SANDIA REPORT

SAND2012-7981
Unlimited Release
Printed September 2012

Site Characterization Methodology for Deep Borehole Disposal

Palmer Vaughn, Bill W. Arnold, Susan J. Altman, Patrick V. Brady, and William Payton Gardner

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865)576–8401
Facsimile: (865)576–5728
E–Mail: reports@adonis.osti.gov
Online ordering: http://www.doe.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

Telephone: (800)553–6847
Facsimile: (703)605–6900
E–Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/ordering.htm

SAND2012-7981
Unlimited Release
Printed September 2012

Site Characterization Methodology for Deep Borehole Disposal

Palmer Vaughn[1], Bill W. Arnold[2], Susan J. Altman[3], Patrick V. Brady[4], and William "Payton" Gardner[2]

[1]Radiological Consequence Management and Response Technologies Department
[2]Advanced Systems Analysis Department
[3]Geochemistry Department
[4]Geoscience Research and Applications Group
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

ABSTRACT

Deep Borehole Disposal (DBD) for radioactive waste has many clear advantages over mined repositories: 1) the possibility of incremental construction and loading at multiple locations, 2) the enhanced natural barriers in the deep continental crystalline basement, and 3) reduced site characterization. This report identifies characterization methods relevant to DBD of spent nuclear fuel or vitrified high-level waste (HLW). A systematic process based on performance assessment methodology and in particular an analysis of features, events, and processes (FEPs) is used to focus the selection of characterization methods.

Exclusion criteria for a DBD site include 1) upward vertical gradient, 2) economically exploitable natural resources, 3) an interconnected zone of high permeability from the waste disposal zone to the surface or shallow subsurface, and 4) the occurrence of Quaternary-age volcanic rocks or igneous intrusions as an indication of a potentially significant probability of future volcanic activity. Based on these criteria, site characterization activitities should be focused on characterizing 1) faults and fractures, 2) stratigraphy, 3) physical, chemical, and transport properties and lithological information, 4) fluid chemistry, 5) well and seal integrity, 6) likelihood of human intrusion, and 7) structural stability. M ethods that can be used for characterizing each of these features or processes are presented and described in detail in appendices.

Methods are divided into surface based and borehole based. Surface geological mapping will be the first activity to screen potential DBD sites. After there is confidence that exclusion conditions are not present, surface-based characterization would be the next step in site characterization. If

it is decided that a site is potentially suitable, surface-based characterization can help guide the drilling program. Bore-hole based characterization can be used for more detailed site characterization and evaluating features that cannot be evaluated from the surface. While the site design of DBD involves an array of disposal boreholes, it is not necessary to characterize each borehole. Characterization of a primary or central borehole should be sufficient for licensing the disposal array.

A previously developed reference design and concept of disposal operations for the disposal of radioactive waste in deep boreholes informs this study. The results of the reference design development and the cost analysis support the technical feasibility of the DBD concept for high-level radioactive waste. Prior to drilling, surface-based characterization methods are used to evaluate sub-surface site suitability and later confirmed by drilling. In the reference concept the disposal borehole would be drilled to a depth of 5,000 m using a telescoping design and would be logged and tested prior to waste emplacement to confirm suitable downhole conditions. Waste canisters would be constructed of carbon steel, sealed by welds, and connected into canister strings with high-strength connections. Waste canister strings of about 200 m length would be emplaced in the lower 2,000 m of the fully cased borehole and be separated by bridge and cement plugs. Sealing of the upper part of the borehole would be done with a series of compacted bentonite seals, cement plugs, cement seals, cement plus crushed rock backfill, and bridge plugs.

While numerous theoretical studies in the literature conclude that DBD could offer robust isolative capabilities, the deep borehole concept has never been tested in the field. The next step is to demonstrate the feasibility of the deep borehole concept at full scale.

ACKNOWLEDGEMENTS

We greatly appreciate funding from the Sandia National Laboratories Laboratory Directed Research and Development (LDRD) program, Energy, Climate, and Infrastructure (ECIS) Investment Area.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The objective of the report is to identify site characterization methods relevant to Deep Borehole Disposal (DBD) site selection and characterization supporting the safety case. Characterization methods needed in the siting and development of DBD are identified. Features, Events, and Processes (FEPs) (as part of performance assessment (PA) methodology) are used to rationalize the selection of readily available characterization methods. A defined site-characterization program that carefully considers the technical needs to support site selection and a safety case, as determined by the PA methodology and FEPs screening processes, is both fiscally pragmatic and time efficient. These siting preferences are not intended to be regulatory requirements, but rather a desirable methodology to narrow the large area of potential land for DBD in the United States to those locations that could offer adequate technical conditions.

We believe that the greater isolation afforded by deeper emplacement of radioactive waste in DBD means that the characterization necessary for site selection and the safety case would be less than that for a mined geological repository. This greater ability of, and confidence in, natural system isolation, results in the waste canister system serving only to deliver the waste contents downhole and not as a primary containment barrier as is common with mined repository concepts. FEPs and associated characterization of these components can therefore be excluded outright.

1.1 Deep Borehole Disposal Background

Deep borehole disposal of high-level radioactive waste 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). International efforts over the last half-century have primarily focused on mined repositories for the disposal of high-level waste and spent nuclear fuel. However, as the reliability of drilling technology has increased and the cost decreased, DBD becomes a viable alternative. Evaluations of DBD have periodically continued in several countries (O'Brien et al., 1979; Woodward and Clyde Consultants, 1983; Juhlin and Sandstedt, 1989; Heiken et al., 1996; NIREX, 2004; Anderson, 2004; Gibb et al., 2008a, b; Jensen and Driscoll, 2008; Sapiie et al., 2010). Fundamental safety or implementation obstacles have not been identified in previous conceptual evaluations and a preliminary PA of DBD (Brady et al., 2009).

The generalized DBD concept is illustrated in Figure 1. The reference design involves drilling a borehole (or array of boreholes) into crystalline basement rock to a depth of about 5,000 m, emplacing waste canisters containing spent nuclear fuel or vitrified high-level waste in the lower 2,000 m of the borehole, and sealing the upper 3,000 m of the borehole. As shown in Figure 1, waste in the deep borehole is several times deeper than in 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.

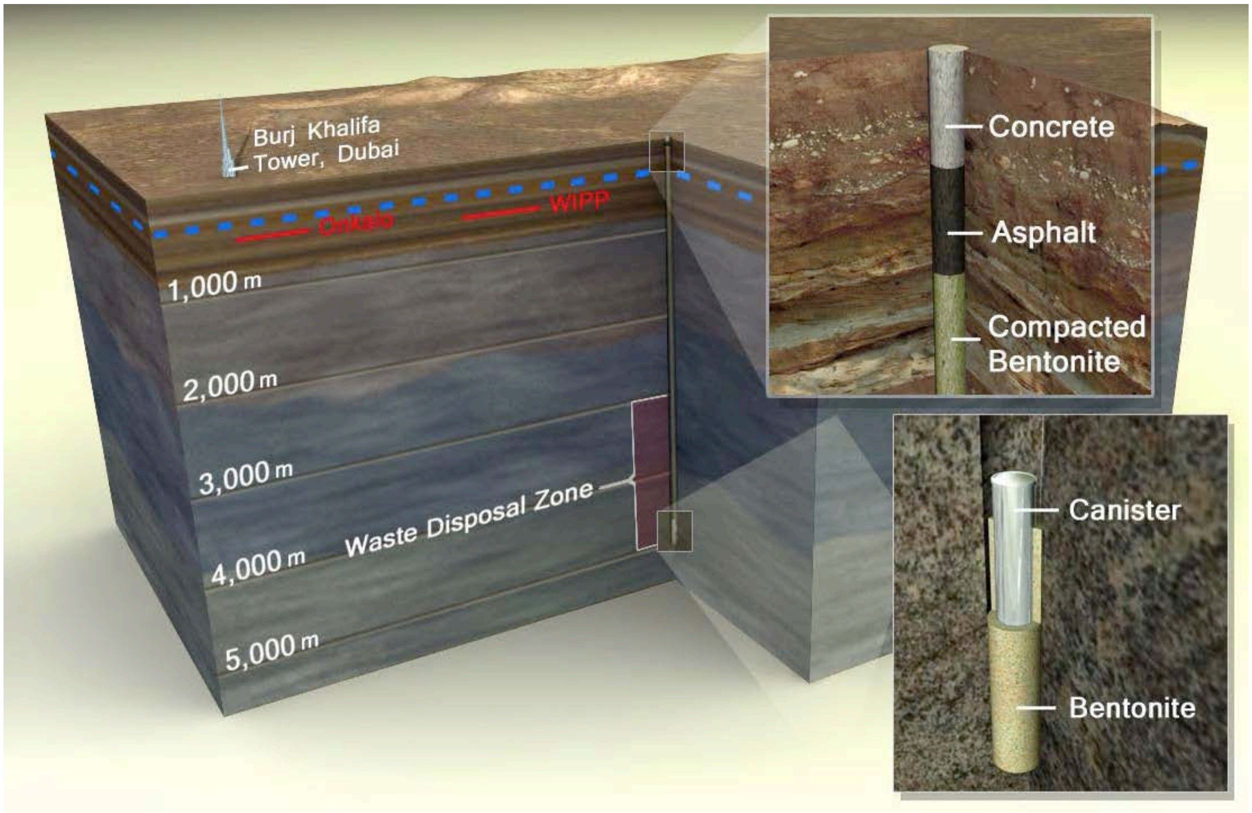

Figure 1. Generalized Concept for Deep Borehole Disposal of High-Level Radioactive Waste.

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.

Several factors suggest that the DBD concept is technically viable and would perform in a manner compliant with anticipated safety regulations. Crystalline basement rocks are relatively common at depths of 2,000 to 5,000 m in stable continental regions, suggesting that numerous potential sites exist (O’Brien et al., 1979; Heiken et al., 1996). Existing drilling technology permits the reliable construction of sufficiently deep and large diameter boreholes (17”, .43m, at a depth of 5,000m) (Brady et al., 2009, Arnold et al., 2011).

There are many distinct advantages to the DBD concept. It facilitates incremental construction and loading at multiple, perhaps regional, locations in contrast to the mined repository concept. Low permeability and high salinity in the deep continental crystalline basement at many locations suggest extremely limited interaction with shallow fresh groundwater resources) (Park et al., 2009), which is the most likely pathway for human exposure (an approximate lower boundary of the fresh groundwater horizon is shown by the dashed blue line in Figure 1). The density stratification of groundwater would also oppose thermally induced groundwater convection from the waste disposal zone to the shallow subsurface. Geochemically reducing conditions in the deep subsurface will serve to both limit the solubility of minerals and enhance sorption of many waste form radionuclides, leading to limited mobility in groundwater.

The reference design, assumptions, and operation procedures for DBD documented in Arnold et al. (2011) are utilized in this report. The primary objective of the design report was to develop a simple and achievable, internally consistent system for waste disposal that meets potential future regulatory requirements for operational safety and long-term performance criteria.

This report also uses the information presented in Brady et al. (2009), particularly for the initial identification of FEPs potentially important to DBD. Brady et al. (2009) documented an evaluation and analysis of several factors (technical, regulatory, safety and performance) concerning the potential for a DBD program, particularly with regard to the U. S., but also relevant to any agency or institution considering the potential for a borehole disposal program. Some of the design aspects presented in Brady et al. (2009) have been refined and updated Arnold et al. (2011); however the FEPs discussion remains consistent with the current vision of DBD and provide meaningful support for this report.

1.2 Exclusion Criteria for Deep Borehole Disposal Characterization

The early steps for site characterization would be placed on ruling out a few conditions or environments that are considered to be less desirable or undesirable. Because there is so many land areas without these conditions, using these exclusion criteria will assist in finding suitable sites. A list of these detractors to site selection and their implications for performance includes:

1) Upward Vertical Gradient: An upward vertical gradient from the disposal depth would be an exclusion criterion. An upward gradient in hydrologic potential within the borehole could result from: a) ambient hydrologic conditions, b) thermal pressurization of fluid within the waste disposal zone from waste heat, c) buoyancy of heated fluid within the waste disposal zone, or d) thermo-chemical reactions that release water and/or gases within the waste disposal zone. Indicators that a site could have an upward vertical gradient include:

    a. Young meteoric groundwater at depth Groundwater in deep crystalline basement rocks of stable continental regions typically has chemical and isotopic characteristics that indicate it is very old. The presence of young meteoric groundwater at depth would indicate an active deep groundwater flow system. Downward vertical migration of young meteoric groundwater implies the potential for corresponding upward groundwater flow that could transport radionuclides to the shallow subsurface.

    b. Low-salinity, oxidizing groundwater at depth: Deep groundwater in the crystalline basement typically has high salinity and strongly reducing geochemical characteristics. The fluid density stratification of highly saline groundwater overlain by fresh groundwater opposes upward groundwater flow. Reducing conditions lead to greater sorption and lower solubility of many radionuclides in spent nuclear fuel. Low-salinity, oxidizing groundwater would indicate greater potential for upward migration of radionuclides, at higher concentrations and rates. Low-salinity, oxidizing groundwater also would be generally indicative of freshwater circulation at depth.

2) Economically exploitable natural resources: The occurrence of subsurface natural resources would increase the potential for subsequent human intrusion via drilling or mining, and the associated release of radionuclides from the DBD system. Examples of natural resources include ore deposits, geothermal heat flow for geothermal energy development, and petroleum resources.

3) Interconnected zone of high permeability from the waste disposal zone to the surface or shallow subsurface (e.g., fault zone): 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.

4) Occurrence of 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.

2 RATIONALE FOR DEEP-BOREHOLE CHARACTERIZATION

2.1 Performance Assessment Methodology

The iterative PA methodology is summarized in Figure 2. The iterations of PA reflect new knowledge states resulting from prior characterization efforts. After performance goals and objectives are defined, system characterization (including site characterization) begins followed by identification of scenarios, model conceptualization, model construction, uncertainty and sensitivity analysis, and evaluate performance. A major part of the scenarios step is the identification and screening of features, events and processes (FEPs) relevant to DBD systems. The results of the FEPs analysis are driven by site characterization and influence what characterization is required. Additionally, the results of the uncertainty and sensitivity analyses identify additional characterization needs and where uncertainty in parameter distributions may need to be reduced.

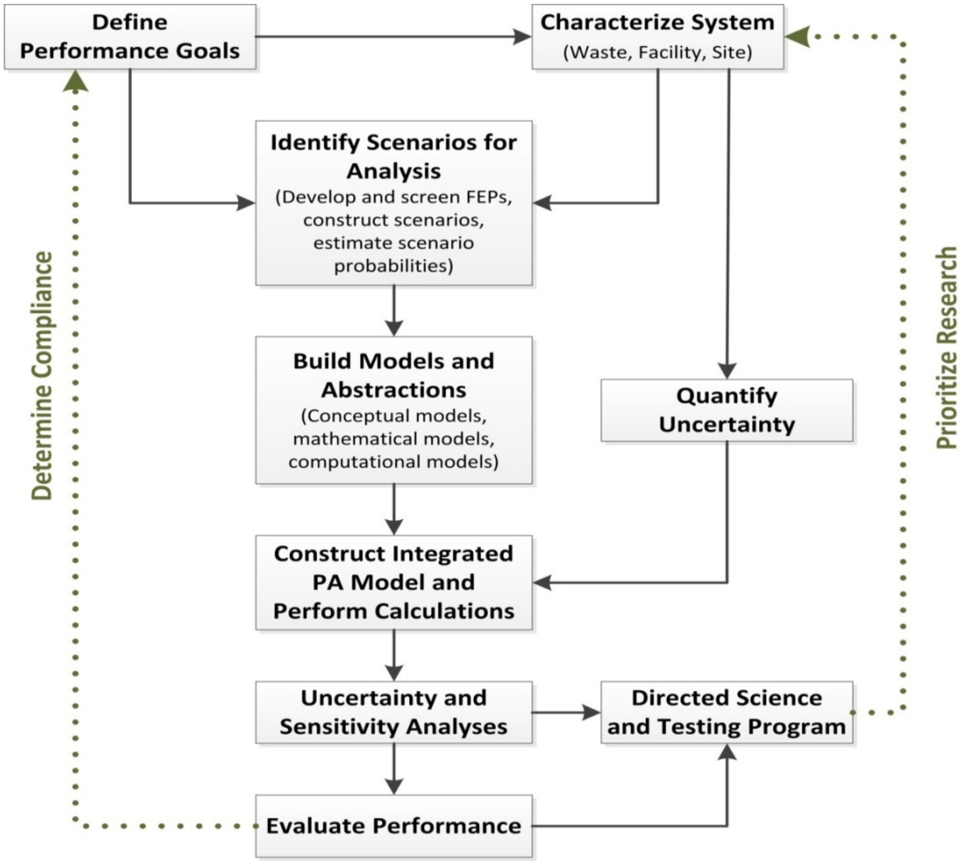

Figure 2. Performance Assessment Methodology (Meacham et al., 2011).

2.2 Scenario Construction and Features, Events, and Processes

The construction of scenarios and the identification and screening of FEPs are important components of the PA methodology and help both to raise the confidence that all factors have been considered and to focus the characterization effort. The processes and events (or sequences of processes and events) that may be relevant over the time frame of interest need to be identified and included in the PA and should be used to identify characterization needs. Relevant (i.e., retained or included) FEPs are used in the construction of the scenarios evaluated in the PA modeling. Results from the PA modeling based on these FEPs further focus the characterization program.

The following definitions are used:

- **Features**—Features are physical, chemical, or thermal characteristics of the site or repository system. For the purposes of identification, classification, and screening of FEPs, a feature is defined as an object, structure, or condition that has a potential to affect disposal system performance (NUREG-1804 2003, Glossary). The waste package is an example of a feature.

- **Events**—Events are occurrences that have a specific starting time and, usually, durations shorter than the time being simulated in a model. For the purposes of identification, classification, and screening of FEPs, an event is defined as a natural or human-caused phenomenon that has a potential to affect disposal system performance and that occurs during an interval that is short compared with the period of performance (NUREG-1804, Glossary). An example of an event is igneous intrusion into the repository.

- **Processes**—Processes are phenomena and activities that have gradual, continuous manifestation within the system being modeled. For the purposes of identification, classification, and screening of FEPs, a process is defined as a natural or human-caused phenomenon that has a potential to affect disposal system performance and that operates during all or a significant part of the period of performance (NUREG-1804 2003, Glossary). General corrosion of the waste package is an example of a process.

