develops in SZ*
Drill Stem Tests of Shut-In Pressure Section 3.2.3.1	Determine hydraulic conductivity (horizontal and vertical), specific storage or storativity, and transmissivity	*2.1.08.03.0A* *2.1.07.04.0A* *2.2.07.12.0A* *2.1.08.09.0A* *2.1.09.08.0B* *2.1.11.09.0A* *2.1.11.09.0C* *2.1.11.10.0A* *2.2.10.13.0A* *2.2.07.15.0A*	*- Repository Dry-Out Due to Waste Heat* *- Hydrostatic Pressure on Waste Package* *- Saturated Groundwater Flow in the Geosphere* *- Saturated Flow in the EBS* *- Advection of Dissolved Radionuclides in EBS* *- Thermal Effects on Flow in the EBS* *- Thermally Driven Flow (Convection) in Drifts* *- Thermal Effects on Transport in EBS* *- Repository-Induced Thermal Effects on Flow in the SZ* *- Advection and Dispersion in the SZ*
Electrical Resistivity Profile (Surface Based – Large Scale)	To exclude overthrusting above sedimentary rocks to exclude drilling for petroleum resources	*1.4.02.02.0A* *1.4.04.00.0A*	*- Inadvertent Human Intrusion* *- Drilling Activities (Human Intrusion)*
	Detect other features in rock such as faults	*2.2.12.00.0B* *1.2.02.02.0A* *1.2.02.03.0A*	*-Undetected Features in the SZ* *-Faults* *-Fault Displacement Damages EBS Components*
	stratigraphy	*2.2.03.01.0A*	*- Stratigraphy*
Fluid Pressure Drawdown Test of Effective Permeability Section 3.2.6.2	Test of effective permeability of seals	*1.1.02.00.0B* *2.1.05.01.0A*	*- Mechanical Effects of Excavation and Construction in EBS* *- Flow Through Seals (Access Ramps and Ventilation*

			Shafts)
Fluid Samples from Packer Testing Section 3.2.2.3	Colloid concentrations of Groundwater samples	*2.2.08.10.0A*	*- Colloidal Transport in the SZ*
	Groundwater chemistry in fluid samples	*2.1.02.01.0A* *2.1.02.02.0A* *2.1.02.03.0A* *2.1.02.07.0A* *2.1.02.14.0A* *2.1.04.02.0A* *2.1.04.03.0A* *2.1.05.02.0A* *2.1.06.01.0A* *2.2.08.01.0A* *2.2.08.03.0A* *2.2.08.06.0A* *2.2.08.07.0A* *2.2.08.10.0A* *2.2.07.06.0B* *2.1.09.01.0A* *2.1.09.01.0B* *2.1.09.02.0A* *2.1.09.04.0A* *2.1.09.05.0A* *2.1.09.06.0A* *2.1.09.06.0B* *2.1.09.08.0A* *2.1.09.10.0A*	*- DSNF Degradation (Alteration, Dissolution, and Radionuclide Release)* *- CSNF Degradation (Alteration, Dissolution, and Radionuclide Release)* *- HLW Glass Degradation (Alteration, Dissolution, and Radionuclide Release)* *- Radionuclide Release from Gap and Grain Boundaries* *- Microbially Influenced Corrosion (MIC) of Cladding* *- Chemical Properties and Evolution of Backfill* *- Erosion or Dissolution of Backfill* *- Radionuclide Transport Through Seals* *- Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS* *- Chemical Characteristics of Groundwater in the SZ* *- Geochemical Interactions and Evolution in the SZ* *- Complexation in the SZ* *- Radionuclide Solubility Limits in the SZ* *- Colloidal Transport in the SZ* *- Long-Term Release of Radionuclides from The Repository* *- Chemical Characteristics of Water in Drifts* *- Chemical Characteristics of Water in Waste Package* *- Chemical Interaction With Corrosion Products* *- Radionuclide Solubility, Solubility Limits, and Speciation in the Waste Form and EBS* *- Sorption of Dissolved Radionuclides in EBS* *- Reduction-Oxidation Potential in Waste Package* *- Reduction-Oxidation Potential in Drifts* *- Diffusion of Dissolved Radionuclides in EBS* *- Secondary Phase Effects on*

		2.1.09.23.0A 2.1.09.24.0A 2.1.09.25.0A 2.1.10.01.0A 2.1.11.08.0A 2.1.12.04.0A 2.2.01.01.0B 2.2.01.04.0A 2.2.08.12.0A 2.2.08.12.0B 2.2.10.08.0A 2.2.01.05.0A 2.1.09.11.0A 2.1.09.27.0A 2.2.07.12.0A 1.3.04.00.0A 1.3.05.00.0A	*Dissolved Radionuclide Concentrations* *- Stability of Colloids in EBS* *- Diffusion of Colloids in EBS* *- Formation of Colloids (Waste-Form) By Co-Precipitation in EBS* *- Microbial Activity in EBS* *- Thermal Effects on Chemistry and Microbial Activity in the EBS* *- Gas Generation (CO2, CH4, H2S) from Microbial Degradation* *- Chemical Effects of Excavation and Construction in the Near-Field* *- Radionuclide Solubility in the Excavation Disturbed Zone* *- Chemistry of Water Flowing into the Drift* *- Chemistry of Water Flowing into the Waste Package* *- Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)* *- Radionuclide Transport in the Excavation Disturbed Zone* *- Chemical Effects of Waste-Rock Contact* *- Coupled Effects on Radionuclide Transport in EBS* *- Saturated Groundwater Flow in the Geosphere* *- Periglacial Effects* *- Glacial and Ice Sheet Effect*
	Microbiological composition of groundwater samples	2.2.09.01.0A	*- Microbial Activity in the SZ*
	Isotopic composition in fluid samples	2.2.08.01.0A 2.2.08.03.0A 2.2.08.06.0A 2.2.07.12.0A 1.3.04.00.0A 1.3.05.00.0A	*- Chemical Characteristics of Groundwater in the SZ* *- Geochemical Interactions and Evolution in the SZ* *- Complexation in the SZ* *- Saturated Groundwater Flow in the Geosphere* *- Periglacial Effects* *- Glacial and Ice Sheet Effect*
Formation Micro Imager Log Section 3.2.1.7	Determine stratigraphic strike and dip, foliation, borehole breakouts, and fracture orientations, filling, and apertures as well as in-situ stress.	2.2.08.08.0A 1.2.02.01.0A 2.2.10.04.0A 2.1.08.01.0A	*- Matrix Diffusion in the SZ* *- Fractures* *-Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository* *- Water Influx at the*