Steps in the identification of relevant FEPs include (1) identifying potential FEPs, (2) classifying the FEPs, (3) screening the FEPs, and (4) thoroughly documenting the results. Each is described below.

Identifying FEPs The goal of identifying FEPs potentially relevant to the long-term performance of the system of interest is to be comprehensive (i.e., nothing is too insignificant or improbable to be considered as potentially relevant). For the purpose of identifying the characterization needs associated with DBD, the comprehensive list of FEPs developed for the Yucca Mountain Project (YMP) License Application (LA) was used (BSC 2005). While the YMP FEPs list was developed for a specific repository concept at a specific location, it makes for a comprehensive starting point for DBD because of its broad-based roots. The FEPs included in the list that not applicable to DBD disposal because they involve YM-specific repository features (e.g. drip shield, invert, pallet, etc) are immediately excluded. The engineered features associated with DBD can be captured generically under a feature: “engineered components”, which is included in the comprehensive list. While this list of FEPs is considered comprehensive, possible enhancements or modifications may be suggested as the characterization program proceeds and the DBD concept matures.

The classification of FEPs The primary objectives of FEP identification and classification are to develop a comprehensive set of FEPs for analysis and to provide a framework for developing and organizing scenario classes. An important consideration in the categorization process is to limit ambiguity and provide a location for all potentially relevant FEPs. References to other relevant categories and FEPs can be annotated in the list to help reduce ambiguity and confusion.

FEP screening the goal of FEB screening is to systematically include or exclude those features, events and processes that are not applicable to a specific disposal system or that do not have the potential of contributing significantly to the performance measure (e.g., integrated radionuclide releases). A FEP may be screened for inclusion or exclusion based on any one or more of the following FEP screening criteria:

- ***Regulatory guidance***. Some FEPs may be specifically excluded by regulations that limit the scope of analysis to specific characteristics, concepts, and definitions (NUREG-1804 2003, Section 2.2.1.2.1.3, Acceptance Criterion 2).
- ***Probability of occurrence***. Regulations often specify a threshold of likelihood below which a process or event may be excluded from consideration. Thus, very unlikely FEPs can be excluded (screened out) from the safety analysis to show compliance with standards on the basis of low probability.
- ***Consequence.*** Regulations often specify a consequence threshold below which a process or event may be excluded from consideration. Regardless of likelihood, if an event or process alone or in combination with other events and processes has little to no potential to affect the performance of the disposal system, it may be omitted, providing there is a reasonable expectation that overall performance would remain essentially unchanged by the omission. Such screening requires sufficient justification often in the form of modeling studies, which rely on characterization information.

Once screening of individual FEPs is completed, scenarios—combinations of FEPs each representing a possible realization of the future state of the system—are developed. The process for scenario construction is similar to that for FEPs development: (1) formulate scenarios using retained FEPs, (2) screen scenarios, and (3) thoroughly document results.

2.3 Evaluation of FEPs Relevancy to the Deep Borehole

The FEPs identified in the comprehensive list were evaluated for the disposal of HLW and SNF in a deep borehole (Brady et al., 2009). The results of this evaluation are also presented in Appendix A, Table A-2. Because the Deep Borehole program is in its early stage, a coarse screening has been done that identifies those FEPs that can most likely be excluded from further consideration and identifies those FEPs that are potentially relevant to DBD. A total of 313 out of 374 FEPs are identified as relevant to DBD with the remaining 61 FEPs (indicated by N/A in the last column of Table A-2) identified as not relevant. Of the 313 relevant FEPs, 107 are identified as key FEPs (indicated by highlight on the FEP number in Table A-2) for DBD. Key FEPs are thought to be important to the safety case and need to be evaluated or justify exclusion. Additionally, an estimate is provided of the level of effort needed to either justify the exclusion of a FEP or to indicate the degree of difficulty required for including a FEP.

2.3.1 Approach and Assumptions

The identification of FEPs relevant to DBD follows the process outlined in Brady et al. (2009). The evaluation of FEPs in the DBD performance assessment is based on the assumption that regulatory requirements for DBD will be similar to EPA and NRC regulations (40 CFR part 197 and 10 CFR 63) for Yucca Mountain. Specifically, the performance measure of interest is assumed to be the mean annual dose to a hypothetical member of the public (the "reasonably maximally exposed individual" of 40 CFR 197.21) who lives in the accessible environment near the disposal site. Consistent with approach taken in 40 CFR 197, it is assumed that the mean annual dose shall include probability-weighted consequences (i.e., risk) of releases due to all significant features, events, and processes (FEPs), and shall account for uncertainty associated with those FEPs. Additionally, the FEPs analysis focuses on performance objectives that are internationally acknowledged to be important to the disposal concept such as containment, limited releases, dispersion, and dilution, and defense in depth. It is expected that once regulations specifically applicable to DBD are promulgated, the conclusions with respect to the characterization program will not be significantly impacted.

In evaluating the FEPs for the DBD performance assessment, the following assumptions (beyond 40 CFR part 197 and 10 CFR 63) are made:

- Biosphere exposure is assumed to occur via a contaminated groundwater well immediately adjacent to the borehole. There is, therefore, no release pathway of interest in the unsaturated zone (UZ). All relevant biosphere pathways associated with contaminated well water (e.g., irrigation, crops, livestock, drinking, etc.) are included.

- No isolative credit taken for waste packaging. Therefore FEPs related to failure or corrosion of the waste package and release of radionuclides from the waste package are excluded from the analysis.

- The "Drift" is the portion of the borehole that contains waste (i.e., the waste disposal zone).

- The engineered barrier system (EBS) includes seals and drifts, but the effective performance contribution comes from the borehole seals.

- Backfill, to the extent that it is used, is the material that is emplaced in the waste disposal zone of the borehole surrounding waste canisters.

- There are two release pathways of primary interest: transport through the EBS (seals), and transport through the saturated zone (SZ) in the surrounding rock.

- Naval and DOE spent fuels (called out specifically in the YM analysis) are omitted from this analysis.

- Retrievability of waste is assumed not to be required as a position of policy.

2.3.2 FEP Screening Results

Table A-2 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 DBD) and also includes a qualitative estimate of the level of effort likely to be required to provide a robust basis for the excluding the FEP. The FEPs that are highlighted in Table A-2 represent those FEPs (107 FEPs) currently considered particularly important to DBD (Brady et al., 2009).

For excluded FEPs listed within Table A-2, 1 means the technical or regulatory basis is readily available and all that is needed is documentation; 2 means new technical work likely is needed, and 3 indicates a potentially significant amount of work is needed.

For included FEPs in Table A-2, 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 DBD. New FEPs were not identified in this evaluation process, confirming that the list of FEPs in Table A-2 is a valid starting point for this preliminary analysis. Additional details justifying the classification may be found in Brady et al., 2009. The preliminary evaluation of FEPs in Brady et al. (2009) exclude FEPs associated with criticality, molecular diffusion, and thermal hydrofracturing.

Consideration of the FEPs that have a preliminary screening of "included" in Table A-2 shows that radionuclides emplaced in deep boreholes might reach the biosphere along one, or a combination, of three principal paths: 1) up the borehole (includes accidental release during emplacement that might occur as fission gas release or dissolve in drilling mud); 2) along the annulus of disturbed rock; and/or 3) radially out through groundwater (Brady et al., 2009). But all require a sustained upward gradient in hydrologic potential. A more complete screening of the FEPs may identify additional scenarios of interest, and may also show that some aspects of the chosen scenarios do not need further analysis.

2.4 Characterization Methods Identified From FEPs Screening

The FEPs analysis provides guidance, focus and direction for the deep borehole site characterization program. Each of the FEPs was evaluated against current characterization techniques. Table A-3 of Appendix A 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-2, showing the characterization methods that support each of the FEPS. The items highlighted in each of the tables indicate the 107 key FEPs for DBD as determined in Brady et al., 2009. As seen in Tables A-2 and A-3, 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-2 are addressed using information not coming from the characterization methods identified.

A number of the characterization methods address many of the same FEPs. 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 shortened list. The focus in this report has been to be comprehensive and so further culling of the identified methods has not been done.

3 DEEP BOREHOLE DISPOSAL CHARACTERIZATION METHODS

In Section 3 we discuss the different aspects of site characterization. We explain what needs to be characterized for DBD and why. In addition, we list the methods that could be used to characterize these different features or properties. The methods are divided into surface-based (Appendix B) and borehole-based (Appendix C).

Surface geological mapping will be the first activity to screen potential DBD sites. Existing high-quality, local-scale geological maps are available for many potential sites. These already available local and regional geologic data will be used to assess potential subsurface site suitability. In addition, the existing literature will be search for exclusion criteria of a site. After there is confidence that exclusion conditions are not present, other site-characterization techniques will be pursued. Therefore, unnecessary expenditures for site-characterization will not be spent on unsuitable sites.

Surface-based characterization (Appendix B) would be the next step to confirming that a site is suitable (or eliminating a site). For example, determining the location of the basement rock using geophysical profiles will help determine the basement rock is deep enough to make the site suitable for DBD. Surface-based methods can also be used to locate 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, bore-hole based characterization can be used for more detailed site characterization. In addition, some features cannot be evaluated without borehole-based characterization.

While the site design of DBD involves an array of disposal boreholes, it is not necessary to characterize each borehole. Characterization of a primary or central borehole should be sufficient for licensing the disposal array.

This section is divided into seven subsections based on which features or properties and be characterized:

- Faults and fractures
- Stratigraphy
- Physical, chemical, and transport properties and lithological information
- Fluid Chemistry (water properties)
- Well/seal integrity
- Likelihood of human intrusion
- Structural stability

3.1 Faults and Fractures

It is important to understand any potential interconnected zone of high permeability from the waste disposal zone to the surface or shallow subsurface (e.g., faults or highly fractured zones). 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, the possibility of these preferential pathways intersecting boreholes at depth needs to be evaluated. 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.

Analysis of fault displacement history to identify active faults near the site provides information for 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 and measuring the properties of the system (see Section 0 and 3.4). 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.

The methods that could assist with characterization of fault and fractures zones are listed in Table 1. This table includes the reference to where the method is described in more detail in Appendix B and C as well as how the method would help with DBD characterization.

3.2 Stratigraphy

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.

The methods that could assist with characterization of stratigraphy are listed in Table 2. To optimize site characterization, these methods will be used in conjunction with each other.

Table 1. Methods for characterizing faults and fractures.

Method	Reference	How
Surface Geological Mapping	Section B.1	Correlate surface structures to inferred subsurface faults identified with surface-based geophysical methods
3D Seismic Imaging	Section B.2	Determine whether the boreholes intersect any high permeability pathways
Borehole Caliper Log	Section C.1.1	Possibly identify larger fractures
Spontaneous Potential Log	Section C.1.4	Identify high permeability features
Temperature Log (high resolution in conjunction with fracture imaging methods such as FMI logs)	Section C.1.5 and Section C.1.7	Identification transmissive fractures and fracture zones
Neutron Porosity Log (in combination with other logging methods)	Section C.1.6	Asses the fracturing in the host rock
Borehole Gravity Log	Section C.1.9	Identify fault zones

Table 2. Methods for characterizing stratigraphy

Method	Reference	How
Surface Geological Mapping	Section B.1	Determine surface lithology, Potential correlation of surface lithology with rock types in the boreholes
3D Seismic Imaging	Section B.2	Image stratigraphy
Gravity and Magnetic Surveys	Section B.3	Find the contact between igneous and sedimentary formations
Electrical Resistivity Profile	Section B.4	Locating the contact of the crystalline basement rock
Gamma Ray Log	Section C.1.2	Differentiate shale and other fine-grained sediments from other sedimentary units and other rock types.
Resistivity Log	Section C.1.3	Provide information about lithostratigraphy,
Spontaneous Potential Log	Section C.1.4	Provide information on lithology
Neutron Porosity Log	Section C.1.6	Contributes to the lithological and structural interpretation of the borehole, in combination with other logging methods
Borehole Gravity Log	Section C.1.9	Provide information on lithology
Drill Cuttings Lithology Log	Section C.2.1	Provide a semi-continuous vertical profile of bedrock lithology
Intermittent Coring	Section C.2.2	Provide a semi-continuous vertical profile of bedrock lithology.

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. Petrophysical characteristics of core from intermittent coring can be correlated to geophysical logging to improve the accuracy of the geophysical logging.

3.3 Physical, Chemical and Transport Properties and Lithological Information

Physical, chemical, and transport properties are needed to develop both conceptual model for groundwater flow and radionuclide transport and provide parameters for flow and transport numerical models. Certain properties must be defined in order to develop conceptual models to determine whether or not a site is suitable and what the important processes are at a site. For example, the potential of an upward fluid potential due to regional and local groundwater flow patterns must be ruled out. In addition, conceptual models are needed in order to develop numerical models. In turn, numerical models must be populated with parameters determined or estimated from site characterization activities.

There are many site characterization methods (Table 3) that can assist in defining the properties. Parameters needed for groundwater flow and/or transport models include porosity, bulk permeability, dispersivity, matrix diffusion rates, sorption coefficients, fluid density, and host-rock density. Some properties can be estimated form others, such as flow porosity based on fracture aperture. Thermal properties and density of the host-rock are needed for thermal coupled process modeling, such as thermal-hydrologic or thermal-hydrologic-chemical calculations. Thermal properties are also important to understand and model canister corrosions. In addition, salinity or ionic strength of groundwater has important implications for potential colloid-facilitated transport of radionuclides.

There are different levels of rigor for developing parameter sets. In general, parameters sets with higher levels of rigor are more expensive to develop. At the lowest level, published literature can be used to extract likely ranges of values based on rock types and/or mineralogy. At the next level core-samples can be used to estimate parameters such as porosity, permeability, sorption coefficients, matrix diffusion parameters, and thermal properties. These measurements are made at a smaller scale than numerical models are generally discretized. The most expensive data sets are generated at the field scale, including pump, tracer and waste canister mockup electrical heater testing. *In situ* property measurements augment laboratory measurements by providing data at a larger scale that is more representative of radionuclide migration from the disposal zone. Finally, it should be noted that different kinds of tracer and pump tests measure different parameters at different scales (see the details in Appendix C).

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.

3.4 Fluid Chemistry

The types of measurements that can be made to assist in site characterization for DBD include:

1. Major ion concentrations of the host-rock groundwater,
2. Salinity and vertical salinity profile,

Table 3. Methods for attaining physical, chemical and transport properties and lithological information

Method	Reference	How
Borehole Caliper Log	Section C.1.1	Infer orientation of anisotropy in horizontal stress
Resistivity Log	Section C.1.3	Provide information about lithostratigraphy, formation permeability, fluid saturations, and water quality.
Temperature Log	Section C.1.5	Assess geological basin hydrodynamics. Estimate fluid viscosity and density. In conjunction with fracture imaging methods such as FMI, infer the vertical hydraulic gradient by identifying zones of groundwater inflow and outflow from the borehole
Neutron Porosity Log	Section C.1.6	Provide an estimate of the porosity, in conjunction with measurements on core samples and other logging methods that image fractures in the borehole wall such as FMI logs
Formation Micro Imager Log (FMI)	Section C.1.7	Provide information to estimate bulk permeability, fracture aperture, and therefore host-rock porosity. Identify vertical gradient direction in conjunction with temperature logging.
Borehole Gravity Log	Section C.1.9	Estimate host-rock bulk density and host-rock porosity. Potential identification of mineral alteration.
Intermittent Coring	Section C.2.2	Provide samples for laboratory testing for parameters such as sorption coefficients, bulk density, porosity, permeability, geo-mechanical properties, thermal properties. Provide information about mineralogy, which is relevant to radionuclide adsorption.
Pump Testing	Section C.3	Estimate hydraulic conductivity (horizontal and vertical), specific storage or storativity, and transmissivity of strata of interest, formation pressure and formation permeability. Fluid samples from pump tests can be used to estimate the salinity and/or salinity profile.
Tracer Testing	Section C.4	Estimate flow porosity, dispersivity, sorption coefficient, and matrix diffusion rate dispersivity and matrix diffusion rate. Estimate the ambient groundwater specific discharge in the host rock.
Waste Canister Mockup Electrical Heater Test	Section C.5.1	Estimate the bulk thermal conductivity of the host rock.

3. Environmental tracers,
4. Isotopic composition of the host-rock groundwater, and

The methods to provide groundwater for these measurements are listed in Table 4. Major-ion groundwater chemistry provides information and constraints on the history and evolution of groundwater in the deep borehole environment. Groundwater chemistry is relevant to the solubility and sorption of radionuclides, especially with regard to chemical speciation and

Table 4. Methods for characterizing fluid chemistry

Method	Reference	How
Resistivity Log	Section C.1.3	Can provide information about water quality
Spontaneous Potential Log	Section C.1.4	Determine pore-water quality (e.g. salinity and ionic concentration)
Fluid Samples from Packer Testing	Section C.2.3	Provide water samples for groundwater chemistry testing
Drill Stem Pump Tests	Section C.3.2	Provide water samples for groundwater chemistry testing
Packer Pump Tests	Sections C.3.3	Provide water samples for groundwater chemistry testing

complexation of radionuclides in high ionic strength fluids. Estimates of the salinity profile could be used to calculate the resistance to upward vertical groundwater flow by salinity stratification. The salinity or ionic strength of groundwater also has important implications for potential colloid-facilitated transport of radionuclides. Environmental tracers and/or isotopic composition of the groundwater provide important insights regarding groundwater provenance, groundwater residence times, flow rates through the system, and the interaction of deep groundwater flow with the shallow hydrosphere. These factors are relevant to waste isolation over geologic time scales.

3.5 Borehole and Seal Integrity

The integrity of the borehole and borehole seals are clearly important for the containment of waste. If needed, site characterization tools can be used to identify and/or characterize important properties and features to address borehole integrity (Table 5): host-rock mechanical properties, stress fields (specifically anisotropy in horizontal stress fields), and faults intersecting boreholes. Mechanical properties of the host rock are relevant to borehole stability and the effectiveness of seals. The identification of these features does not necessarily eliminate a site for DBD. Borehole seals can be used to fill in borehole breakouts and isolate faults that intersect boreholes.