		2.2.07.13.0A 2.2.03.02.0A 2.2.07.12.0A 2.1.08.09.0A 2.1.09.08.0B 2.1.11.09.0A 2.1.11.09.0C 2.1.11.10.0A 2.2.10.13.0A 2.2.07.15.0A 1.2.02.02.0A 1.2.02.03.0A	*Repository* *- Water-Conducting Features in the SZ* *- Rock Properties of Host Rock and Other Units* *- Saturated Groundwater Flow in the Geosphere* *- Saturated Flow in the EBS* *- Advection of Dissolved Radionuclides in EBS* *- Thermal Effects on Flow in the EBS* *- Thermally Driven Flow (Convection) in Drifts* *- Thermal Effects on Transport in EBS* *- Repository-Induced Thermal Effects on Flow in the SZ* *- Advection and Dispersion in the SZ* *- Faults* *- Fault Displacement Damages EBS Components*
Gamma Ray Log Section 3.2.1.2	Determine Lithology, stratigraphy, potential resources	1.4.02.02.0A 1.4.04.00.0A 1.4.05.00.0A 2.2.03.01.0A	*- Inadvertent Human Intrusion* *- Drilling Activities (Human Intrusion)* *- Mining and Other Underground Activities (Human Intrusion)* *- Stratigraphy*
Gravity and Magnetic Surveys Section 3.1.2	To exclude ore deposits and identify features of the host formations such as faults, folds, igneous intrusions, and salt domes	1.4.02.02.0A 1.4.04.00.0A 1.4.05.00.0A	*- Inadvertent Human Intrusion* *- Drilling Activities (Human Intrusion)* *- Mining and Other Underground Activities (Human Intrusion)*
Intermittent Coring Section 3.2.2.2	Diffusion rock properties	2.2.08.08.0A 2.2.07.17.0A	*- Matrix Diffusion in the SZ* *- Diffusion in the SZ*
	Mineral composition of rock	2.2.10.04.0A	*-Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository*
	Sorption rock properties	2.2.01.05.0A 2.2.08.09.0A	*- Radionuclide Transport in the Excavation Disturbed Zone* *- Sorption in the SZ*
	Thermal rock properties	2.2.01.02.0A 2.2.10.04.0A	*- Thermally-Induced Stress Changes in the Near-Field* *- Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository*
	Stratigraphy and basic rock properties	2.2.03.01.0A 2.2.03.02.0A	*- Stratigraphy* *- Rock Properties of Host Rock and Other Units*
Neutron Porosity Log	Estimate the porosity of the host rock. Assess the	2.2.08.09.0A 2.2.03.01.0A	*- Sorption in the SZ* *- Stratigraphy*

Section 3.2.1.6	lithology, alteration, and fracturing in the host rock	2.2.01.05.0A 2.2.03.02.0A	*- Radionuclide Transport in the Excavation Disturbed Zone* *- Rock Properties of Host Rock and Other Units*
Packer Pump Tests Section 3.2.3.3	Determine the variability in borehole and formation transmissivity and storage coefficient from which permeability and porosity can be derived. Provide water samples for analysis.	*2.2.10.03.0A* *1.3.04.00.0A* *1.3.05.00.0A* *2.1.08.01.0A* *2.2.07.12.0A* *2.1.08.09.0A* *2.1.09.08.0B* *2.1.11.09.0A* *2.1.11.09.0C* *2.1.11.10.0A* *2.2.10.13.0A* *2.2.07.15.0A* *2.2.10.02.0A*	*- Natural Geothermal Effects on Flow in the SZ* *- Periglacial Effects* *- Glacial and Ice Sheet Effect* *- Water Influx at the Repository* *- Saturated Groundwater Flow in the Geosphere* *- Saturated Flow in the EBS* *- Advection of Dissolved Radionuclides in EBS* *- Thermal Effects on Flow in the EBS* *- Thermally Driven Flow (Convection) in Drifts* *- Thermal Effects on Transport in EBS* *- Repository-Induced Thermal Effects on Flow in the SZ* *- Advection and Dispersion in the SZ* *- Thermal Convection Cell Develops in SZ*
Push-Pull Tracer Testing Section 3.2.4.2	Provides information on dispersivity, matrix diffusion, reaction rates in reactive tracers, and ambient groundwater flow rates	*2.2.01.05.0A*	*- Radionuclide Transport in the Excavation Disturbed Zone*
Resistivity Log (Borehole Based) Section 3.2.1.3	**Determine lithostratigraphy**, formation permeability, and fluid saturations	*2.2.10.03.0A* *2.1.08.01.0A* *2.2.07.12.0A* *2.1.08.09.0A* *2.1.09.08.0B* *2.2.07.15.0A*	*- Natural Geothermal Effects on Flow in the SZ* *- Water Influx at the Repository* *- Saturated Groundwater Flow in the Geosphere* *- Saturated Flow in the EBS* *- Advection of Dissolved Radionuclides in EBS* *- Advection and Dispersion in the SZ*
	Stratigraphy	*2.2.03.01.0A*	*- Stratigraphy*
	Water Quality	*2.2.08.01.0A* *2.1.09.01.0A* *2.1.09.01.0B* *2.1.09.02.0A*	*- Chemical Characteristics of Groundwater in the SZ* *- Chemical Characteristics of Water in Drifts* *- Chemical Characteristics of Water in Waste Package* *- Chemical Interaction With Corrosion Products*
Spontaneous Potential Log Section 3.2.1..4	Provide information on lithology, the presence of high permeability beds or features, the volume of shale	*2.2.03.01.0A*	*- Stratigraphy*