Table 5: Methods for evaluating borehole and seal integrity

Method	Reference	How
Borehole Caliper Log	Section C.1.1	Measure borehole breakouts, cave ins or swelling and where casing or cementation is needed
Formation Micro Imager Log (FMI)	Section C.1.7	Determine the location of borehole breakouts and drilling induced-fractures
Dipole Shear-Wave Velocity Log	Section C.1.8	Estimate the directions of *in situ* maximum and minimum horizontal stresses, and their difference in magnitude
Intermittent Coring	Section C.2.2	Provide mechanical characteristics of the various lithologies encountered.
Downhaul Force Mechanical Testing	Section C.6.1	Estimate the strength of borehole seals and plugs
Fluid Pressure Drawdown Test of Effective Permeability	Section C.6.2	Provide information on the potential migration of fluids through and around borehole seals and plugs

It may also necessary to characterize the properties of the borehole seals and plugs. The strength of borehole seals is primarily related to the bond between the seal and the borehole wall and/or casing. Borehole plugs in the waste disposal zone must support the weight of overlying waste canisters and withstand the potential force of expanding fluids during the period of peak temperature generated by thermal output from the waste. The effective permeability of the seals may also be necessary for risk assessment modeling.

3.6 Likelihood of Human Intrusion

Potential of human intrusion is an exclusion criterion for the development of a deep borehole field. In general, any potential subsurface resources, would make human intrusion a possibility. Underground resources include, petroleum reserves, ore deposits an geothermal sources. The methods listed in Table 6 could all be used to identify such resources.

Table 6. Methods for evaluating the likelihood of human intrusion

Method	Reference	How
3D Seismic Imaging	Section B.2	Identify potential underground resources
Gravity and Magnetic Surveys	Section B.3	Identify potential underground resources
Electrical Resistivity Profile	Section B.4	Identify potential underground resources
Gamma Ray Log	Section C.1.2	Identify underground uranium resources
Temperature Log	Section C.1.5	Determination of the geothermal gradient and the potential for geothermal resource development

3.7 Structural Stability

A site with the potential for earthquakes (or a history of earthquakes) would not be suitable for DBH disposal. There are several site-characterization methods that can be used to determine the earthquake potential (Table 7). Differential horizontal stress may give geological evidence regarding the tectonic history and structural stability of the site. 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. As discussion in Section 3.1, analysis of fault displacement history is important to understand seismic risk.

In addition, potential overpressured conditions could also rule-out a site. The salinity profile would be used in determining the vertical gradient in fluid potential and identifying potential overpressured conditions. Methods to determine the salinity profile are listed in Appendix C.

Table 7. Methods for characterizing structural stability of a site

Method	Reference	How
Formation Micro Imager Log (FMI)	Section C.1.7	Determine the location of borehole breakouts and drilling induced-fractures
Dipole Shear-Wave Velocity Log	Section C.1.8	Measure horizontal stress fields.
Intermittent Coring	Section C.2.2	Provide geochemical characteristics of the various lithologies encountered
Drill Stem Tests of Shut-In Pressure	Section C.3.1	Provides information on formation pressure

4 CONCLUSION

Characterization methods have been identified that support DBD site characterization for site selection and generate the data needed to support the development of the safety case and licensing. A systematic process based on performance assessment methodology and in particular an analysis of features, events, and processes (FEPs) are used to focus the selection of characterization methods. The characterization methods identified directly support site selection leading to a successful DBD demonstration or operating facility as well as provide justification for excluding FEPs or for including them in a subsequent safety assessment.

The process consisted of the following steps:

1. Identify a comprehensive list of FEPs.
2. Classify FEPs to provide a framework for scenario development
3. Screen FEPs for relevancy to DBD.

A previous FEPs evaluation (Brady et al., 2009) is presented and used as a basis for this study. The comprehensive list of 375 FEPs selected for evaluation initially developed for the Yucca Mountain Project (YMP) License Application (LA) was used (BSC 2005). An evaluation of those FEPs indicates 107 FEPs are relevant to DBD.

Additionally, a previously developed reference design and concept of disposal operations for the disposal of radioactive waste in deep boreholes (Arnold et al., 2011) helps inform this study. The results of the reference design development and the cost analysis support the technical feasibility of the DBD concept for high-level radioactive waste. In concept the disposal borehole would be drilled to a depth of 5,000 m using a telescoping design and would be logged and tested prior to waste emplacement. Waste canisters would be constructed of carbon steel, sealed by welds, and connected into canister strings with high-strength connections. Waste canister strings of about 200 m length would be emplaced in the lower 2,000 m of the fully cased borehole and be separated by bridge and cement plugs. Sealing of the upper part of the borehole would be done with a series of compacted bentonite seals, cement plugs, cement seals, cement plus crushed rock backfill, asphalt, if needed, and bridge plugs.

Numerous studies in the literature have concluded that DBD of high-level radioactive waste can be inherently safe for a number of reasons, e.g.

- 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,
- Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the retardation of key radionuclides.

Highest priority for site characterization would be placed on ruling out a few conditions or environments that would make a site less suitable than others. These exclusion criteria include:

1) upward vertical gradient,

2) economically exploitable natural resources,

3) an interconnected zone of high permeability from the waste disposal zone to the surface or shallow subsurface,

4) the occurrence of Quaternary-age volcanic rocks or igneous intrusions as an indication of a potentially significant probability of future volcanic activity.

Based on these criteria, site characterization activities should be focused on characterizing:
1) faults and fractures,
2) stratigraphy,
3) physical, chemical, and transport properties and lithological information, 4) fluid chemistry,
4) well and seal integrity,
5) likelihood of human intrusion, and
6) structural stability.

A total of 24 characterization methods were identified addressing 89 FEPs (63 key FEPs for DBD). The characterization methods are organized into Surface Based Methods (Appendix B) and Borehole Based Methods (Appendix C).

Despite numerous positive theoretical studies, the deep borehole disposal concept has never been tested in the field. The next logical step is to demonstrate the feasibility of the deep borehole concept at full scale. Such full-scale demonstration would provide: 1) values on time and costs of drilling specific to DBD-relevant terrains, 2) ability to test predictions of downhole characteristics with actual conditions, 3) a test-bed for operations research (canister handling, canister emplacement and retrieval, plugging and sealing operations, etc.), and 4) insights into the engineering and data needs supporting eventual licensing.

In addition to demonstrating the feasibility of DBD, a demonstration would provide the opportunity to evaluate the characterization methods and potentially reduce their number to a critical subset needed. A pilot project could also be considered for emplacement of surrogate waste once the characterization stage is complete. Given the potential for standardizing the borehole design, and thus the ready extension to multiple borehole facilities, a single pilot project could provide significant gains on the scientific and engineering issues needing to be resolved, enable the development of international standards, and accelerate the realization of deep borehole disposal as an accepted practice. The characterization techniques identified would be important in siting a facility and collecting the necessary information for a successful DBD demonstration or operating facility.

REFERENCES

10 CFR 63. 2007. *Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada*. Internet Accessible.

40 CFR 197 66 F R 32074. *Public Health and Environmental Radiation Protection Standards for Yucca Mountain*, NV; Final Rule. ACC: MOL.20050418.0113.

Anderson, V. K., 2004, An Evaluation of the Feasibility of Disposal of Nuclear Waste in Very Deep Boreholes. Dept. of Nuclear Engineering. Cambridge, MA, MIT.

Ariffin, T., G. Solomon, S. Ujang, M. Bee, S. Jenkins, C. Corbett, G. Dorn, H. Ozdemir, C. Pearse, 1995, Seismic tools for reservoir management, Oilfield Review, vol. 7, no. 4, pp. 4-17.

Arnold, Bill W., Patrick V Brady, Stephen J. Bauer, Courtney Herrick, Stephen Pye, and John Finger, 2011, *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011-6749, Sandia National Laboratories, Albuquerque, NM.

Brady, Patrick V., Bill W. Arnold, Geoff A . Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechard, and Joshua S. Stein, 2009, *Deep Borehole Disposal of High-Level Radioactive Waste.* SAND2009-4401, Sandia National Laboratories, Albuquerque, NM.

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

Chen, Jui-Sheng, Chen-Wuing Liu, Yi-Chieh Chan, Chuen-Fa Ni, and Ke-Kang Kao, 2011, Effect of transverse dispersion on solute transport in a vertical dipole flow test with a tracer, *J. of Hydrology*, vol 402, no. 3-4, p. 206-216.

Cranwell, R.M., R.V. Guzowski, J.E. Campbell, and N.R. Ortiz, 1990, *Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure.* SAND80-1429, NUREGICR-1667. Albuquerque, NM: Sandia National Laboratories.

Daniels, D. L., R. P. Kucks, and P. L. Hill, Illinois, Indiana, and Ohio Magnetic and Gravity Maps and Data, U.S.G.S., DS, 321, 2008.

Di Maio, R., P. Mauriello, D. Patella, Z. Petrillo, S. Piscitelli, and A. Siniscalchi (1998), Electric and electromagnetic outline of the Mount Somma-Vesuvius structural setting, *Journal of Volcanology and Geothermal Research*, *82*(1-4), 219-238.

Freeze, G.A., N.S. Brodsky, and P.N. Swift, 2001, *The Development of Information Catalogued in REV00 of the YMP FEP Database.* TDR-WIS-MD-000003 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company.

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

Gallé, C., 1994, Neutron porosity logging and core porosity measurements in the
Beauvoir granite, Massif Central Range, France, *J. of Applied Geophysics*, vol. 32, 125-137.

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., N.A. McTaggart, K.P. Travis, D. Burley, 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.

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*, vol. 21, p. 676-684.

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

Healey, D. L., F. G. Clutsom, and D. A. Glover, 1986, Borehole Gravity Meter Survey in Drillhole USW G-4, Yucca Mountain Area, Nye County, Nevada*, USGS-OFR-86-205, U.S. Geological Survey, Denver, CO*

Heiken, G., G. Woldegabriel, R. Morley, H. Plannerer, J. Rowley, 1996, *Disposition of Excess Weapon Plutonium in Deep Boreholes – Site Selection Handbook*. Los Alamos, NM, Los Alamos National Laboratory.

Holmes, R.R., Jr., Terrio, P.J., Harris, M.A., and Mills, P.C., 2001, Introduction to Field Methods for Hydrologic and Environmental Studies. U.S. Geological Survey Open-File Report 01-50. p. 236 Chapter 4 Ground Water Data Collection.

Jensen, K. G., and M. J. Driscoll, 2008, *Siting of a deep borehole repository for high level nuclear waste in the United States*, 83 pp, Massachusetts Institute of Technology, Cambridge, MA.

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.

Keys, W. Scott, 1989, Borehole Geophysics Applied to Ground-Water Investigations, Techniques of Water Resources Investigations, Chapter E2, U.S. Geological Survey.

Leap, Darrel I. and Paul 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*, *vol. 24, p. 993-998.*

Meacham, P.G., D.R. Anderson, E.J. Bonano, and M.G. Marietta, 2011, *Sandia National Laboratories Performance Assessment Methodology for Long-Term Environmental Programs: The History of Nuclear Waste Management*. SAND2011-8270. Albuquerque, NM: Sandia National Laboratories.

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

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

NEA (Nuclear Energy Agency), 1992, *Systematic Approaches to Scenario Development: A Report of the NEA Working Group on Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal*. Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.

NEA (Nuclear Energy Agency), 1999, *An International Database of Features, Events and Processes*. Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.

Neretnieks, Ivars, 2007, Single well injection withdrawal tests (SWIW) in fractured rock - Some aspects on interpretation, SKB R-07-54, Svensk Kärnbränslehantering AB, Stockholm, Sweden.

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

NUREG-1804, 2003, *Yucca Mountain Review Plan, Final Report. NUREG-1804, Rev. 2*. U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards, Washington, D.C.

O'Brien, M.T, L.H. Cohen, T.N. Narasimhan, T.L. Simkin, H.A. Wollenberg, W.F. Brace, S. Green, H.P. Platt, 1979, *The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste Disposal*, Berkeley, CA, Lawrence Berkeley Laboratory, LBL-7089.

Park, Y.-J., E.A. Sudicky, and J.F. Sykes, 2009, Effects of shield brine on the safe disposal of waste in deep geologic environments, *Advances in Water Resources* 32: 1352-1358.

Reimus, Paul W. and Timothy 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, Gillian N., 2009, *Development of the Dipole Flow and Reactive Tracer Test (DFRTT) for Aquifer Parameter Estimation*, M.S. Thesis, University of Waterloo, Waterloo, Canada.

Sandia National Laboratories (SNL), 2008, Features, Events, and Processes for the Total System Performance Assessment: Methods. ANL-WIS-MD-000026 REV 00. Sandia National Laboratories, Las Vegas, Nevada.

Sanford, William E., Peter G. Cook, and John C. Dighton, 2002, Analysis of a vertical dipole tracer test in highly fractured rock, *Ground Water*, vol. 40, no. 5, p. 535-542.

Sapiie, B., M. J. Driscoll, and K. G. Jensen, 2010, Regional Examples of Geological Settings for Nuclear Waste Disposal in Deep Boreholes, Rep. MIT-NFC-TR-113, 40 pp, Center for Afvanced Nuclear Energy Systems, Massachusetts Institute of Technology, Cambrige, MA.

Selker, John S., Luc The´venaz, Hendrik Huwald, Alfred Mallet, Wim Luxemburg, Nick van de Giesen, Martin Stejskal, Josef Zeman, Martijn Westhoff, and Marc B. Parlange, 2006, Distributed fiber-optic temperature sensing for hydrologic systems, *Water Resources Research*, vol. 42, W 12202, doi:10.1029/2006WR005326, 2006.

Smith, B. D., J. D. Abraham, J. C., Cannia, B. J. Minsley, L. B. Ball, G. V. Steele, M. Deszcz-Pan, Helicopter electromagnetic and magnetic geophysical survey data, Swedeburg and Sprague study areas, eastern Nebraska, May 2009. U. S. G. S. Open File Report, OFR 2010-1288, 2011

Theis, Charles V. (1935). The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Transactions, American Geophysical Union* **16**: 519–524.

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

Wightman, W. E., F. Jalinoos, P. Sirles, and K. Hanna, 2003, Application of Geophysical Methods to Highway Related Problems. Federal Highway Administration, Central Federal Lands Highway Division, Lakewood, CO, Publication No. FHWA-IF-04-021, September 2003. ***http://www.cflhd.gov/resources/agm/***

APPENDIX A: DETAILED RESULTS OF FEPS ANALYSIS

Appendix A contains detailed results of the FEPs analysis for DBD and the identification of characterization needs. Table A-1 outlines the FEPs classification hierarchy used to organize the FEPs. Table A-2 presents the comprehensive list of FEPs used to determine likely screening decisions and characterization needs for DBD. Finally, Table A-3 identifies each of the characterization methods and associates them with the FEPs they address.

A variety of classification schemes have served as organizational tools to aid in determining completeness (Cranwell et al., 1990; NEA, 1992; NEA, 1999). These are sorting and organizing approaches used to support consistent and multidiscipline analysis of the FEPs. In this analysis, the disposal system FEPs are categorized and organized following the system developed for the Yucca Mountain License Application, (Sandia National Laboratories, 2008). As discussed above, this FEP classification structure has as its basis the categorization hierarchy established by the NEA, (NEA 1999). The hierarchical classification consists of levels and layers, which define the organizational structure into which individual FEPs are mapped. There are 5 levels and multiple layers to the hierarchy. The FEPs number system used is reflective of this hierarchy. The FEPs numbering is of the form #.#.##.##.0x, where each of the alphanumerics separated by a decimal point coincides with the levels (level 1 being the right most and level 5 the left most). The first three groups (#.#.##) are numeric and are based on the hierarchical classification levels in the NEA International FEP Database and correspond to NEA Layer, Category, and Heading (Freeze et al., 2001, Section 3.1). The fourth digit groupings are subjective numbering for multiple FEPs that are mapped to the level 3 category. The final group is alphanumeric with the form .0A, .0B, .0C, etc. The designator 0A is generally assigned to the FEP but if that FEP requires further refinement because the resulting screening decision is ambiguous then designators 0B, OC, etc. are used.

1) Classification Structure for FEPs relevant to Deep Borehole Disposal

Table A-1. Hierarchical Classification Levels for FEPs relevant to Deep Borehole Disposal (adapted from NEA 1999, pp. 28 to 34; Freeze et al., 2001, Section 3).

Level 1	Level 2	Level 3
0. Assessment Basis	0.1	0.1.01 Impacts of concern
		0.1.02 Timescales of concern
		0.1.03 Spatial domain of concern
		0.1.04 Repository assumptions
		0.1.05 Future human action assumptions
		0.1.06 Future human behavior (target group) assumptions
		0.1.07 Dose response assumptions
		0.1.08 Aims of the assessment
		0.1.09 Regulatory requirements and exclusions
		0.1.10 Model and data issues
1. External Factors	1.1 Repository Issues	1.1.01 Site investigation
		1.1.02 Excavation/construction
		1.1.03 Emplacement of wastes and backfilling
		1.1.04 Closure and repository sealing
		1.1.05 Records and markers, repository
		1.1.06 Waste allocation
		1.1.07 Repository design
		1.1.08 Quality control
		1.1.09 Schedule and planning
		1.1.10 Administrative control, repository site

		1.1.11 Monitoring of repository
		1.1.12 Accidents and unplanned events
		1.1.13 Retrievability
	1.2 Geological Processes and Effects	1.2.01 Tectonic movements and orogeny
		1.2.02 Deformation, elastic, plastic or brittle
		1.2.03 Seismicity
		1.2.04 Volcanic and magmatic activity
		1.2.05 Metamorphism
		1.2.06 Hydrothermal activity
		1.2.07 Erosion and sedimentation
		1.2.08 Diagenesis
		1.2.09 Salt diapirism and dissolution
		1.2.10 Hydrological/hydrogeological response to geological changes
	1.3 Climatic Processes and Events	1.3.01 Climate change, global
		1.3.02 Climate change, regional and local
		1.3.03 Sea level change
		1.3.04 Periglacial effects
		1.3.05 Glacial and ice sheet effects, local
		1.3.06 Warm climate effects (tropical and desert)
		1.3.07 Hydrological/hydrogeological response to climate changes
		1.3.08 Ecological response to climate changes
		1.3.09 Human response to climate changes
	1.4 Future Human Actions	1.4.01 Human influences on climate
		1.4.02 Motivation and knowledge issues (inadvertent/deliberate human actions)
		1.4.03 Un-intrusive site investigation
		1.4.04 Drilling activities (human intrusion)
		1.4.05 Mining and other underground activities (human intrusion)
		1.4.06 Surface environment, human activities
		1.4.07 Water management (wells, reservoirs, dams)
		1.4.08 Social and institutional developments
		1.4.09 Technological developments
		1.4.10 Remedial actions
		1.4.11 Explosions and crashes
	1.5 Other	1.5.01 Meteorite impact
		1.5.02 Species evolution
		1.5.03 Miscellaneous and FEPs of uncertain relevance
2. Disposal System Domain: Environmental Factors	2.1 Wastes and Engineered Features	2.1.01 Inventory, radionuclide and other material
		2.1.02 Waste form materials and characteristics
		2.1.03 Container materials and characteristics
		2.1.04 Buffer/backfill materials and characteristics
		2.1.05 Seals, cavern/tunnel/shaft
		2.1.06 Other engineered features materials and characteristics
		2.1.07 Mechanical processes and conditions (in wastes and EBS)
		2.1.08 Hydraulic/hydrogeological processes and conditions (in wastes and EBS)
		2.1.09 Chemical/geochemical processes and conditions (in wastes and EBS)
		2.1.10 Biological/biochemical processes and conditions (in

		wastes and EBS)
		2.1.11 Thermal processes and conditions (in wastes and EBS)
		2.1.12 Gas sources and effects (in wastes and EBS)
		2.1.13 Radiation effects (in wastes and EBS)
		2.1.14 Nuclear criticality
	2.2 Geological Environment	2.2.01 Excavation disturbed zone, host rock
		2.2.02 Host rock
		2.2.03 Geological units, other
		2.2.04 Discontinuities, large scale (in geosphere)
		2.2.05 Contaminant transport path characteristics (in geosphere)
		2.2.06 Mechanical processes and conditions (in geosphere)
		2.2.07 Hydraulic/hydrogeological processes and conditions (in geosphere)
		2.2.08 Chemical/geochemical processes and conditions (in geosphere)
		2.2.09 Biological/biochemical processes and conditions (in geosphere)
		2.2.10 Thermal processes and conditions (in geosphere)
		2.2.11 Gas sources and effects (in geosphere)
		2.2.12 Undetected features (in geosphere)
		2.2.13 Geological resources
	2.3 Surface Environment	2.3.01 Topography and morphology
		2.3.02 Soil and sediment
		2.3.03 Aquifers and water-bearing features, near surface
		2.3.04 Lakes, rivers, streams and springs
		2.3.05 Coastal features
		2.3.06 Marine features
		2.3.07 Atmosphere
		2.3.08 Vegetation
		2.3.09 Animal populations
		2.3.10 Meteorology
		2.3.11 Hydrological regime and water balance (near-surface)
		2.3.12 Erosion and deposition
		2.3.13 Ecological/biological/microbial systems
	2.4 Human Behavior	2.4.01 Human characteristics (physiology, metabolism)
		2.4.02 Adults, children, infants and other variations
		2.4.03 Diet and fluid intake
		2.4.04 Habits (non-diet-related behaviour)
		2.4.05 Community characteristics
		2.4.06 Food and water processing and preparation
		2.4.07 Dwellings
		2.4.08 Wild and natural land and water use
		2.4.09 Rural and agricultural land and water use (incl. fisheries)
		2.4.10 Urban and industrial land and water use
		2.4.11 Leisure and other uses of environment
3. Disposal System Domain: Radionuclide/Contaminant Factors	3.1 Contaminate Characteristic	3.1.01 Radioactive decay and in-growth
		3.1.02 Chemical/organic toxin stability
		3.1.03 Inorganic solids/solutes
		3.1.04 Volatiles and potential for volatility
		3.1.05 Organics and potential for organic forms
		3.1.06 Noble gases
	3.2 Contaminate Release/ Migration Factors	3.2.01 Dissolution, precipitation and crystallization, contaminant

		3.2.02 Speciation and solubility, contaminant
		3.2.03 Sorption/desorption processes, contaminant
		3.2.04 Colloids, contaminant interactions and transport with
		3.2.05 Chemical/complexing agents, effects on contaminant speciation/transport
		3.2.06 Microbial/biological/plant-mediated processes, contaminant
		3.2.07 Water-mediated transport of contaminants
		3.2.08 Solid-mediated transport of contaminants
		3.2.09 Gas-mediated transport of contaminants
		3.2.10 Atmospheric transport of contaminants
		3.2.11 Animal, plant and microbe mediated transport of contaminants
		3.2.12 Human-action-mediated transport of contaminants
		3.2.13 Food chains, uptake of contaminants
	3.3 Exposure Factors	3.3.01 Drinking water, foodstuffs and drugs, contaminant concentrations in
		3.3.02 Environmental media, contaminant concentrations in
		3.3.03 Non-food products, contaminant concentrations in
		3.3.04 Exposure modes
		3.3.05 Dosimetry
		3.3.05 Dosimetry
		3.3.06 Radiological toxicity/effects
		3.3.07 Non-radiological toxicity/effects
		3.3.08 Radon and radon daughter exposure

2) Comprehensive FEPs list for Deep Borehole Disposal

Table A-2. 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.) (Brady et al., 2009)

Note: Highlighted entry indicates key[1] FEP for Deep Borehole Disposal.

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
0.1.02.00.0A	Timescales of Concern	Include	1	Address with other information
0.1.03.00.0A	Spatial Domain of Concern	Include	1	Address with other information
0.1.09.00.0A	Regulatory Requirements and Exclusions	Include	3 Regulations and laws will need to be revised	Address with other information
0.1.10.00.0A	Model and Data Issues	Include	1	Address with other information
1.1.01.01.0A	Open Site Investigation Boreholes	Exclude	1	N/A
1.1.01.01.0B	Influx Through Holes Drilled in Drift Wall or Crown	Exclude	1	N/A
1.1.02.00.0A	Chemical Effects of Excavation and Construction in EBS	Exclude	2	Address with other information
1.1.02.00.0B	Mechanical Effects of Excavation and Construction in EBS	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)	Exclude	1	Address with existing data and engineering mitigation
1.1.02.02.0A	Preclosure Ventilation	Exclude (NA)	1	N/A
1.1.02.03.0A	Undesirable Materials Left	Exclude	2	Address with other information
1.1.03.01.0A	Error in Waste Emplacement	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	Include	Maybe 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	Exclude	2	Address with engineering demonstration
1.1.05.00.0A	Records and Markers for the Repository	Exclude)	1	Address with other information regulatory
1.1.07.00.0A	Repository Design	Include	1	Address with other

---

[1] Key FEPs are thought to be important to the safety case and need to be evaluated or justify exclusion.

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
				information
1.1.08.00.0A	Inadequate Quality Control and Deviations from Design	Exclude	1	Address with other information regulatory or low consequence
1.1.09.00.0A	*Schedule and Planning*	*Exclude*	*1*	Address with other information
1.1.10.00.0A	*Administrative Control of the Repository Site*	*Exclude*	*1*	Address with other information
1.1.11.00.0A	*Monitoring of the Repository*	*Exclude*	*1*	Address with other information
1.1.12.01.0A	*Accidents and Unplanned Events During Construction and Operation*	*Exclude*	*1*	Address with other information
1.1.13.00.0A	*Retrievability*	*Exclude*	*2*	Address with engineering demonstration
1.2.01.01.0A	*Tectonic Activity - Large Scale*	*Exclude*	*1*	Address with existing data
1.2.02.01.0A	*Fractures*	*Include*	*2*	Formation micro imager log, temperature log,
1.2.02.02.0A	*Faults*	*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*	*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*	*Exclude*	*2*	Address with other information
1.2.03.02.0B	*Seismic-Induced Rockfall Damages EBS Components*	*Exclude*	*1*	N/A
1.2.03.02.0C	*Seismic-Induced Drift Collapse Damages EBS Components*	*Exclude*	*1*	N/A
1.2.03.02.0D	*Seismic-Induced Drift Collapse Alters In-Drift Thermohydrology*	*Exclude*	*1*	N/A
1.2.03.02.0E	*Seismic-Induced Drift Collapse Alters In-Drift Chemistry*	*Exclude*	*1*	N/A
1.2.03.03.0A	*Seismicity Associated With Igneous Activity*	*Exclude*	*1*	Address with other information
1.2.04.02.0A	*Igneous Activity Changes Rock Properties*	*Exclude*	*2* *Need to evaluate potential for igneous activity at each site (should generically be low), also need to determine if repository heat can contribute to rock melting*	Address with other information

DBD/YMP FEP Number	**DBD/YMP FEP Name**	**Likely DBD Decision**	**Estimated DBD Level of Effort**	
1.2.04.03.0A	*Igneous Intrusion Into Repository*	*Exclude*	*2*	Address with other information
1.2.04.04.0A	*Igneous Intrusion Interacts With EBS Components*	*Exclude*	*2*	Address with other information
1.2.04.04.0B	*Chemical Effects of Magma and Magmatic Volatiles*	*Exclude*	*2* *Volatiles may impact transport*	Address with other information
1.2.04.05.0A	*Magma Or Pyroclastic Base Surge Transports Waste*	*Exclude*	*1*	Address with other information
1.2.04.06.0A	*Eruptive Conduit to Surface Intersects Repository*	*Exclude*	*2*	Address with other information
1.2.04.07.0A	*Ashfall*	*Exclude*	*1*	Address with other information A
1.2.04.07.0B	*Ash Redistribution in Groundwater*	*Exclude*	*1*	Address with other information
1.2.04.07.0C	*Ash Redistribution Via Soil and Sediment Transport*	*Exclude*	*1*	Address with other information
1.2.05.00.0A	*Metamorphism*	*Exclude*	*2* *Repository heat may create metamorphic conditions*	Address with other information
1.2.06.00.0A	*Hydrothermal Activity*	*Exclude*	*3* *Repository heat may create local hydrothermal activity*	Address with other information
1.2.07.01.0A	*Erosion/Denudation*	*Exclude*	*1*	Address with other information
1.2.07.02.0A	*Deposition*	*Exclude*	*1*	Address with other information
1.2.08.00.0A	*Diagenesis*	*Exclude*	*2*	Address with other information
1.2.09.00.0A	*Salt Diapirism and Dissolution*	*Exclude*	*1*	Address with other information
1.2.09.01.0A	*Diapirism*	*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*	*Exclude*	*1*	Address with other information
1.2.10.01.0A	*Hydrologic Response to Seismic Activity*	*Exclude*	*1*	Address with other information
1.2.10.02.0A	*Hydrologic Response to Igneous Activity*	*Exclude*	*2*	Address with other information
1.3.01.00.0A	*Climate Change*	*Exclude*	*1*	Address with other information
1.3.04.00.0A	*Periglacial Effects*	*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*	*Exclude*	*2* *Need to consider fluid pressure effects of future ice sheet loading*	Address with existing data, groundwater chemistry and isotopic composition in fluid samples from packer testing
1.3.07.01.0A	*Water Table Decline*	*Exclude*	*1*	Address with other

DBD/YMP FEP Number	**DBD/YMP FEP Name**	**Likely DBD Decision**	**Estimated DBD Level of Effort**	
				information
1.3.07.02.0A	*Water Table Rise Affects SZ*	*Exclude*	*1*	Address with other information
1.3.07.02.0B	*Water Table Rise Affects UZ*	*Exclude*	*1* *All UZ FEPs are simplified*	Address with other information
1.4.01.00.0A	*Human Influences on Climate*	*Exclude*	*1*	Address with other information
1.4.01.01.0A	*Climate Modification Increases Recharge*	*Exclude*	*1*	Address with other information
1.4.01.02.0A	*Greenhouse Gas Effects*	*Exclude*	*1*	Address with other information
1.4.01.03.0A	*Acid Rain*	*Exclude*	*1*	Address with other information
1.4.01.04.0A	*Ozone Layer Failure*	*Exclude*	*1*	Address with other information
1.4.02.01.0A	*Deliberate Human Intrusion*	*Exclude*	*1*	Address with other information
1.4.02.02.0A	*Inadvertent Human Intrusion*	*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*	*Exclude*	*1*	Address with other information
1.4.02.04.0A	*Seismic Event Precedes Human Intrusion*	*Exclude*	*1*	Address with other information
1.4.03.00.0A	*Unintrusive Site Investigation*	*Exclude*	*1*	Address with other information
1.4.04.00.0A	*Drilling Activities (Human Intrusion)*	*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*	*Exclude*	*1*	Address with other information
1.4.05.00.0A	*Mining and Other Underground Activities*	*Exclude*	*1* *Includes natural resource*	Mineral composition of core and cuttings samples,

DBD/YMP FEP Number	**DBD/YMP FEP Name**	**Likely DBD Decision**	**Estimated DBD Level of Effort**	
	(Human Intrusion)		*issues*	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*	*Exclude*	*1*	Address with other information
1.4.07.01.0A	*Water Management Activities*	*Exclude*	*1*	Address with existing data for characterization of the reference biosphere
1.4.07.02.0A	*Wells*	*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*	*Exclude*	*1*	Address with other information
1.4.08.00.0A	*Social and Institutional Developments*	*Exclude*	*1*	Address with other information
1.4.09.00.0A	*Technological Developments*	*Exclude*	*1*	Address with other information
1.4.11.00.0A	*Explosions and Crashes (Human Activities)*	*Exclude*	*1*	Address with other information
1.5.01.01.0A	*Meteorite Impact*	*Exclude*	*1*	Address with other information
1.5.01.02.0A	*Extraterrestrial Events*	*Exclude*	*1*	Address with other information
1.5.02.00.0A	*Species Evolution*	*Exclude*	*1*	Address with other information
1.5.03.01.0A	*Changes in the Earth's Magnetic Field*	*Exclude*	*1*	Address with other information
1.5.03.02.0A	*Earth Tides*	*Exclude*	*1*	Address with other information
2.1.01.01.0A	*Waste Inventory*	*Include*	*1*	Address with other information
2.1.01.02.0A	Interactions Between Co-Located Waste	Exclude	1	Address with other information
2.1.01.02.0B	Interactions Between Co-Disposed Waste	Exclude	1	N/A
2.1.01.03.0A	Heterogeneity of Waste Inventory	Include	1	Address with other information
2.1.01.04.0A	Repository-Scale Spatial Heterogeneity of Emplaced Waste	Include	1	Address with other information
2.1.02.01.0A	DSNF Degradation (Alteration, Dissolution, and Radionuclide Release)	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)	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 (Alteration, Dissolution, and Radionuclide Release)	Exclude	1 Assume no credit for HLW waste form	Address with other information, groundwater chemistry in fluid samples

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
				from packer testing
2.1.02.04.0A	Alpha Recoil Enhances Dissolution	Exclude	1	Address with other information
2.1.02.05.0A	HLW Glass Cracking	Exclude	1	Address with other information
2.1.02.06.0A	HLW Glass Recrystallization	Exclude	1	Address with other information
2.1.02.07.0A	Radionuclide Release from Gap and Grain Boundaries	Exclude	1	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.02.08.0A	Pyrophoricity from DSNF	Exclude	1	Address with other information
2.1.02.09.0A	Chemical Effects of Void Space in Waste Package	Exclude	1	Address with other information
2.1.02.10.0A	Organic/Cellulosic Materials in Waste	Exclude	1	Address with other information
2.1.02.11.0A	Degradation of Cladding from Waterlogged Rods	Exclude	1	Address with other information
2.1.02.12.0A	Degradation of Cladding Prior to Disposal	Exclude	1	Address with other information
2.1.02.13.0A	General Corrosion of Cladding	Exclude	1	Address with other information
2.1.02.14.0A	Microbially Influenced Corrosion (MIC) of Cladding	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	Exclude	1	Address with other information
2.1.02.16.0A	Localized (Pitting) Corrosion of Cladding	Exclude	1	Address with other information
2.1.02.17.0A	Localized (Crevice) Corrosion of Cladding	Exclude	1	Address with other information
2.1.02.18.0A	Enhanced Corrosion of Cladding from Dissolved Silica	Exclude	1	Address with other information
2.1.02.19.0A	Creep Rupture of Cladding	Exclude	1	Address with other information
2.1.02.20.0A	Internal Pressurization of Cladding	Exclude	1	Address with other information
2.1.02.21.0A	Stress Corrosion Cracking (SCC) of Cladding	Exclude	1	Address with other information
2.1.02.22.0A	Hydride Cracking of Cladding	Exclude	1	Address with other information
2.1.02.23.0A	Cladding Unzipping	Exclude	1	Address with other information
2.1.02.24.0A	Mechanical Impact on Cladding	Exclude	1	Address with other information
2.1.02.25.0A	DSNF Cladding	Exclude	1	Address with other information
2.1.02.25.0B	Naval SNf Cladding	Exclude	1	N/A, Exclude Naval SNF from analysis completely
2.1.02.26.0A	Diffusion-Controlled Cavity	Exclude	1	Address with other

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
	Growth in Cladding			information
2.1.02.27.0A	Localized (Fluoride Enhanced) Corrosion of Cladding	Exclude	1	Address with other information
2.1.02.28.0A	Grouping of DSNF Waste Types Into Categories	Exclude	1	Address with other information
2.1.02.29.0A	Flammable Gas Generation from DSNF	7Exclude	1	Address with other information
2.1.03.01.0A	General Corrosion of Waste Packages	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.01.0B	General Corrosion of Drip Shields	Exclude	1	N/A, no drip- shield
2.1.03.02.0A	Stress Corrosion Cracking (SCC) of Waste Packages	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.02.0B	Stress Corrosion Cracking (SCC) of Drip Shields	Exclude	1	N/A, no drip- shield
2.1.03.03.0A	Localized Corrosion of Waste Packages	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.03.0B	Localized Corrosion of Drip Shields	Exclude	1	N/A, no drip- shield
2.1.03.04.0A	Hydride Cracking of Waste Packages	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.04.0B	Hydride Cracking of Drip Shields	Exclude	1	N/A, no drip- shield
2.1.03.05.0A	Microbially Influenced Corrosion (MIC) of Waste Packages	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.05.0B	Microbially Influenced Corrosion (MIC) of Drip Shields	Exclude	1	N/A, no drip- shield
2.1.03.06.0A	Internal Corrosion of Waste Packages Prior to Breach	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.07.0A	Mechanical Impact on Waste Package	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	Exclude	1	N/A, no drip- shield
2.1.03.08.0A	Early Failure of Waste Packages	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.03.08.0B	Early Failure of Drip Shields	Exclude	1	N/A, no drip- shield
2.1.03.09.0A	Copper Corrosion in EBS	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	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	Exclude (NA)	1	N/A, no drip- shield
2.1.03.11.0A	Physical Form of Waste Package and Drip Shield	Include	1	Address with other information
2.1.04.01.0A	Flow in the Backfill	Include	1 Include FEPs that degrade backfill by assuming no	Address with other information