	in permeable beds, the formation water resistivity, pore water quality (e.g. salinity, ionic concentration) and correlations between wells		
Surface Geological Mapping Section 3.1.4	Fault analysis including location, orientation, displacement, and displacement history. Surface lithology.	*1.2.02.02.0A* *1.2.02.03.0A*	*- Faults* *- Fault Displacement Damages EBS Components*
Temperature Log Section 3.2.1.5	Obtain vertical temperature profiles used to calculate fluid viscosity and density, apply thermal corrections to other geophysical logs, assess geological basin hydrodynamics, model hydrocarbon maturation, identify zones of fluid inflow, and detect zones of potential overpressure in petroleum engineering.	*1.2.02.01.0A* *2.1.08.01.0A* *2.2.07.13.0A* *2.2.07.12.0A* *2.1.08.09.0A* *2.1.09.08.0B* *2.1.11.09.0A* *2.1.11.09.0C* *2.1.11.10.0A* *2.2.10.13.0A* *2.2.07.15.0A* *2.2.10.03.0A*	*Fractures* *- Water Influx at the Repository* *- Water-Conducting Features in the SZ* *- Saturated Groundwater Flow in the Geosphere* *- Saturated Flow in the EBS* *- Advection of Dissolved Radionuclides in EBS* *- Thermal Effects on Flow in the EBS* *- Thermally Driven Flow (Convection) in Drifts* *- Thermal Effects on Transport in EBS* *- Repository-Induced Thermal Effects on Flow in the SZ* *- Advection and Dispersion in the SZ* *- Natural Geothermal Effects on Flow in the SZ*
	To exclude geothermal sources	*1.4.02.02.0A* *1.4.04.00.0A*	*- Inadvertent Human Intrusion* *- Drilling Activities (Human Intrusion)*
Vertical Dipole Tracer Testing Section 3.2.4.1	Estimate the radionuclide transport characteristics of the host rock and borehole disturbed zone such as such as sorption and matrix diffusion, porosity, dispersivity	*2.2.07.15.0A* *2.2.01.05.0A*	*- Advection and Dispersion in the SZ* *- Radionuclide Transport in the Excavation Disturbed Zone*
Waste Canister Mockup Electrical Heater Test Section 3.2.5.1	Estimate thermal properties of host rock such as bulk thermal conductivity and bulk coefficient of thermal expansion	*1.2.06.00.0A* *2.1.04.04.0A* *2.1.04.05.0A* *2.1.08.01.0A* *2.1.08.01.0B* *2.1.08.03.0A* *2.1.08.11.0A*	*- Hydrothermal Activity* *- Thermal-Mechanical Effects of Backfill* *- Thermal-Mechanical Properties and Evolution of Backfill* *- Water Influx at the Repository* *- Effects of Rapid Influx into the Repository* *- Repository Dry-Out Due to Waste Heat* *- Repository Resaturation*

			Due to Waste Cooling
		2.1.09.12.0A	*- Rind (Chemically Altered Zone) Forms in the Near-Field*
		2.1.11.07.0A	*- Thermal Expansion/Stress of in-Drift EBS Components*
		2.1.11.09.0A	*- Thermal Effects on Flow in the EBS*
		2.1.11.09.0C	*- Thermally Driven Flow (Convection) in Drifts*
		2.1.11.10.0A	*- Thermal Effects on Transport in EBS*
		2.2.01.02.0A	*- Thermally-Induced Stress Changes in the Near-Field*
		2.2.07.11.0A	*- Resaturation of Geosphere Dry-Out Zone*
		2.2.10.02.0A	*- Thermal Convection Cell Develops in SZ*
		2.2.10.03.0A	*- Natural Geothermal Effects on Flow in the SZ*
		2.2.10.04.0A	*- Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository*
		2.2.10.04.0B	*- Thermo-Mechanical Stresses Alter Characteristics of Faults Near Repository*
		2.2.10.05.0A	*- Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below The Repository*
		2.2.10.08.0A	*- Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)*
		2.2.10.12.0A	*- Geosphere Dry-Out Due to Waste Heat*
		2.2.10.13.0A	*- Repository-Induced Thermal Effects on Flow in the SZ*
Highlighted entry indicates key FEP for Deep Borehole Disposal (Brady et al., 2009)			

Appendix B. Activities Relevant to Deep Borehole Demonstration

Table B-1. Potential Activities Supporting the Deep Borehole Demonstration and Categorization.

Activity	Siting Demo	Drilling or Completion	Demo	Proof of Concept	
				Preclosure	Postclosure
SCIENCE ACTIVITIES					
<u>Characterization Methods</u>:					
3D Seismic Imaging	Y		Y		Y
Borehole Caliper Log		Y			
Borehole Gravity Log		Y	Y		Y
Dipole Shear- Wave Velocity Log		Y			Y
Downhaul Force Mechanical Testing			Y		Y
Drill Cuttings		Y	Y		Y
Drill Stem Pump Tests			Y		Y
Drill Stem Tests of Shut-In Pressure		?	Y		Y
Electrical Resistivity Profile	Y				Y
Fluid Pressure Drawdown Test of Effective Permeability			Y		Y
Fluid Samples from Packer Testing			Y		Y
Formation Micro Imager Log		Y	Y		Y
Gamma Ray Log			Y		Y
Gravity and Magnetic Surveys	Y				Y
Intermittent Coring			Y		Y
Neutron Porosity Log			Y		Y
Packer Pump Tests			Y		Y
Push-Pull Tracer Testing			Y		Y
Resistivity Log (Borehole Based)			Y		Y
Spontaneous Potential Log			Y		Y
Surface Geological Mapping	Y				Y
Temperature Log			Y		Y
Vertical Dipole Tracer Testing			Y		Y
Waste Canister Mockup Electrical Heater Test			Y		Y
Cross-hole Tomography			Y		Y
Multi-well Hydraulic Testing			Y		Y
Downhole Camera Logging		Y			
Directional Surveys		Y			
<u>Other Potential Science Activities:</u>					
Long-Term Radiological Monitoring					Y
Waste Canister Degradation Testing			Y	Y	Y
Waste Form Degradation Testing			Y		Y
Radionuclide Characterization			Y		Y
Seal Zone Sorbent Testing			Y		Y
Bentonite Degradation Testing			Y	Y	Y
Cement Degradation Testing			Y	Y	Y
Seal Integrity Testing			Y	Y	Y
Chemical Equilibrium Modeling			Y	Y	Y
Chemical Kinetics Modeling			Y	Y	Y
Source Term Modeling			Y		Y

TH Modeling			Y		Y
THMC Modeling			Y		Y
Multi-Borehole Modeling			Y		Y
FEPs Evaluation			Y	Y	Y
Scenario Design			Y		Y
Conceptual Model Design			Y		Y
Numerical Model Implementation of Sub-Models			Y		Y
Construction of System Model			Y		Y
ENGINEERING ACTIVITIES					
<u>Engineering Activities Supporting Drilling Technology:</u>		Y			
Directional Control		Y			
Drill Rig Engineering		Y			
Drill bit design		Y			
<u>Engineering Activities Supporting Borehole Logging:</u>		Y	Y	Y	Y
<u>Engineering Activities Supporting Borehole Construction:</u>					
Casing Design		Y	Y	Y	
Liner Design		Y	Y	Y	
Verification Size and Casing Strength		Y	Y	Y	
Verification of Liner Hanger and Smooth Transition		Y	Y	Y	
Cementing Related Activities:		Y	Y	Y	
Demonstration of Drilling and Control		Y	Y	Y	
Demonstration of Casing emplacement		Y	Y	Y	
Demonstration of Liner emplacement		Y	Y	Y	
Monitoring Activities:		Y	Y	Y	
<u>Engineering Activities Supporting Test Canister Design:</u>					
Dimension Verification: During Demonstration			Y	Y	Y
Mechanical Load Testing: During Demonstration, Structural Integrity (during loading, transportation, handling, emplacement)			Y	Y	
Drop Testing: During demonstration to simulate emplacement failure or transportation accident.			Y	Y	
Hydrostatic Fluid Pressure Testing: During Demonstration			Y	Y	
Weld Integrity Testing: During Demonstration:					
Pre Load			Y	Y	
Post Load:X-ray Imaging			Y	Y	
Package Connection Testing: Package Connection Functionality and Durability (emplacement and retrieval)			Y	Y	

Yield Strength Testing			Y	Y	
Engineering Activities Supporting Canister Loading Operation:					
Fuel rod consolidation using unirradiated fuels assemblies			Y	Y	
Loading of defense HLW using unirradated glass pours			Y	Y	
Canister Sealing			Y	Y	
Canister Handling			Y	Y	
Engineering Activities Supporting Waste Handling:					
Transference to and from shipping cask using test canister and shipping cask mock ups			Y	Y	
Transference to borehole using test canister mock ups			Y	Y	
Engineering Activities Supporting Waste Canister Emplacement:					
Waste canister string testing using test canister mock ups to assemble, lower, and disengaging waste canister strings			Y	Y	
Grout Emplacement			Y	Y	
Bridge Plug Emplacement			Y	Y	
Remote Methods: Proof of concept to remotely assemble, lower, and disengaging waste canister strings				Y	
Engineering Activities Supporting Radiological Preclosure Monitoring:					
Personnel Dosimeters				Y	
Equipment Monitoring				Y	
Monitoring of Circulating Drilling Fluids				Y	
Engineering Activities Supporting Seals Design:					
Bentonite Seal Emplacement			Y	Y	
Cement Plug Emplacement:			Y	Y	
Cement Seal Emplacement			Y	Y	
Crushed Rock/Cement Backfill Emplacement:			Y	Y	
Mechanical Testing of Emplaced Bridge Plugs			Y	Y	
Engineering Activities Supporting Operational Retrievability:					
Borehole Caliper			Y	Y	
Disposal Caliper Tool Testing			Y	Y	

Testing Retrieval Operations:			Y	Y	
Using Drill Rig			Y	Y	
Mining from Surface			Y	Y	

Appendix C. Importance of FEPS to Deep Borehole Disposal from UFD R&D Road Map

Table C-1. Synopsis of FEPs Priority Ranking for the Deep Borehole Natural System.