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
			credit due to difficulty in ensuring full emplacement	
2.1.04.02.0A	Chemical Properties and Evolution of Backfill	Include	1	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.04.03.0A	Erosion or Dissolution of Backfill	Include	1	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.04.04.0A	Thermal-Mechanical Effects of Backfill	Include	1	Address with other information
2.1.04.05.0A	Thermal-Mechanical Properties and Evolution of Backfill	Include	1	Address with other information
2.1.04.09.0A	Radionuclide Transport in Backfill	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)	Include	3	Fluid pressure drawdown test of effective permeability of seals
2.1.05.02.0A	Radionuclide Transport Through Seals	Include	3	Address with other information, groundwater chemistry in fluid samples from packer testing
2.1.05.03.0A	Degradation of Seals	Include	3	Address with other information
2.1.06.01.0A	Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS	Include (Seals are EBS, so one entire release pathway to RMEI is in EBS)	3	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	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	Exclude	1	Address with other information
2.1.06.05.0A	Mechanical Degradation of Emplacement Pallet	Exclude	1	N/A, no pallet
2.1.06.05.0B	Mechanical Degradation of Invert	Exclude	1	N/A, no invert
2.1.06.05.0C	Chemical Degradation of Emplacement Pallet	Exclude)	1	N/A, no pallet
2.1.06.05.0D	Chemical Degradation of Invert	Exclude)	1	N/A, no invert
2.1.06.06.0A	Effects of Drip Shield on	Exclude	1	N/A, no drip shield

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
	Flow			
2.1.06.06.0B	Oxygen Embrittlement of Drip Shields	Exclude	1	N/A, no drip shield
2.1.06.07.0A	Chemical Effects at EBS Component Interfaces	Include	2	Address with other information
2.1.06.07.0B	Mechanical Effects at EBS Component Interfaces	Exclude	3	Address with other information
2.1.07.01.0A	Rockfall	Exclude	1	Address with other information
2.1.07.02.0A	Drift Collapse	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	Include	2	Drill stem tests of shut-in pressure
2.1.07.04.0B	Hydrostatic Pressure on Drip Shield	Exclude	1	N/A, no drip shield
2.1.07.05.0A	Creep of Metallic Materials in the Waste Package	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.07.05.0B	Creep of Metallic Materials in the Drip Shield	Exclude	1	N/A, Assume no flow barrier credit for WP
2.1.07.06.0A	Floor Buckling	Exclude	1	N/A, no floor
2.1.08.01.0A	Water Influx at the Repository	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	Exclude	1	Address with other information
2.1.08.02.0A	Enhanced Influx at the Repository	Exclude	1	Address with other information
2.1.08.03.0A	Repository Dry-Out Due to Waste Heat	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)	Exclude	1	N/A, no roof
2.1.08.04.0B	Condensation Forms at Repository Edges (Repository-Scale Cold Traps)	Exclude	1	Address with other information
2.1.08.05.0A	Flow Through Invert	Exclude	1	N/A, no invert
2.1.08.06.0A	Capillary Effects (Wicking) in EBS	Exclude	1	Address with other information
2.1.08.07.0A	Unsaturated Flow in the EBS	Exclude	1	N/A, borehole is in saturated zone
2.1.08.09.0A	Saturated Flow in the EBS	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	Include	1	Address with other information
2.1.08.12.0A	Induced Hydrologic Changes in Invert	Exclude (NA)	1	N/A, no invert

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
2.1.08.14.0A	Condensation on Underside of Drip Shield	Exclude (NA)	1	N/A, no drip shield
2.1.08.15.0A	Consolidation of EBS Components	Include	3	Address with other information
2.1.09.01.0A	Chemical Characteristics of Water in Drifts	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	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.02.0A	Chemical Interaction With Corrosion Products	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	Exclude	1	Address with other information
2.1.09.03.0B	Volume Increase of Corrosion Products Impacts Waste Package	Exclude	1	Address with other information
2.1.09.03.0C	Volume Increase of Corrosion Products Impacts Other EBS Components	Exclude	1	Address with other information
2.1.09.04.0A	Radionuclide Solubility, Solubility Limits, and Speciation in the Waste Form and EBS	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	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	Include	1	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.06.0B	Reduction-Oxidation Potential in Drifts	Include	1	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.07.0A	Reaction Kinetics in Waste Package	Exclude	2	Address with other information
2.1.09.07.0B	Reaction Kinetics in Drifts	Exclude	2	Address with other information
2.1.09.08.0A	Diffusion of Dissolved Radionuclides in EBS	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	Include	3	Packer pump tests, drill stem pump tests, formation micro imager log, drill stem tests of shut-in pressure, temperature log
2.1.09.09.0A	Electrochemical Effects in	Exclude	1	Address with other

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
	EBS			information
2.1.09.10.0A	Secondary Phase Effects on Dissolved Radionuclide Concentrations	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	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	Exclude	2	Address with other information
2.1.09.13.0A	Complexation in EBS	Exclude	2	Address with other information
2.1.09.15.0A	Formation of True (Intrinsic) Colloids in EBS	Exclude	1	Address with other information
2.1.09.16.0A	Formation of Pseudo-Colloids (Natural) in EBS	Exclude	1	Address with other information
2.1.09.17.0A	Formation of Pseudo-Colloids (Corrosion Product) in EBS	Exclude	1	Address with other information
2.1.09.18.0A	Formation of Microbial Colloids in EBS	Exclude	1	Address with other information
2.1.09.19.0A	Sorption of Colloids in EBS	Exclude	1	Address with other information
2.1.09.19.0B	Advection of Colloids in EBS	Exclude	1	Address with other information
2.1.09.20.0A	Filtration of Colloids in EBS	Exclude	1	Address with other information
2.1.09.21.0A	Transport of Particles Larger Than Colloids in EBS	Exclude	1	Address with other information
2.1.09.21.0B	Transport of Particles Larger Than Colloids in the SZ	Exclude	1	Address with other information
2.1.09.21.0C	Transport of Particles Larger Than Colloids in the UZ	Exclude	1	Address with other information
2.1.09.22.0A	Sorption of Colloids at Air-Water Interface	Exclude	1	Address with other information
2.1.09.23.0A	Stability of Colloids in EBS	Include	3	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.24.0A	Diffusion of Colloids in EBS	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	Include	?	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.09.26.0A	Gravitational Settling of Colloids in EBS	Exclude	1	Address with other information
2.1.09.27.0A	Coupled Effects on	Include	2	Groundwater chemistry in

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

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
2.1.12.01.0A	Gas Generation (Repository Pressurization)	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	Exclude	3	Address with other information
2.1.12.03.0A	Gas Generation (H_2) from Waste Package Corrosion	Exclude	3	Address with other information
2.1.12.04.0A	Gas Generation (CO_2, CH_4, H_2S) from Microbial Degradation	Exclude	2	Groundwater chemistry in fluid samples from packer testing, address with other information
2.1.12.06.0A	Gas Transport in EBS	Exclude	2	Address with other information
2.1.12.07.0A	Effects of Radioactive Gases in EBS	Exclude	1	Address with other information
2.1.12.08.0A	Gas Explosions in EBS	Exclude	1	Address with other information
2.1.13.01.0A	Radiolysis	Exclude	2	Address with other information
2.1.13.02.0A	Radiation Damage in EBS	Exclude	1	Address with other information
2.1.13.03.0A	Radiological Mutation of Microbes	Exclude	1	Address with other information
2.1.14.15.0A	In-Package Criticality (Intact Configuration)	Exclude	3	Address with other information
2.1.14.16.0A	In-Package Criticality (Degraded Configurations)	Exclude	3 Criticality exclusion on Prob. of geometry? Consequence is low, but hard to quantify because of thermal effects	Address with other information
2.1.14.17.0A	Near-Field Criticality	Exclude	2	Address with other information
2.1.14.18.0A	In-Package Criticality Resulting from a Seismic Event (Intact Configuration)	Exclude	1	Address with other information
2.1.14.19.0A	In-Package Criticality Resulting from a Seismic Event (Degraded Configurations)	Exclude	1	Address with other information
2.1.14.20.0A	Near-Field Criticality Resulting from a Seismic Event	Exclude	1	Address with other information
2.1.14.21.0A	In-Package Criticality Resulting from Rockfall (Intact Configuration)	Exclude	1	Address with other information
2.1.14.22.0A	In-Package Criticality Resulting from Rockfall (Degraded Configurations)	Exclude	1	N/A
2.1.14.23.0A	Near-Field Criticality Resulting from Rockfall	Exclude	1	N/A
2.1.14.24.0A	In-Package Criticality Resulting from an Igneous Event (Intact Configuration)	Exclude	2	Address with other information

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
2.1.14.25.0A	In-Package Criticality Resulting from an Igneous Event (Degraded Configurations)	Exclude	2	Address with other information
2.1.14.26.0A	Near-Field Criticality Resulting from an Igneous Event	Exclude	1	Address with other information
2.2.01.01.0A	Mechanical Effects of Excavation and Construction in the Near-Field	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	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	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	Exclude	1	Address with other information
2.2.01.03.0A	Changes In Fluid Saturations in the Excavation Disturbed Zone	Exclude	1	Address with other information
2.2.01.04.0A	Radionuclide Solubility in the Excavation Disturbed Zone	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	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	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	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 Rock	Exclude	1	Address with other information
2.2.06.02.0A	Seismic Activity Changes Porosity and Permeability of Faults	Exclude	1	Address with other information

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

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

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
				information
2.2.08.10.0A	Colloidal Transport in the SZ	Include	3	Chemical composition and colloid concentrations of groundwater samples from packer testing
2.2.08.10.0B	Colloidal Transport in the UZ	Exclude	1	Address with other information
2.2.08.11.0A	Groundwater Discharge to Surface Within The Reference Biosphere	Exclude	1	Address with other information
2.2.08.12.0A	Chemistry of Water Flowing into the Drift	Include	2	Chemical composition of groundwater samples from packer testing
2.2.08.12.0B	Chemistry of Water Flowing into the Waste Package	Include	2	Chemical composition of groundwater samples from packer testing
2.2.09.01.0A	Microbial Activity in the SZ	Exclude	2	Microbiological composition of groundwater samples from packer testing
2.2.09.01.0B	Microbial Activity in the UZ	Exclude	1	Address with other information
2.2.10.01.0A	Repository-Induced Thermal Effects on Flow in the UZ	Exclude	1	Address with other information
2.2.10.02.0A	Thermal Convection Cell Develops in SZ	Exclude	3	Packer pump tests, drill stem pump tests
2.2.10.03.0A	Natural Geothermal Effects on Flow in the SZ	Include	2	Temperature log, packer pump tests, drill stem pump tests
2.2.10.03.0B	Natural Geothermal Effects on Flow in the UZ	Exclude	1	Address with other information
2.2.10.04.0A	Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository	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	Exclude	3	Address with other information
2.2.10.05.0A	Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below The Repository	Exclude	3	Address with other information
2.2.10.06.0A	Thermo-Chemical Alteration in the UZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)	Exclude	1	Address with other information
2.2.10.07.0A	Thermo-Chemical Alteration of the Calico Hills Unit	Exclude (NA)	1	N/A, no formation
2.2.10.08.0A	Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)	Exclude	3	Chemical composition of groundwater samples from packer testing
2.2.10.09.0A	Thermo-Chemical Alteration of the Topopah Spring Basal Vitrophyre	Exclude	1	N/A, no formation

DBD/YMP FEP Number	DBD/YMP FEP Name	Likely DBD Decision	Estimated DBD Level of Effort	
2.2.10.10.0A	Two-Phase Buoyant Flow/Heat Pipes	Exclude	1	Address with other information
2.2.10.11.0A	Natural Air Flow in the UZ	Exclude	1	Address with other information
2.2.10.12.0A	Geosphere Dry-Out Due to Waste Heat	Include	1	Address with other information
2.2.10.13.0A	Repository-Induced Thermal Effects on Flow in the SZ	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	Exclude	3	Address with other information
2.2.11.01.0A	Gas Effects in the SZ	Exclude	2	Address with other information
2.2.11.02.0A	Gas Effects in the UZ	Exclude	1	Address with other information
2.2.11.03.0A	Gas Transport in Geosphere	Exclude	1	Address with other information
2.2.12.00.0A	Undetected Features in the UZ	Exclude	1	Address with other information
2.2.12.00.0B	Undetected Features in the SZ	Include	1	3D seismic imaging; Electrical Resistivity (Surface Based – Large Scale)
2.2.14.09.0A	Far-Field Criticality	Exclude	1	Address with other information
2.2.14.10.0A	Far-Field Criticality Resulting from a Seismic Event	Exclude	1	Address with other information
2.2.14.11.0A	Far-Field Criticality Resulting from Rockfall	Exclude	1	N/A
2.2.14.12.0A	Far-Field Criticality Resulting from an Igneous Event	Exclude	1	Address with other information
2.3.01.00.0A	Topography and Morphology	Exclude	1	Address with other information
2.3.02.01.0A	Soil Type	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	Include	1	Address with existing data
2.3.02.03.0A	Soil and Sediment Transport in the Biosphere	Exclude	1	Address with other information
2.3.04.01.0A	Surface Water Transport and Mixing	Exclude	1	Address with other information
2.3.06.00.0A	Marine Features	Exclude	1	Address with other information
2.3.09.01.0A	Animal Burrowing/Intrusion	Exclude	1	Address with other information
2.3.11.01.0A	Precipitation	Exclude	1	Address with other information
2.3.11.02.0A	Surface Runoff and Evapotranspiration	Exclude	1	Address with other information
2.3.11.03.0A	Infiltration and Recharge	Exclude	1	Address with existing data
2.3.11.04.0A	Groundwater Discharge to	Exclude	1	Address with existing data

DBD/YMP FEP Number	**DBD/YMP FEP Name**	**Likely DBD Decision**	**Estimated DBD Level of Effort**	
	Surface Outside The Reference Biosphere			
2.3.13.01.0A	Biosphere Characteristics	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	Include	1	Address with existing data
2.3.13.03.0A	Effects of Repository Heat on The Biosphere	Exclude	1	Address with other information
2.3.13.04.0A	Radionuclide Release Outside The Reference Biosphere	Exclude	1	Address with other information
2.4.01.00.0A	Human Characteristics (Physiology, Metabolism)	Include	1	Address with existing data
2.4.04.01.0A	Human Lifestyle	Include	1	Address with existing data
2.4.07.00.0A	Dwellings	Include	1	Address with existing data
2.4.08.00.0A	Wild and Natural Land and Water Use	Include	1	Address with existing data
2.4.09.01.0A	Implementation of New Agricultural Practices Or Land Use	Exclude	1	Address with other information
2.4.09.01.0B	Agricultural Land Use and Irrigation	Include	1	Address with existing data
2.4.09.02.0A	Animal Farms and Fisheries	Include	1	Address with existing data
2.4.10.00.0A	Urban and Industrial Land and Water Use	Include	1	Address with existing data
3.1.01.01.0A	Radioactive Decay and Ingrowth	Include	1	Address with existing data
3.2.07.01.0A	Isotopic Dilution	Exclude	1	Address with other information
3.2.10.00.0A	Atmospheric Transport of Contaminants	Exclude	1	Address with other information
3.3.01.00.0A	Contaminated Drinking Water, Foodstuffs and Drugs	Include	1	Address with existing data
3.3.02.01.0A	Plant Uptake	Include	1	Address with existing data
3.3.02.02.0A	Animal Uptake	Include	1	Address with existing data
3.3.02.03.0A	Fish Uptake	Include	1	Address with existing data
3.3.03.01.0A	Contaminated Non-Food Products and Exposure	Include	1	Calculated from PA model
3.3.04.01.0A	Ingestion	Include	1	Calculated from PA model
3.3.04.02.0A	Inhalation	Include	1	Calculated from PA model
3.3.04.03.0A	External Exposure	Include	1	Calculated from PA model
3.3.05.01.0A	Radiation Doses	Include	1	Calculated from PA model
3.3.06.00.0A	Radiological Toxicity and Effects	Exclude	1	Address with other information
3.3.06.01.0A	Repository Excavation	Exclude	1	Address with other information
3.3.06.02.0A	Sensitization to Radiation	Exclude	1	Address with other information
3.3.07.00.0A	Non-Radiological Toxicity and Effects	Exclude	1	Address with other information
3.3.08.00.0A	Radon and Radon Decay Product Exposure	Include	1	Calculated from PA model

3) Characterization Methods Identified as Supporting FEPs Relevant to Deep Borehole Disposal

Table A-3. Characterization Methods supporting Deep Borehole FEPs.

Note: Highlighted entry indicates key[2] 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 rock and characteristics such as porosity, density, lithoilogy, 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)*

---

[2] Key FEPs are thought to be important to the safety case and need to be evaluated or justify exclusion.