GEOSPHERE →		**Borehole**
1.2.01. LONG-TERM PROCESSES (tectonic activity)		Low
1.2.03. SEISMIC ACTIVITY		
Effects on EBS		High
Effects on NS		Low
1.3.01. CLIMATIC PROCESSES AND EFFECTS		Low
2.2.01. EXCAVATION DISTURBED ZONE (EDZ)		High
2.2.02 HOST ROCK (properties)		High
2.2.03 OTHER GEOLOGIC UNITS (properties)		Medium
2.2.05. FLOW AND TRANSPORT PATHWAYS		Medium
2.2.07. MECHANICAL PROCESSES		Low
2.2.08. HYDROLOGIC PROCESSES		Medium
2.2.09. CHEMICAL PROCESSES - CHEMISTRY		Medium - High
2.2.09. CHEMICAL PROCESSES - TRANSPORT		Medium - High
2.2.10. BIOLOGICAL PROCESSES		Low
2.2.11. THERMAL PROCESSES		Medium
2.2.12. GAS SOURCES AND EFFECTS		Low
2.2.14. NUCLEAR CRITICALITY		Low

Notes: Shading for an entry indicates that research in that area has been undertaken in other geologic disposal programs.
FEP number lists includes all FEPs beneath the third level.

Table C-2. Synopsis of FEPs Priority Ranking for the Deep Borehole Engineered System.

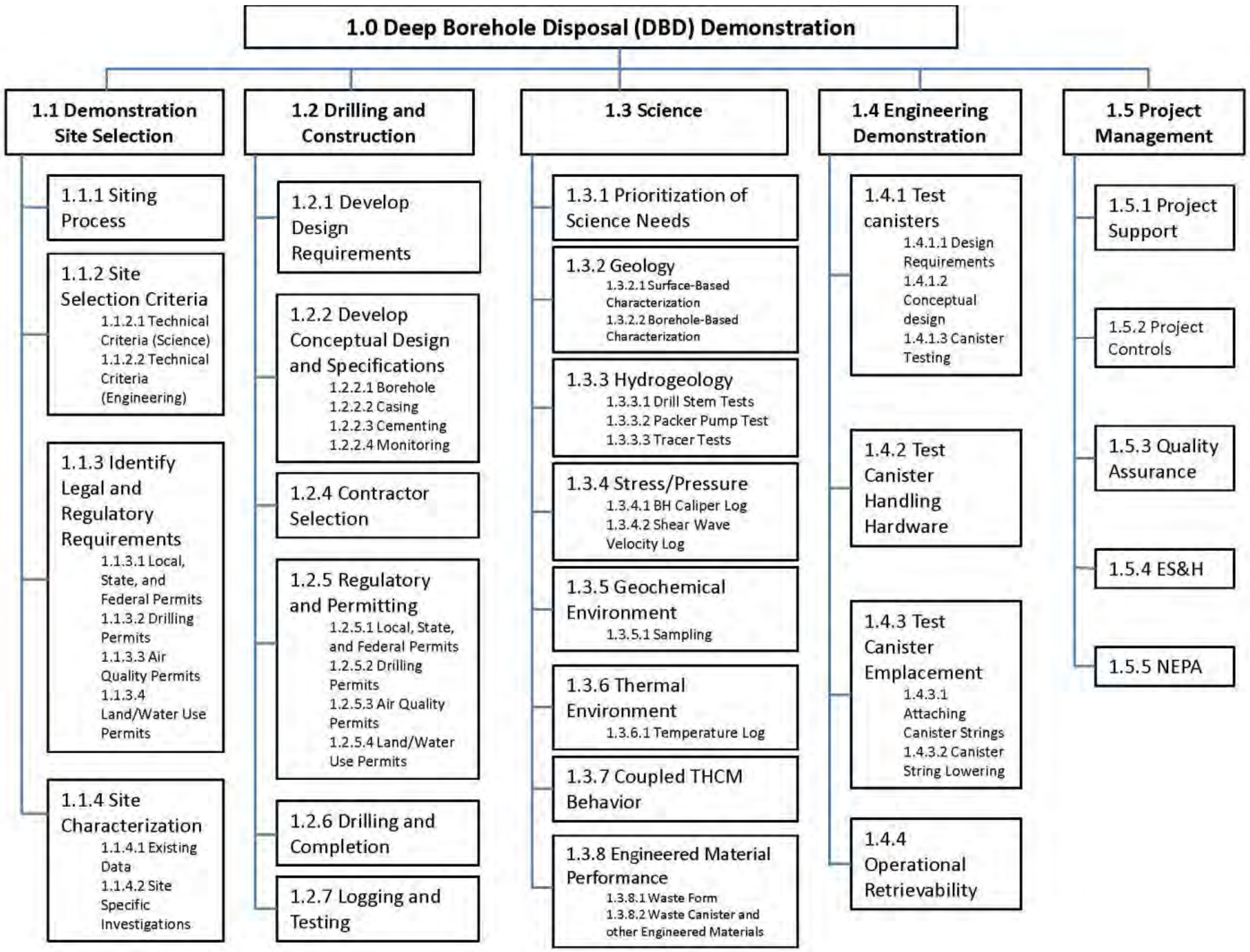
WASTE MATERIALS → SNF, Glass, Ceramic, Metal	
2.1.01.01, .03, .04: INVENTORY	Low
2.1.02.01, .06, .03, .05: WASTE FORM	High
WASTE PACKAGE MATERIALS → Steel, Copper, Other Alloys, Novela Materials	Steel
2.1.03.01, .02, .03, .04, .05, .08: WASTE CONTAINER	High
2.1.07.03, .05, .06, .09: MECHANICAL PROCESSES	Medium
2.1.08.02, .07, .08: HYDROLOGIC PROCESSES	Low
2.1.09.01, .02, .09, .13: CHEMICAL PROCESSES - CHEMISTRY	Medium
Radionuclide speciation/solubility	High
2.1.09.51, .52, .53, .54, .55, .56, .57, .58, .59: CHEMICAL PROCESSES - TRANSPORT	Low
Advection, diffusion, and sorption	Medium
2.1.10.x: BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
2.1.11.01, .02, .04: THERMAL PROCESSES	Medium
2.1.12.01: GAS SOURCES AND EFFECTS	Low
2.1.13.02: RADIATION EFFECTS	Low
2.1.14.01: NUCLEAR CRITICALITY	Low
BUFFER / BACKFILL MATERIALS → Cementitious, bituminous, mixed materials: clay, salt, crystalline environments	
2.1.04.01: BUFFER/BACKFILL	High
2.1.07.02, .03, .04, 09: MECHANICAL PROCESSES	Medium
2.1.08.03, .07, .08: HYDROLOGIC PROCESSES	Medium
2.1.09.01, .03, .07, .09, .13: CHEMICAL PROCESSES - CHEMISTRY	Medium
Radionuclide speciation/solubility	High
2.1.09.51, .52, .53, .54, .55, .56, .57, .58, .59, .61: CHEMICAL PROCESSES – TRANSPORT	Medium
Colloid facilitated transport	Low
2.1.10.x: BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
2.1.11.04: THERMAL PROCESSES	Medium
2.1.12.01, .02, .03: GAS SOURCES AND EFFECTS	Medium
2.1.13.02: RADIATION EFFECTS	Low