Characterization Method	**Information Needed**	**FEP Number Addressed**	**FEP Title Addressed**
	Sorption properties of samples from drill cuttings	*2.2.01.05.0A*	*- Radionuclide Transport in the Excavation Disturbed Zone*
		2.2.08.09.0A	*- 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*	*- Natural Geothermal Effects on Flow in the SZ*
		2.1.08.01.0A	*- Water Influx at the Repository*
		2.2.07.12.0A	*- Saturated Groundwater Flow in the Geosphere*
		2.1.08.09.0A	*- Saturated Flow in the EBS*
		2.1.09.08.0B	*- Advection of Dissolved Radionuclides in EBS*
		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*
		2.2.10.13.0A	*- Repository-Induced Thermal Effects on Flow in the SZ*
		2.2.07.15.0A	*- Advection and Dispersion in the SZ*
		2.2.10.02.0A	*- 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*	*- Repository Dry-Out Due to Waste Heat*
		2.1.07.04.0A	*- Hydrostatic Pressure on Waste Package*
		2.2.07.12.0A	*- Saturated Groundwater Flow in the Geosphere*
		2.1.08.09.0A	*- Saturated Flow in the EBS*
		2.1.09.08.0B	*- Advection of Dissolved Radionuclides in EBS*
		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*
		2.2.10.13.0A	*- Repository-Induced Thermal Effects on Flow in the SZ*
		2.2.07.15.0A	*- 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*	*- Inadvertent Human Intrusion*
		1.4.04.00.0A	*- Drilling Activities (Human Intrusion)*
	Detect other features in rock such as Faults	*2.2.12.00.0B*	*-Undetected Features in the SZ*
		1.2.02.02.0A	*-Faults*
		1.2.02.03.0A	*-Fault Displacement Damages EBS Components*
	stratigraphy	*2.2.03.01.0A*	*- Stratigraphy*

Characterization Method	**Information Needed**	**FEP Number Addressed**	**FEP Title Addressed**
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*	*- 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*

Characterization Method	Information Needed	FEP Number Addressed	FEP Title Addressed
			Potential in Waste Package
		2.1.09.06.0B	*- Reduction-Oxidation Potential in Drifts*
		2.1.09.08.0A	*- Diffusion of Dissolved Radionuclides in EBS*
		2.1.09.10.0A	*- Secondary Phase Effects on Dissolved Radionuclide Concentrations*
		2.1.09.23.0A	*- Stability of Colloids in EBS*
		2.1.09.24.0A	*- Diffusion of Colloids in EBS*
		2.1.09.25.0A	*- Formation of Colloids (Waste-Form) By Co-Precipitation in EBS*
		2.1.10.01.0A	*- Microbial Activity in EBS*
		2.1.11.08.0A	*- Thermal Effects on Chemistry and Microbial Activity in the EBS*
		2.1.12.04.0A	*- Gas Generation (CO2, CH4, H2S) from Microbial Degradation*
		2.2.01.01.0B	*- Chemical Effects of Excavation and Construction in the Near-Field*
		2.2.01.04.0A	*- Radionuclide Solubility in the Excavation Disturbed Zone*
		2.2.08.12.0A	*- Chemistry of Water Flowing into the Drift*
		2.2.08.12.0B	*- Chemistry of Water Flowing into the Waste Package*
		2.2.10.08.0A	*- Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)*
		2.2.01.05.0A	*- Radionuclide Transport in the Excavation Disturbed Zone*
		2.1.09.11.0A	*- Chemical Effects of Waste-Rock Contact*
		2.1.09.27.0A	*- Coupled Effects on Radionuclide Transport in EBS*
		2.2.07.12.0A	*- Saturated Groundwater Flow in the Geosphere*
		1.3.04.00.0A	*- Periglacial Effects*
		1.3.05.00.0A	*- 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*	*- Chemical Characteristics of Groundwater in the SZ*
		2.2.08.03.0A	*- Geochemical Interactions and Evolution in the SZ*
		2.2.08.06.0A	*- Complexation in the SZ*
		2.2.07.12.0A	*- Saturated Groundwater Flow in the Geosphere*
		1.3.04.00.0A	*- Periglacial Effects*
		1.3.05.00.0A	*- Glacial and Ice Sheet Effect*

Characterization Method	Information Needed	FEP Number Addressed	FEP Title Addressed
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* *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*	*- Matrix Diffusion in the SZ* *- Fractures* *-Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository* *- Water Influx at the 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*	*- Thermally-Induced Stress Changes in the Near-Field*

Characterization Method	Information Needed	FEP Number Addressed	FEP Title Addressed
		2.2.10.04.0A	*- 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 Section 3.2.1.6	Estimate the porosity of the host rock. Assess the lithology, alteration, and fracturing in the host rock.	*2.2.08.09.0A* *2.2.03.01.0A* *2.2.01.05.0A* *2.2.03.02.0A*	*- Sorption in the SZ* *- Stratigraphy* *- 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*	*- Chemical Characteristics of Groundwater in the SZ* *- Chemical Characteristics of Water in Drifts*

Characterization Method	**Information Needed**	**FEP Number Addressed**	**FEP Title Addressed**
		2.1.09.01.0B *2.1.09.02.0A*	*- 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 in permeable beds, the formation water resistivity, pore water quality (e.g. salinity, ionic concentration) and correlations between wells	*2.2.03.01.0A*	*- Stratigraphy*
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	Estimate thermal properties of host rock such as bulk thermal conductivity and	*1.2.06.00.0A* *2.1.04.04.0A*	*- Hydrothermal Activity* *- Thermal-Mechanical Effects of Backfill*

Characterization Method	**Information Needed**	**FEP Number Addressed**	**FEP Title Addressed**
Section 3.2.5.1	bulk coefficient of thermal expansion	*2.1.04.05.0A*	*- Thermal-Mechanical Properties and Evolution of Backfill*
		2.1.08.01.0A	*- Water Influx at the Repository*
		2.1.08.01.0B	*- Effects of Rapid Influx into the Repository*
		2.1.08.03.0A	*- Repository Dry-Out Due to Waste Heat*
		2.1.08.11.0A	*- 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: BACKGROUND ON SURFACE-BASED SITE-CHARACTERIZATION METHODS

Appendix B describes the surface-based characterization methods that are relevant to DBD. This Appendix is intended to give the reader further background on the methods referred to in Section 3.

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).

B.1 Surface Geological Mapping

Geological maps provide surface based interpretations of geological features such as lithology, stratigraphy, faults and folds. Surface geological mapping would be used in the characterization of a DBD system by identifying of the location, displacement, and orientation of faults exposed at the surface, analyzing the fault displacement history, and potentially correlating the lithology at the surface with rock types in the boreholes. The benefit of surface geological mapping, is that much of the United States has already been mapped and is readily available. More detailed mapping could be conducted at a relatively small expense compared to other site-characterization methods.

B.2 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 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. The petroleum industry uses 3D seismic to image at depths relevant to DBD.

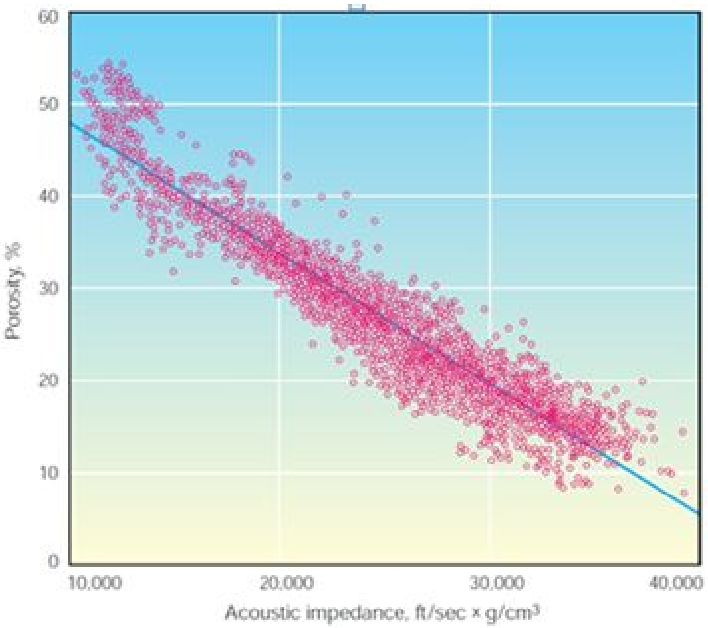

Figure B-1. Example correlation between acoustic impedance and porosity derived from sonic, density, and porosity logs (Ariffin et al., 1995).

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 (Figure B-1). 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.

B.3 Gravity and Magnetic Surveys

Gravity and Magnetic Surveying are used to identify or map gravity or magnetic anomalies. 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 (Figure B-2). Figure B-3 presents representative examples of gravity and magnetic survey maps.

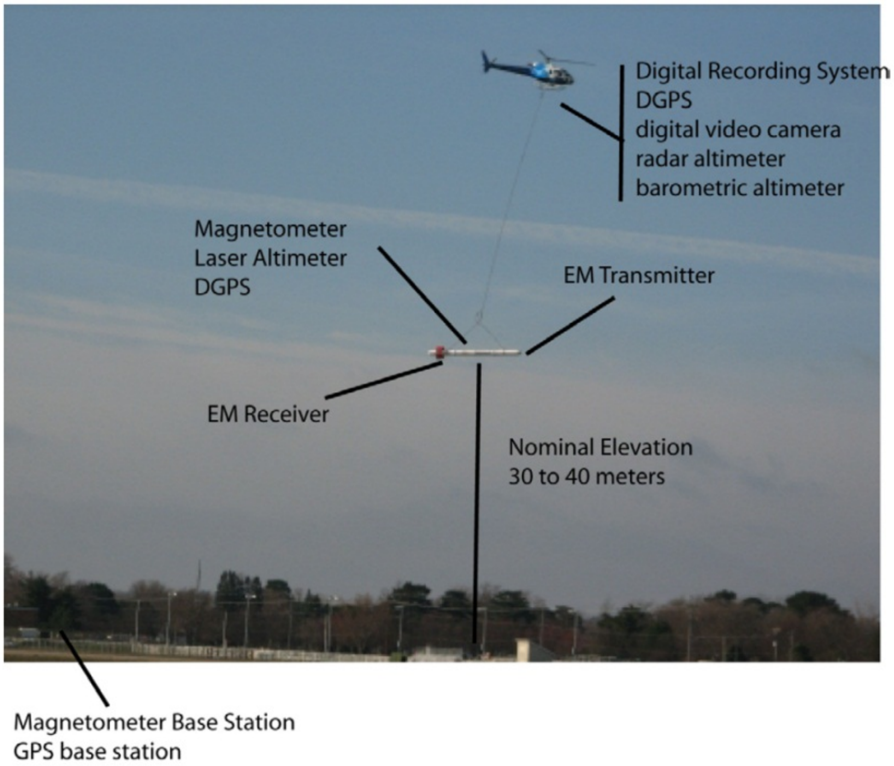

Figure B-2. Helicopter-borne Resolve geophysical system: Electromagnetic, magnetic, GPS, and laser altimeter sensors are housed in a "bird", a cigar-shaped 9-m long tube, which is kept at about 30–40 m above ground (Smith et al., 2011).

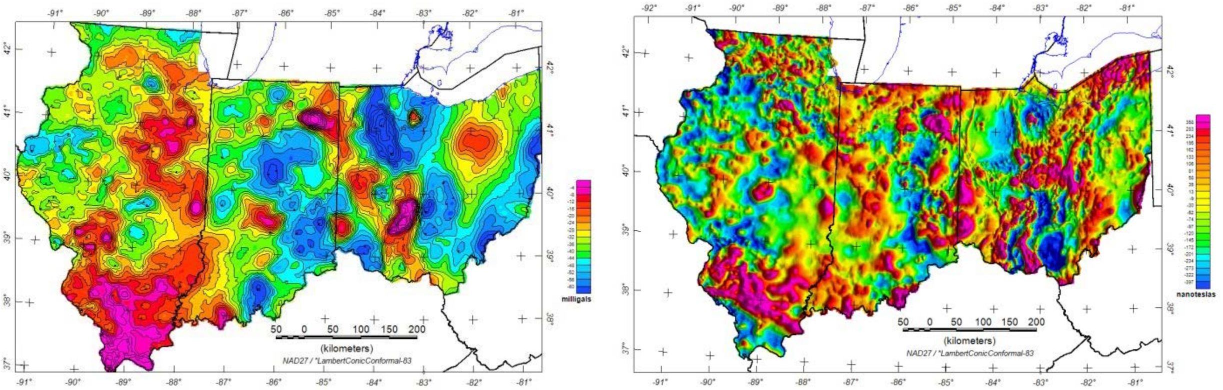

Figure B-3. **Example gravity (left) and magnetic (right) anomaly maps of Illinois, Indiana and Ohio (Daniels et al., 2008).**

B.4 Electrical Resistivity 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 (Figure B-4).

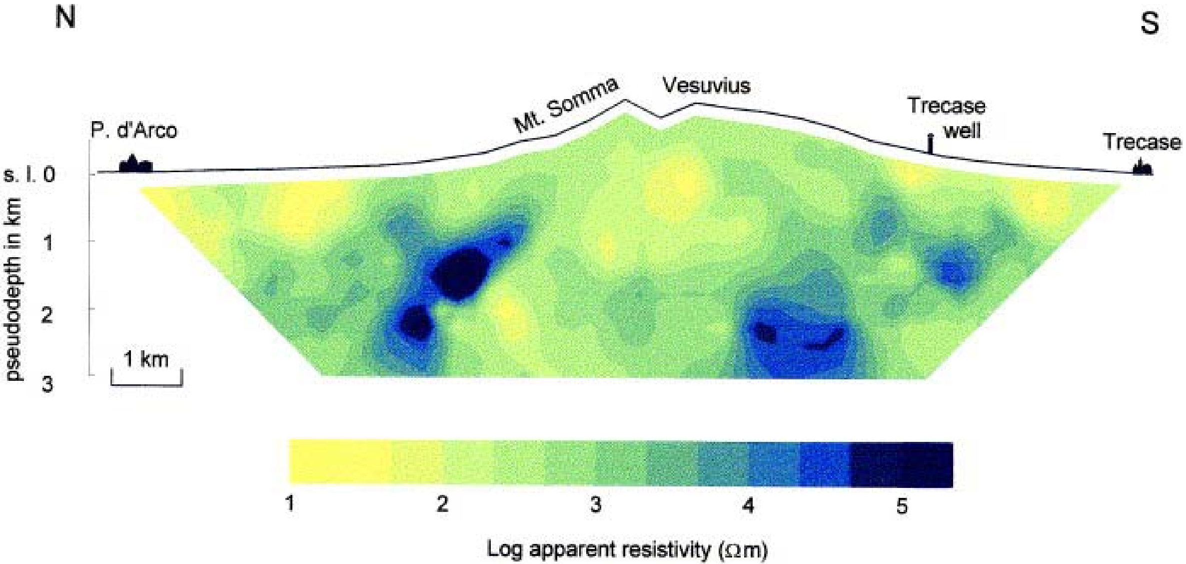

Figure B-4. **Dipolar geoelectrics apparent resistivity pseudosection showing a coarse horizontal set of alternating conductive and resistive bodies. (Di Maio et al., 1998).**

APPENDIX C: BACKGROUND ON BOREHOLE-BASED SITE-CHARACTERIZATION METHODS

Borehole-based characterization includes:

- Geophysical logging
- Geological and hydrological testing, and
- Water sampling and analysis.

These methods measure characteristics of the drilled borehole, the formations intersected by the borehole, and pore fluid. The methods vary with respect to the distance from 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 includes chemical, thermal, hydrologic, and geologic such as rock type, formation density, porosity, permeability, fracture spacing and aperture, water quality and composition. Characterization of testing in a single borehole is considered adequate for the purposes of DBD.

C.1 Geophysical Logging

Geophysical logging includes nine methods: Borehole Caliper Log, Gamma Ray Log, Resistivity Log, Spontaneous Potential Log, Temperature Log, Neutron Porosity Log, Formation Micro Imager Log, Anisotropic Shear Wave Velocity Log, and Borehole Gravity Log.

C.1.1 Borehole Caliper Log

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

C.1.2 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.

C.1.3 Resistivity Log

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 resistance changes of the rock traversed by the borehole.

Resistivity is a fundamental material property which represents how strongly a material impedes the flow of electric 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. Drilling fluids will penetrate into the surrounding host rock during drilling. The depth of penetration is dependent on the host rock characteristics. In resistivity logging, the resistivity of this invaded host rock zone is measured. The various resistivity measuring techniques interrogated the invasion zone at different depths.

Resistivity logging is sometimes used in oil and gas exploration and water-well drilling and provides information about lithostratigraphy, formation permeability, fluid saturations, and water quality. Resistivity logging is often used in conjunction with other logging methods such as gamma ray logs (Section C.1.2), neutron logs (Section C.1.6), or spontaneous potential logs (Section C.1.4).

Compared to multi- point methods, single point logging offers a number of advantages but also has some important disadvantages. The equipment required to make single-electrode measurements is smaller, simpler, less expensive, and easier to operate. The interpretation is straightforward and consistent (not prone to signal reversals). The single point log has higher vertical resolution; however, the single point logging methods have less lateral penetration than multiple-electrode measurements. The most important drawback is that single-point logs cannot be used for quantitative interpretation because the resulting measurement is dependent on the path length the current travels and this is not known. Of particular interest to deep borehole characterization the resolution of measurements made with a single electrode decreases as the salinity of the drilling mud increases and as the diameter of the borehole increases. Under these conditions thin beds may not be observable and boundaries between the thick beds may be diffuse.

There are a number of multi-electrode techniques including

1) **Normal Resistivity Log:** Normal resistivity is used in groundwater hydrology and can be interpreted quantitatively when they are properly calibrated. An important application of normal resistivity logs and other multi-electrode logs is to determine water quality. Normal logs measure apparent resistivity; true resistivity is obtained by correcting measurements with departure curves.

2) **Lateral Resistivity Log:** Lateral logs are designed to measure resistivity beyond the invaded zone, which is achieved by using long electrode spacing. They have several limitations that have restricted their use in environmental and engineering applications. The logs are difficult to interpret.

3) **Focused Resistivity Log:** Focused resistivity measures the resistivity of thin beds or high-resistivity rocks in wells containing highly conductive fluids. These logs provide very high resolution and great penetration under conditions where other resistivity

systems may fail. Focused-resistivity devices use guard electrodes above and below the current electrode to force the current to flow out into the rocks surrounding the well.

C.1.4 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. Because of its simplicity it can be combined with little additional expense with other electrical based log devices such as gamma ray logging.

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.

The magnitude and direction of the charge deflection depends mainly on the salinity contrast between drilling mud and formation water, and the clay content of the permeable bed. Relative to the borehole fluid, the salt content of formation water in clays and shales will generate one charge and those of more permeable formations will generate an opposite one. This is a reflection of the differing abilities of the dissolved ions to access pore space.

Figure C-1 is a schematic of a typical SP device. The device is extremely simple, consisting of a single electrode in a well that is connected to a good surface ground by a voltmeter and recorder. A small battery is often also used to scale the readings. While the equipment used to generate an SP log is very simple, the interpretation of the log is complex and prone to misinterpretation. This is because of the large volume of material being represented and the resulting measurement is reflective of a number contributing phenomena such as the chemical activities of fluids in the borehole and adjacent rocks, the temperature, and the type and amount of clay present; it is not directly related to porosity and permeability. The spontaneous potential consists of 2 electrochemical components (diffusion potential and membrane potential) and 2 electrokinetic components (mudcake potential and wall potential). The electrokinetic contributions depend upon fluid flow, and hence are larger when there is a substantial difference in pressure between the borehole and the formation. The contributions also depend upon the development of an electrical double layer at mineral surfaces, which is larger for low salinity fluids. Hence, these contributions are also more important for fresh formation waters or mud filtrates. The four potential components are identified below:

- **Diffusion potential:** This potential develops between the invaded and the non-invaded zone, and is the direct result of the difference in salinity between the mud and the formation fluid.

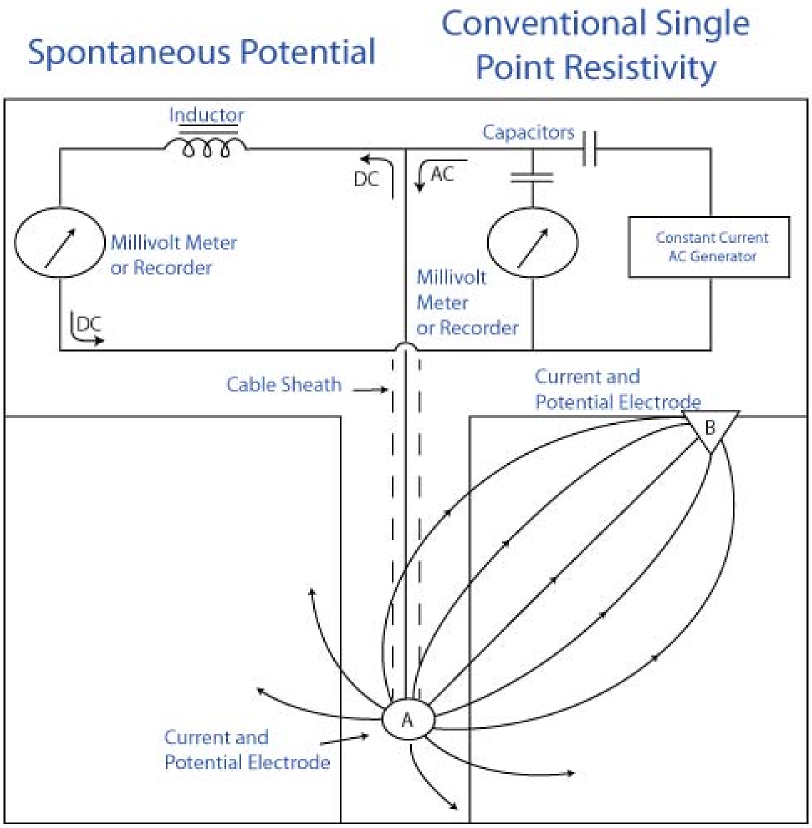

Figure C-1. Typical SP configuration, Wightman et al, 2003.

- **Membrane potential:** This potential arises between the non-invaded zone and the less permeable rock sandwiching the permeable bed. This potential is a result of anion exclusion, which is more effective for shale and less so for other rock types. The strength of this effect depends upon the shale mineralogy, the fluid concentration, and the fluid pH.

- **Mudcake potential:** This potential arises from the movement of ions through the mudcake and invaded zone in a permeable formation. The magnitude of this potential depends upon the hydraulic pressure drop.

- **Wall potential:** This potential arises from the movement of ions between the borehole and less permeable formations such as shale.

SP measurements are influenced by borehole diameter, thickness of the formations, the depth of drilling fluid penetration into the formation, the resistivity of the formation, the resistivity of the borehole fluid and its make-up, shale content, and hydrocarbon content. The log gives only an indication of relative changes in SP and has low vertical resolution. In reading the SP log it is best to first define a *shale base line*. This can be found by comparing the SP log with the GR log response. Permeable formations will then show as deviations from this baseline.

C.1.5 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.

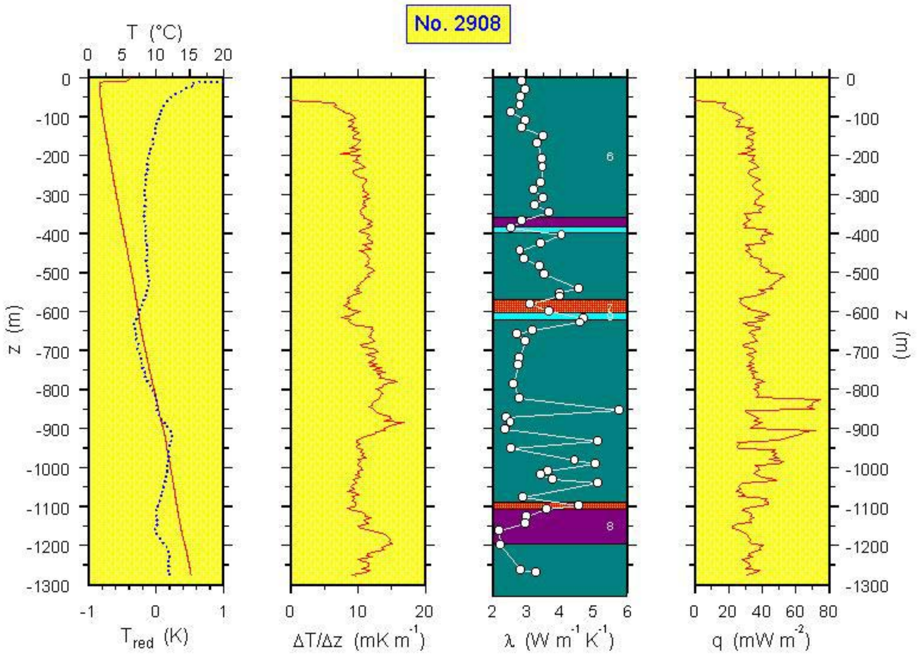

Figure C-2. **Example borehole temperature log with plots of vertical temperature gradient, measured values of thermal conductivity, and calculated heat flux. (Source: http://www.geophysik.rwth-aachen.de/Forschung/Geothermik/kola/kola-1.htm#CONTENT)**

C.1.6 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.

The use of neutron porosity logging in crystalline rocks can be complicated by several factors, including the low value of porosity, the presence of hydrous minerals, and additional mineralogical effects (see example log from Gallé, 1994, Figure C-3), which primarily result in

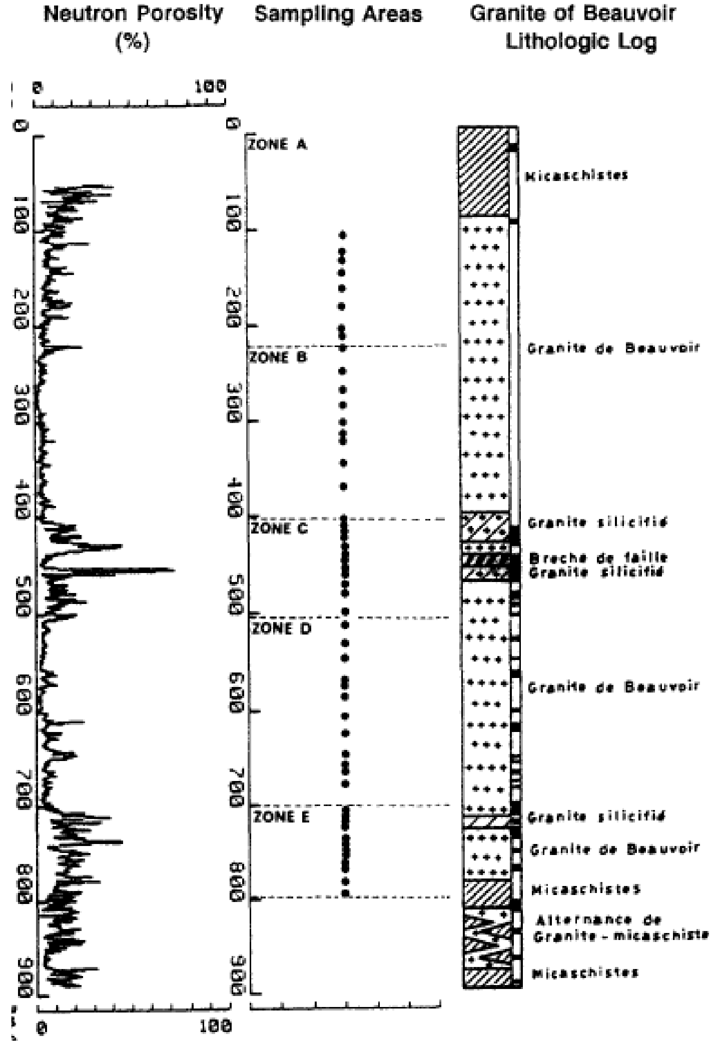

Figure C-3. Example neutron porosity log from a borehole in granitic rock (from Gallé, 1994).

overestimates of the porosity. In addition, the neutron porosity measurements do not distinguish among fracture porosity, interconnected primary porosity, and isolated porosity, such as intragranular fluid inclusions. The absolute value of porosity in crystalline rocks should be estimated from various sources, including measurements core samples. Nonetheless, neutron porosity logs can help to distinguish fracture zones, metamorphic rocks, and zones of mineralogic alteration in granitic rocks, especially in combination with other geophysical logging tools (Keys, 1989).

C.1.7 Formation Micro Imager Log (FMI)

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 C-4.

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.

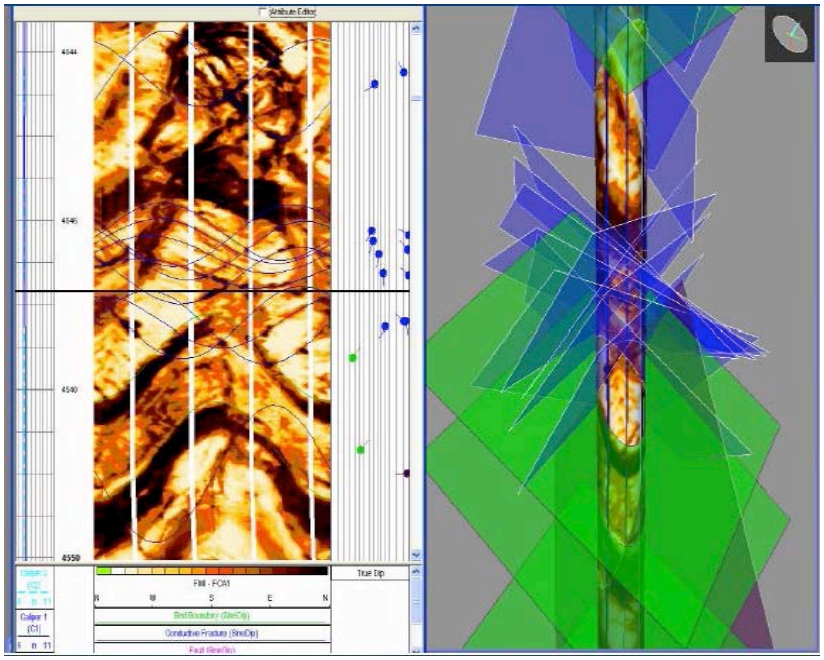

Figure C-4. Example FMI log with interpreted fracture orientations.

C.1.8 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.

C.1.9 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, as shown in the example in Figure C-5. 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 survey data can also be correlated with lithology and potentially structure.

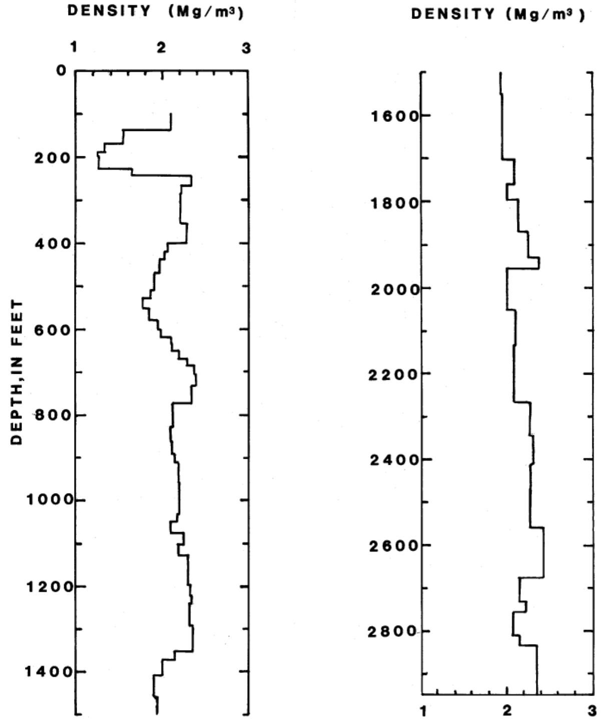

Figure C-5. **Example density log calculated from the borehole gravity survey in well USW G-4 at Yucca Mountain (Healey et al., 1986).**

C.2 Geological and Hydrologic Testing and Water Sampling and Analyses

The Geologic and Hydrological Testing and Water Sampling and Analysis methods include 11 methods: Drill Cuttings Lithology Log, Intermittent Coring, Fluid Samples from Packer Testing, Borehole Hydrological Testing (Drill Stem Tests of Shut-In Pressure, Drill Stem Pump Tests, Packer Testing and Packer Pump Test), Tracer Testing (Vertical Dipole Tracer Testing, Push-Pull Tracer Testing), Thermal Testing (Waste Canister Mockup Electrical Heater Test), Borehole Seals Testing (Downhaul Force Mechanical Testing, Fluid Pressure Drawdown Test of Effective Permeability).

C.2.1 Drill Cuttings Lithology Log

Standard logging of drill cuttings lithology provides a record of rock type, 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.

C.2.2 Intermittent Coring

Intermittent coring acquires 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 DBD system in the following ways:

C.2.3 Fluid Samples from Packer Testing

In situ fluid samples are obtained in conjunction with packer pump tests, drill stem pump tests, and key first-strike water occurrences encountered while drilling. Obtaining representative groundwater samples that are not contaminated by drilling fluids can be challenging in low-permeability rocks, such as the crystalline basement rocks that are the target of DBD. Opportunities for obtaining high-quality fluid samples will have to be evaluated on a case-by-case basis for particular boreholes. Special sampling considerations, such as maintaining pressurization, are involved in obtaining representative fluid samples for dissolved gas tracers.

The chemical and isotopic composition of groundwater in the deep borehole environment will be determined from pore water samples collected within the borehole at various depths. In situ fluid samples. The total salinity and salinity profile in the rocks penetrated by the borehole are important to the stratification of fluid density in the system and the associated resistance to upward vertical groundwater flow. The salinity/density profile of fluids is also required to calculate the fluid potential as a function of depth in the system and the determination of vertical fluid potential gradients. Bulk groundwater chemistry results, in part, from the water-rock interactions the fluids have experienced, their evolution, and the degree of fluid isolation in the system. A wide variety of natural isotopic and environmental tracers can be used to infer groundwater provenance, groundwater residence times, flow rates through the system, and the degree of interaction of deep groundwater with the shallow hydrosphere.

A common application of isotope hydrology is for groundwater "age-dating", or the estimation of the time it has taken a fluid parcel to get to the sampling location. Shallow, rapidly circulating water will be young, while deep, slow moving water will be old. There are a variety of naturally occurring isotopes in water which either decay (parent) or are produced from decay (daughter) that can be used to provide information on the residence time of the fluid. Each tracer provides information on different time scale. Using multiple age tracers it is possible to constrain circulation rates, fluid velocities and mixing of water from different flow paths. There are several radioisotopes which can be used, each of which has a different half life: ^{222}Rn – 4 days - ^{3}H – 12 years, ^{85}Kr – 11years, ^{39}Ar – 270 years, ^{14}C – 5, ^{730}years, ^{36}Cl – 300,000 years, ^{81}Kr – 80 million years, ^{129}I – 15.7 million years.

Produced from alpha decay of naturally occurring U and Th in minerals, ^{4}He is an accumulating tracer. Water in contact with the atmosphere has a known concentration of ^{4}He, but as water flows underground, the longer it flows, the more helium it accumulates. If we know the accumulation rate (based on U and Th concentrations in the host rock), then the concentration of the 4He can be used to calculate the residence time. The ^{4}He system has the advantage of working over a broad time scale and has been used to date waters on time scales ranging from 10's of years to millions of years.

The stable isotopes within H_2O are exceptionally powerful tools for understanding the provenance of fluid. In the atmospheric part of the hydrosphere, the stable isotopic composition of water is affected by many processes including temperature, relative humidity, elevation, evaporation and latitude and distance from the ocean. Thus stable isotopes can be used to give evidence on the provenance and climate of meteoric water. Rocks have very different hydrogen and oxygen isotopic compositions, so the interaction of water with rock at different temperature can be preserved in the stable isotopic composition of groundwater.

All waters that have interacted with the atmosphere contain noble gases in known amounts. The amount of dissolved noble gases in the meteoric water is directly related to the physical conditions at recharge. More quantitative treatment of the noble gas concentrations allows for the estimation of temperature, pressure and salinity at recharge, providing a means of calculating the climate from which the groundwater originated. The various large-scale reservoirs in the earth have very different noble gas compositions, so noble gases can be used to estimate the addition of fluids from the mantle, crust and or interactions with hydrocarbon reservoirs.

C.3 Borehole Hydrological Testing

C.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. Figure C-6 shows a typical DST configuration.