2.1.14.02: NUCLEAR CRITICALITY	Low

SEAL / LINER MATERIALS → Cementitious, Asphalt, Metal, Polymers	
2.1.05.01: SEALS	Medium
2.1.06.01: OTHER EBS MATERIALS	Medium
2.1.07.02, .08, .09: MECHANICAL PROCESSES	Medium
2.1.08.04, .05, .07, .08, .09: HYDROLOGIC PROCESSES	Low
Flow through seals	Medium
2.1.09.01, .04, .07, .09, .13: CHEMICAL PROCESSES – CHEMISTRY	Medium
Radionuclide speciation/solubility	High
2.1.09.51, .52, .53, .54, .55, .56, .57, .58, .59: CHEMICAL PROCESSES - TRANSPORT	Low
Advection, diffusion, and sorption	Medium
2.1.10.x: BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
2.1.11.04: THERMAL PROCESSES	Medium
2.1.12.02, .03: GAS SOURCES AND EFFECTS	Low
2.1.13.02: RADIATION EFFECTS	Low
2.1.14.02: NUCLEAR CRITICALITY	Low
OTHER MATERIALS → Low pH Cements, Salt-Saturated Cements, Geo-polymers, Barrier Additives	
2.1.06.01: OTHER EBS MATERIALS	Medium
2.1.07.08, .09: MECHANICAL PROCESSES	Medium
2.1.08.04, .05: HYDROLOGIC PROCESSES	Medium
2.1.09.04, .07, .09, .13: CHEMICAL PROCESSES - CHEMISTRY	Medium
Radionuclide speciation/solubility	High
2.1.09.51, .52, .53, .54, .55, .56, .57, .58, .59: CHEMICAL PROCESSES – TRANSPORT	Low
Advection, diffusion, and sorption	Medium
2.1.10.x: BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
2.1.11.04 THERMAL PROCESSES	Medium
2.1.12.02, .03: GAS SOURCES AND EFFECTS	Low
2.1.13.02: RADIATION EFFECTS	Low
2.1.14.02: NUCLEAR CRITICALITY	Low

Notes: Shading for an entry indicates that research in that area has been undertaken in other geologic disposal programs.
FEP number lists delimited by commas show only the change in the fourth field of the FEP.