DST is typically done with two packers (see Section C.3.3). The two packers are set to isolate the measurement zone. Inflatable rubber packers are installed as part of the test assembly such that one packer will be set above and the other below the zone of interest. Multiple zones are tested

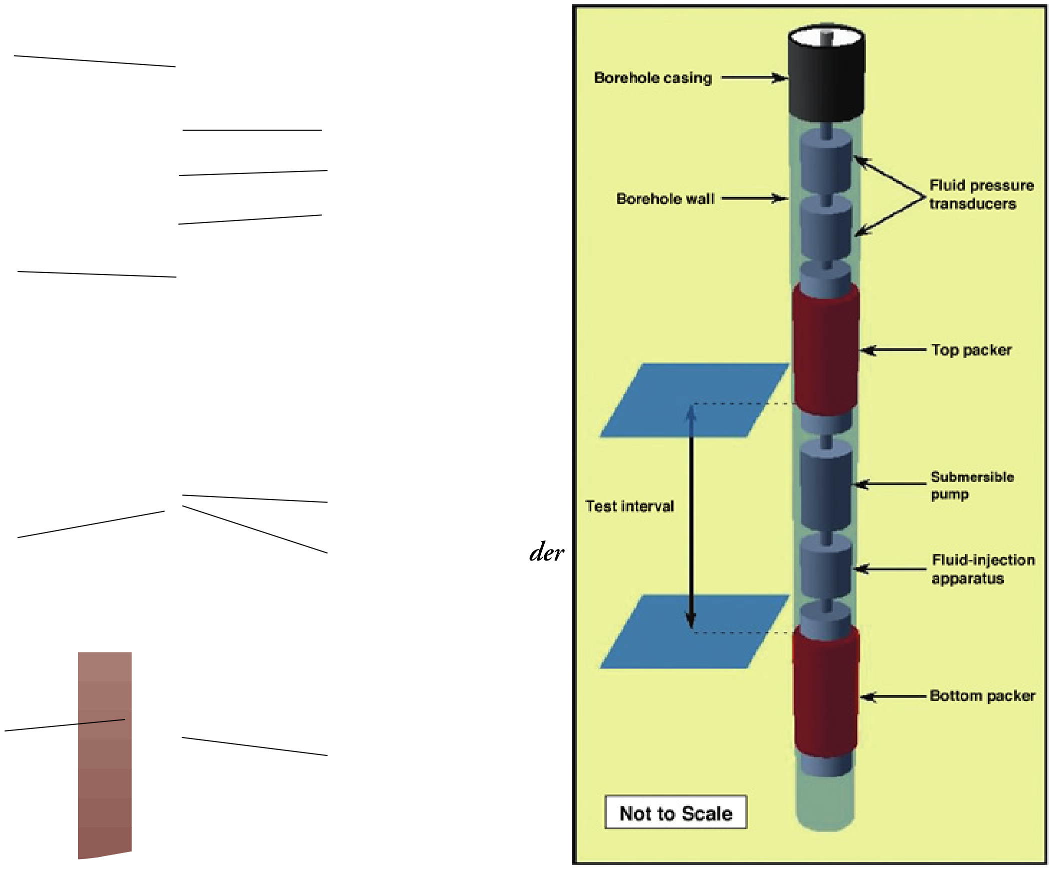

Figure C-6. Typical Drill Stem Test configuration with single (left) and double (right) packer.

by moving the packer system and repeating the shut–in test procedure. In this fashion information from all relevant zones traversed by the borehole may be tested. Testing may be done at any time during the drilling operation. Sometimes only a single packer is used if the measurement zone can be adequately isolated from the reminder of the borehole.

In a two packer configuration, valves are located between the packers and above the top packer. The valves are initially closed as the instrumented drill string is lowered into borehole. Once the packers are inflated, the valves are opened to permit formation flow. Pressure is recorded as a function of time and a sample is extracted.

The typical DST consists of four phases: Initial Flow phase, Initial shut-in phase, Main Flow Phase, and Final Shut-in Phase. The duration of each phase is dependent on site-specific conditions. Pressure, flow rate, and fluid samples are collected throughout the test as a function of time.

Initial Flow Phase

After the packer (s) is set and the valves are open there is communication to the atmosphere and pressure drops rapidly. The purpose of this pre-flow phase is to relieve pressure build up in the annulus of the isolated test interval that occurs when the packers were set. The duration of the initial flow period is typically 5 to 10 minutes but may be longer for very permeable intervals or if there is a large initial pressure drop as occur in very deep boreholes.

Initial Shut In Phase

After pressure has stabilized in the initial flow period, the valves are closed and pressure builds back up. After a sufficient period of time to permit the determination of maximum pressure in the isolated test interval, the valves are opened for a second time.

Main Flow Phase

When the valves are open again, pressures drops. The purpose of this second flowing period is to allow formation fluid to re-enter the drill string. The duration of the Main Flow phase is 1 to 3 hours for an uncased hole and as long as 10 hours for a cased hole. Flowing pressures and temperatures will be recorded and fluid samples are collected.

http://toxics.usgs.gov/photo_gallery/bat3.html

Final Shut-In Phase

After the Main Flow phase, the valves are closed for a final shut-in period where the pressure builds back up. The duration of the second shut-in period should be approximately 2 times as long as the Main Flow phase. In low permeability zones longer shut-in times are necessary for proper reservoir evaluation. Pressure build up is measured and recorded again. The shape of the pressure curve is analyzed revealing information about the permeability of the formation and any formation damage possibly caused by drilling.

This concludes the test cycle and the packers are released and the drill string is either pulled to the surface or re-located at the next interval to be tested.

C.3.2 Drill Stem 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). In this case, the pump test consists of the drill-stem testing equipment described in Section C.3.1.

When water is pumped from the pumping well the pressure in the surrounding formation declines. This decline results in a fall in the water level known as drawdown (change in hydraulic head). Drawdown decreases with radial distance from the pumping well and drawdown increases with the length of time that the pumping continues. Drawdown can be visualized as a cone of lower water elevations (depression) around the pumping well. The size of this depression is a function of the pumping rate and the formations hydrologic properties. Analysis of the drawdown response and comparisons to solutions of well flow equations permits determination of the hydrologic properties.

There are four common types of pumping tests:

- <u>Constant-rate tests</u>: maintain pumping at the control well at a constant rate.
- <u>Step-drawdown tests</u>: proceed through a sequence of constant-rate steps at the control well to determine its well loss and well efficiency characteristics. whereas during the step-drawdown test, the well is pumped at successively greater rates over short periods of time.
- <u>Slug Test</u>: A slug test is a variation on the typical aquifer test where an instantaneous change (increase or decrease) is made, and the effects are observed in the same well. This is often used in geotechnical or engineering settings to get a quick estimate (minutes instead of days) of the aquifer properties immediately around the well.
- <u>Recovery tests</u>: In a recovery test water-level measurements are recorded after the termination of pumping. Recovery-test data are generally more reliable than the drawdown data because the natural recovery is a constant rate process. The data from a recovery test can also be used to check the calculations made on the basis of the drawdown data.

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 sometime called type curve fitting. The more straightforward type curve analyses use the Theis solution, (Theis, 1935). More complex analyses are based on solutions that relax one of 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. There are a variety of representations based on the type of formation, their initial and boundary conditions, such as:

- Formation type (e.g. unconsolidated, consolidated fractured, single or dual porosity, homogeneous, heterogeneous, anisotropic, etc.).
- Formation Boundary conditions (e.g. confined, unconfined, or leaky.
- Pumping wells that are fully penetrating or partially penetrating.

Difficulties in interpretation arise when there is large uncertainty in the selection of the proper representation of the formation. The solutions to the flow equations are not always unique and there may be no obvious "best fit" of the data. If the wrong representation is selected then the formation properties that are extracted will also be incorrect. This uncertainty can be reduced by collecting other information on the formation using some of the other methods discussed in Section 3.

C.3.3 Packer Pump Tests

Packer Pump Tests are carried out to assess the variability in a borehole and the hydrological units it intersects to help understand the detailed hydrogeological properties and to provide water samples for analysis. This knowledge is essential to ensuring that the deep borehole is placed in a suitable hydro-geologic environment.

The equipment to support these tests consists of one of 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. Figure C-7 shows a schematic for a typical dual packer system.

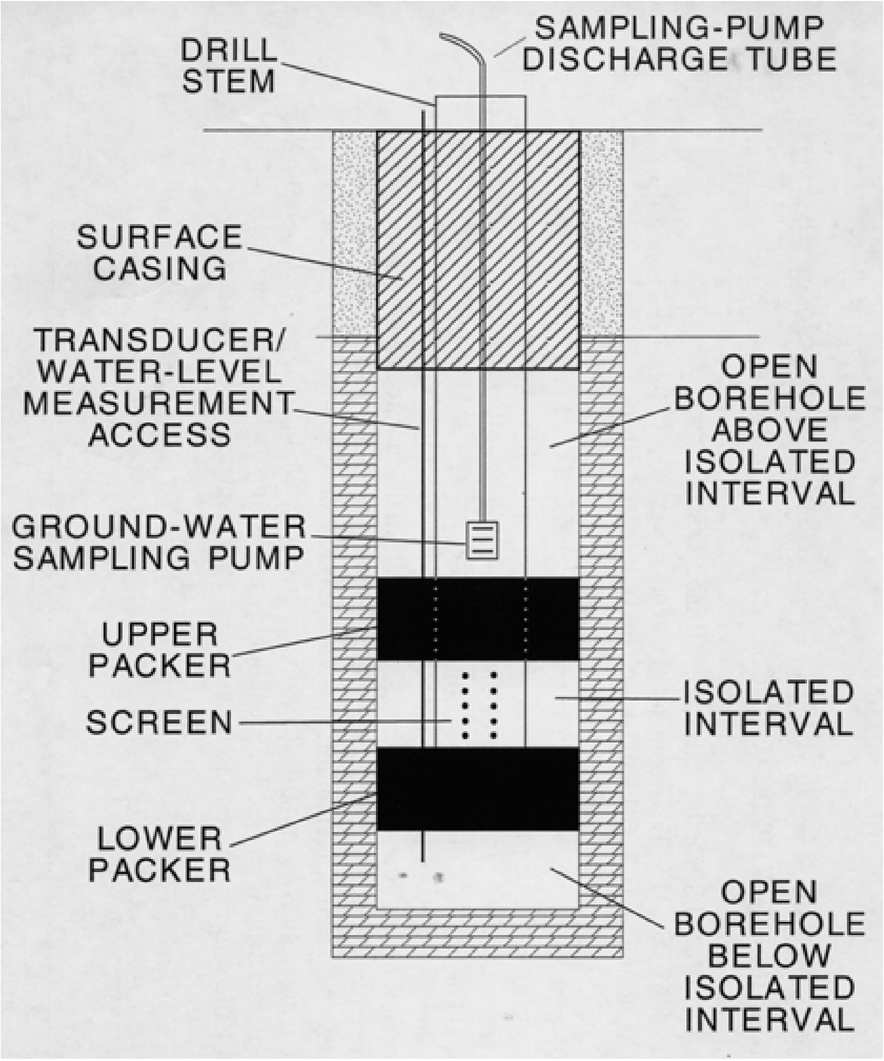

Figure C-7. Schematic of dual packer pump system (Holmes et al, 2001).

Packer Pump Tests consist of isolating specific sections of a bedrock borehole with inflatable packers so that water-quality samples can be collected and aquifer tests can be conducted. 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. In conjunction with nearby monitoring wells permeable intervals within the formation can be identified and data from packer tests can inform the positioning of future monitoring wells.

The operation of various Packer Pump Tests 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 common Packer Pump 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.

Packers may be inflated either hydraulically or pneumatically. Hydraulic inflation systems may utilize single or dual lines: one for inflation and one for deflation. For application to the deep borehole, safety consideration may preclude the use of pneumatic systems since the energy associated with the high pressure of the compressed gas required at depth places severe demands on the pressure lines and fittings and could result in an explosive release of gas if they are compromised. Hydraulic inflation may be preferred in the deep borehole application. Because of the depths involved in the deep borehole application dual lines may be cost prohibitive and take up too much space. In the single line arrangement inflation and deflation are accomplished through the same line.

There are some operational considerations for packers. Packer glands are made of rubber materials that can be damaged if they scrap 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 increase pressures required and is exasperated 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.

C.4 Tracer Testing

C.4.1 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 C-8. In situ transport

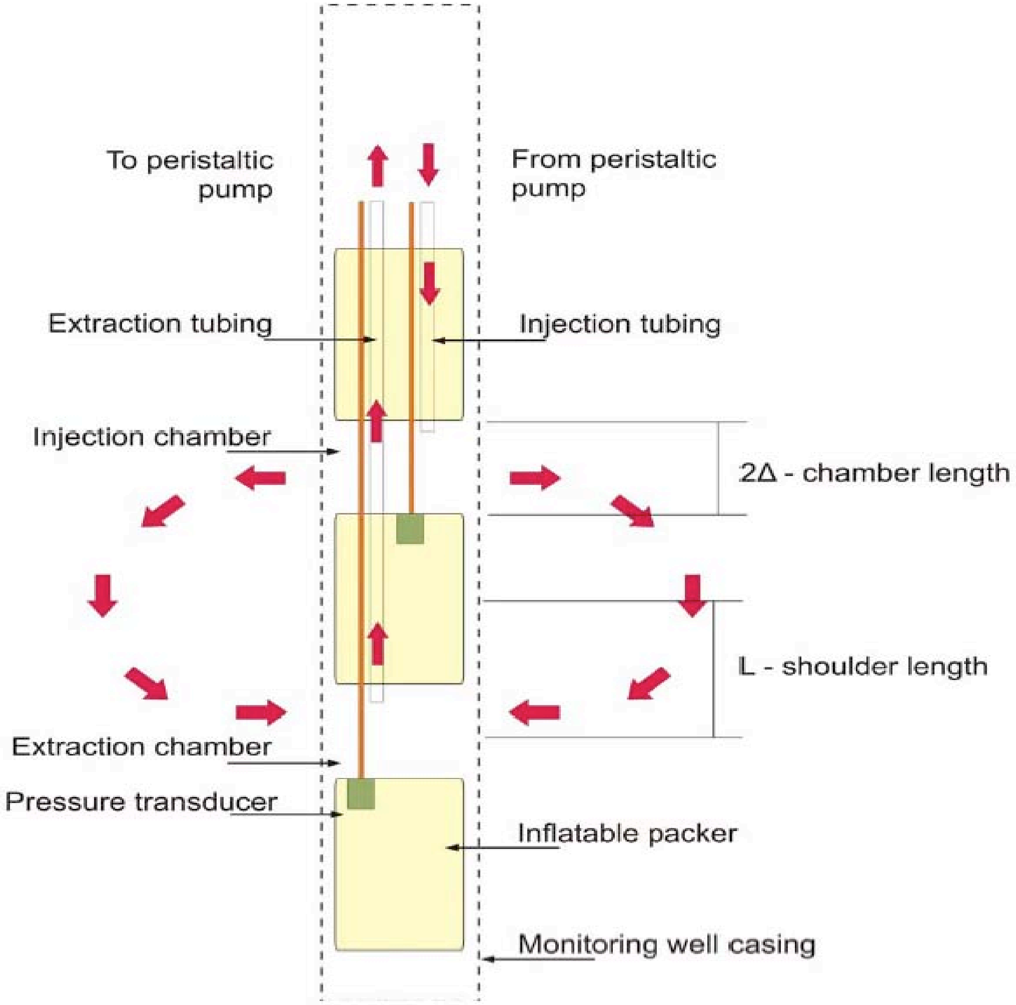

Figure C-8. **Schematic diagram of the vertical dipole tracer test configuration (from Roos, 2009).**

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 DBD 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.

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).

C.4.2 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 C-9. A rest period between injection and withdrawal may be included in the test to allow the tracer plume to drift under ambient flow conditions.

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

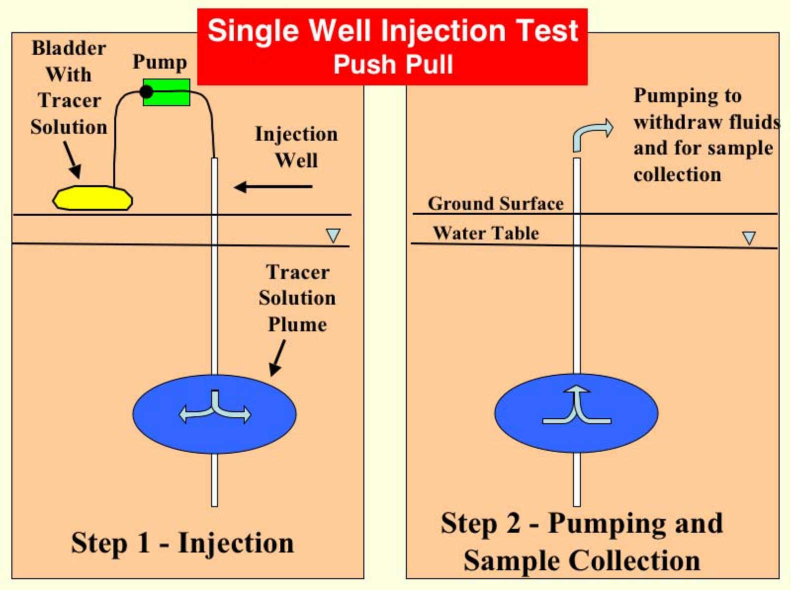

Figure C-9. Schematic diagram of a push-pull tracer test configuration.

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).

C.5. Thermal Testing

C.5.1 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

C.6 Borehole Seals Testing

C.6.1 Downhaul Force Mechanical Testing

Downhaul Force Mechanical Testing examine the mechanical integrity of borehole seals. A force is applied to the seal to estimate the failure strength of the seal. Compacted bentonite seals and cement plugs would be tested by applying the weight of the overlying drill string and/or downhaul force from the drill rig to the seal after seals have expanded or cured in place. Seals and plugs could be tested to failure or to the maximum force that could be applied by the drilling equipment. This would be useful for the situation where sealing and plugging are being tested in a demonstration prior to use in an operating facility.

C.6.2 Fluid Pressure Drawdown Test of Effective Permeability

Fluid Pressure Drawdown Testing of Effective Permeability tests the effectiveness of borehole seals as barriers to fluid migration. The fluid pressure is decreased (or increased) above the seal and the fluid pressure in the underlying sealed borehole interval monitored. Transmission of the fluid pressure to the sealed interval would be a function of the permeability (and fluid storage) in the seal itself, the disturbed rock zone, and the surrounding rock. By testing a borehole zone with little fracturing and no evidence of borehole breakouts, the influence of permeability in the disturbed rock zone and host rock would be minimized and the effective permeability of the seal or plug estimated more accurately.

Fluid pressure drawdown testing of seals would be used in the characterization of a DBD system for estimating the effective permeability of borehole seals and plugs. This testing would provide information on the potential migration of fluids through and around borehole seals and plugs.

DISTRIBUTION

Internal (Electronic Copy)

1	MS0771	S. A. Orrell, 6200
1	MS0736	P. Swift, 6220
1	MS0779	P. Vaughn, 6222
1	MS0747	B. Arnold, 6224
1	MS0747	R. MacKinnon, 6224
1	MS0735	J. Merson, 6910
1	MS0735	P. Brady, 6910
1	MS0754	S. Altman, 6915
1	MS0754	M. Rigali, 6915
1	MS0359	D. Chavez, LDRD Office, 1911
1	MS0899	Technical Library, 9536

Sandia National Laboratories