Appendix D. WBS Chart

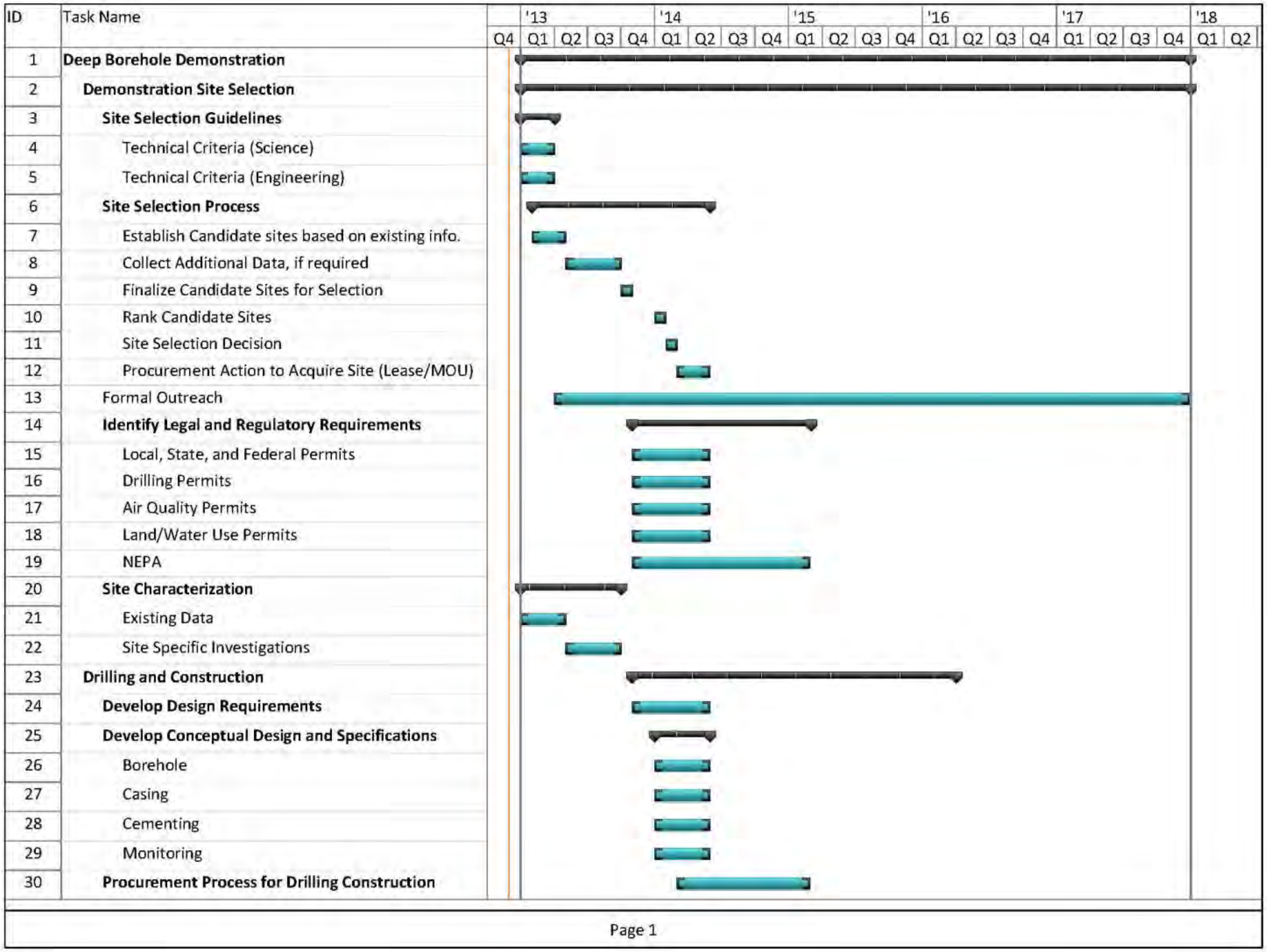


Appendix E. Preliminary Cost Estimate

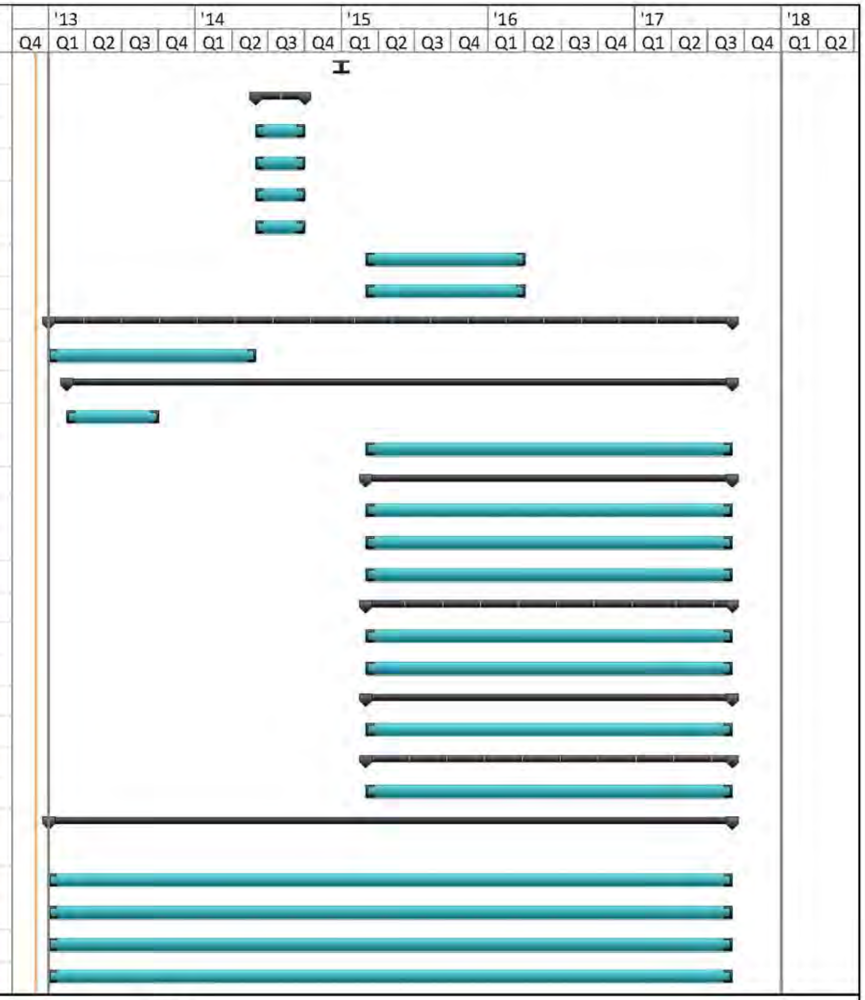
Table E-1. Preliminary Cost Estimates.

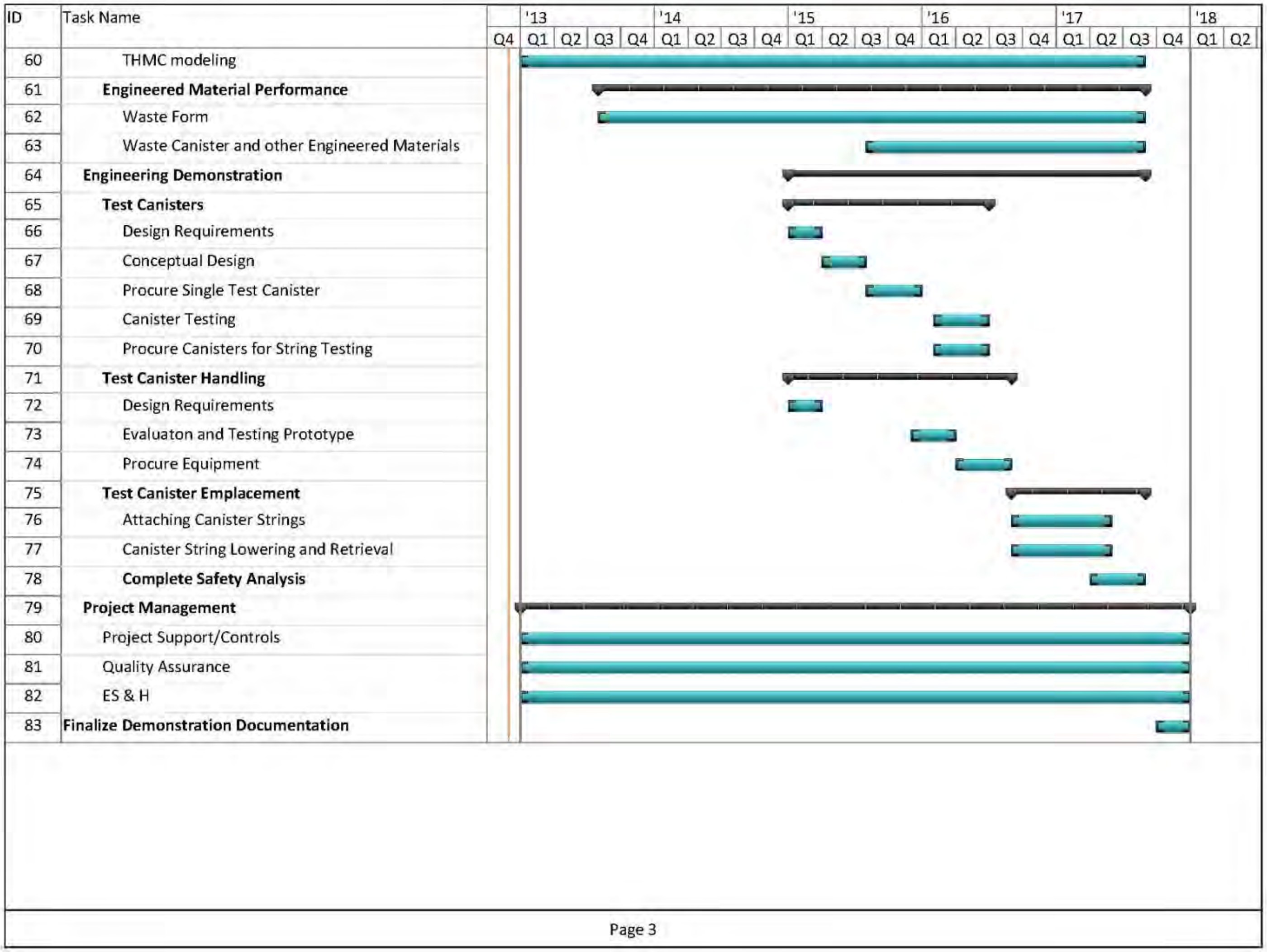
ACTIVITY	ESTIMATED COST($M)
I. SITE CHARACTERIZATION	$3.0
II. SITE SELECTION	$2.0
III. REGULATORY REQUIREMENTS/PERMITS (NEPA, AIR QUALITY, DRILLING, NPDES, ETC.)	$3.5
IV. DRILLING AND CONSTRUCTION	$45.0
V. SCIENCE R&D	$10.0
VI. ENGINEERING DEMONSTRATION	$8.0
VII. PROJECT MANAGEMENT	$3.5
TOTAL	$75.0

Appendix F. DBD Demonstration Project Schedule



ID	Task Name
31	**Contractor Selection**
32	**Regulatory and Permitting**
33	Local, State, and Federal Permits
34	Drilling Permits
35	Air Quality Permits
36	Land/Water Use Permits
37	**Drilling and Well Completion**
38	**Logging and Testing**
39	**Science and Engineering**
40	**Prioritization of Science Needs**
41	**Geology**
42	Surface-Based Characterization
43	Borehole-Based Characterization
44	**Hydrology**
45	Drill Stem Tests
46	Packer Pump Test
47	Tracer Tests
48	**Stress/Pressure**
49	BH Caliper Log
50	Shear Wave Velocity Log
51	**Geochemical Environment**
52	Sampling
53	**Thermal Environment**
54	Temperature Log
55	**System and Subsystem Modeling (Coupled THCM Behavior, etc.)**
56	Disposal System Modeling
57	Waste Form Modeling
58	Transport Modeling
59	TH modeling




ID
Task Name
'13
'14
'15
'16
'17
'18
Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2
60 THMC modeling
61 Engineered Material Performance
62 Waste Form
63 Waste Canister and other Engineered Materials
64 Engineering Demonstration
65 Test Canisters
66 Design Requirements
67 Conceptual Design
68 Procure Single Test Canister
69 Canister Testing
70 Procure Canisters for String Testing
71 Test Canister Handling
72 Design Requirements
73 Evaluaton and Testing Prototype
74 Procure Equipment
75 Test Canister Emplacement
76 Attaching Canister Strings
77 Canister String Lowering and Retrieval
78 Complete Safety Analysis
79 Project Management
80 Project Support/Controls
81 Quality Assurance
82 ES & H
83 Finalize Demonstration Documentation
Page 3