Conceptual Design and Requirements for Characterization and Field Test Boreholes:

Deep Borehole Field Test

Fuel Cycle Research & Development

Prepared for
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ACRONYMS

CB	characterization borehole (component of the DBFT)
DBD	deep borehole disposal
FTB	field test borehole (component of the DBFT)
DBFT	deep borehole field test
DOE	US Department of Energy
DQO	data quality objectives
DRZ	disturbed rock zone
DST	drill-stem test
ECP	external casing packer
KTB	Kontinentale Tiefbohrprogramm (German scientific drilling program)
NMR	nuclear magnetic resonance
PA	performance assessment
RFI	request for information
RFP	request for proposal
SAFOD	San Andreas fault zone observatory at depth (California borehole observatory)
SNL	Sandia National Laboratories
TRL	technology readiness level
UFD	used fuel disposition (DOE Office of Nuclear Energy program)
US	United States
VSP	vertical seismic profiling

This report is prepared as part of the US Department of Energy Office of Nuclear Energy Used Fuel Disposition (UFD) campaign, for Work Package FT-15SN081708 (WBS 1.02.08.17). This report satisfies milestone M2FT-15SN0817081, and is a revision to preliminary report FCRD-UFD-2015-000131 issued on June 4, 2015.

DEEP BOREHOLE FIELD TEST: CONCEPTUAL DESIGN REQUIREMENTS

1. INTRODUCTION

Deep Borehole Disposal (DBD) of high-level radioactive wastes has been considered an option for geological isolation for many years (Hess et al. 1957). Recent advances in drilling technology have decreased costs and increased reliability for large-diameter (i.e., ≥50 cm [19.7”]) boreholes to depths of several kilometers (Beswick 2008; Beswick et al. 2014). These advances have therefore also increased the feasibility of the DBD concept (Brady et al. 2009; Cornwall 2015), and the current field test, introduced herein, is a demonstration of the DBD concept and these advances.

The US Department of Energy (DOE) *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste* (DOE 2013) specifically recommended developing a research and development plan for DBD. DOE’s *Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel* (DOE 2014a) concludes “effective implementation of a strategy for management and disposal of all High-Level Waste and Spent Nuclear Fuel” would include focused research on deep boreholes, especially to retain flexible options for disposal of physically smaller DOE-managed solid radioactive waste forms. More information regarding the characteristics, quantities, and sizes of these smaller waste forms is in *Evaluation of Options for Permanent Geologic Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste* (SNL 2014).

As a first step, DOE issued a Request for Information (RFI) (DOE 2014b) to “seek interest in, and input from, States, local communities, individuals, private groups, academia, or any other stakeholders willing to host a Deep Borehole Field Test” (DBFT). The DBFT includes drilling two boreholes nominally 200 m [660’] apart to approximately 5 km [16,400’] total depth. The characterization borehole (CB) is the smaller-diameter (i.e., 21.6 cm [8.5”] diameter at total depth) borehole, and will be drilled first. The majority of the geologic, geohydrologic, geochemical, geomechanical and thermal testing (Vaughn et al. 2012) will take place in the CB. The field test borehole (FTB) is the larger-diameter (i.e., 43.2 cm [17”] diameter at total depth) borehole. The surface handling and borehole emplacement operations are planned to be tested at the FTB to demonstrate engineering feasibility and safety of disposing expected waste forms.

Subsequent to the RFI, the DOE issued draft (DOE 2015a, April 7, 2015) and final (DOE 2015b, July 11, 2015) Requests for Proposal (RFP) to seek competitive bids from teams who will provide a site to perform the DBFT (accommodating both boreholes) and a site-management contractor who will sub-contract drilling and testing to be done in the initial CB portion of the DBFT. A June 2015 preliminary version of this report (Kuhlman et al. 2015) provided supplemental information on characterization objectives for the CB as part of the DBFT RFP process (DOE 2015b). This report is an extension of that preliminary report, and includes the conceptual design of the second, larger-diameter borehole in the DBFT. The FTB construction and demonstration will be performed under a second RFP and contracting process.

Two boreholes provide a robust approach to achieve the overall goals of the DBFT. First, downhole characterization can be achieved with standard logging technology and methodology in the CB, whereas characterization in the larger-diameter FTB would present additional technical challenges. Second, the diameter of the CB will be large enough to accommodate testing the system for emplacing smaller waste forms such as $CsCl/SrF_2$ capsules (SNL 2014). Third, by conducting characterization activities in the smaller CB, the costs associated with those activities could be reduced significantly compared to the costs for characterization activities in the FTB. Finally, two holes will provide the unique opportunity for cross-hole testing at depth, if such testing is deemed necessary. Both geophysical and geohydrological cross-hole testing could be used in the DBFT to assess the viability of only performing future characterization at a DBD site from a single borehole.

The draft (DOE 2015a) and final RFPs (DOE 2015b) specify the site management contractor will prepare detailed drilling and testing plans for final review by DOE and the DBFT Technical Lead (Sandia National Laboratories). These plans will include details regarding site construction, sample collection, sample handling, testing procedures, and data management. This conceptual design document summarizes objectives of the DBFT at a high level without a specific site, while the drilling and testing plans will specify more detail and will be site specific.

The DBFT Technical Lead will provide or organize analysis of samples (e.g., cores and water samples) and data (e.g., geophysical logs, hydrological test data, and hydraulic fracturing test data) collected during the DBFT.

1.1 DBFT in Relation to DBD Concept

The overall goal of the DBFT is to conduct research, development, and testing in several important areas to confirm the viability of the DBD concept. This goal will be achieved by completing the following objectives:

- Evaluation and verification of geological, geochemical, geomechanical, and geohydrological conditions at a representative location (*the top-level characterization objective*);
- Demonstration of drilling technology and borehole construction to 5 km depth in crystalline basement with sufficient diameter for cost-effective waste disposal;
- Evaluation of package, waste, and seals materials at representative temperature, pressure, salinity, and geochemical conditions in the laboratory;
- Development and testing of engineering methods for test package loading, shielded surface operations, test package emplacement, and borehole seals deployment; and
- Demonstration of pre-closure and post-closure safety.

This document focuses on the conceptual design requirements of the DBFT, specifically the construction and completion of both boreholes and the characterization activities to be performed in the CB.

We specifically address key data necessary to confirm the viability of the concept, particularly unproven or especially critical components (e.g., collecting diagnostic geochemical and environmental tracer profiles from deep low-permeability crystalline rocks at possibly elevated temperatures – Section 2), and not the broader objectives that would be required for site characterization supporting actual implementation of the DBD concept. For example, the DBFT will conduct limited sampling and testing of formations in the overburden above the crystalline bedrock because such sampling and testing is standard practice in the groundwater or oil and gas industries. There is a high degree of confidence this aspect of the DBD concept can be performed successfully (i.e., these activities have a high technology readiness level [TRL]). Section 9 includes further discussion of the activities at a DBD site in contrast to those planned for the DBFT.

1.2 DBFT Drivers

Figure 1 illustrates the DBFT drivers or motivators and how they influence the design choices of the two boreholes in the DBFT. Each level depends on or logically flows from the levels above it. The DBFT drivers are above all other levels, while the drilling method and borehole design choices are at the bottom and depend on all other levels. Characterization targets (i.e., things we can measure) don't directly depend on DBFT drivers, but they do constrain what characterization activities can be done in the CB.

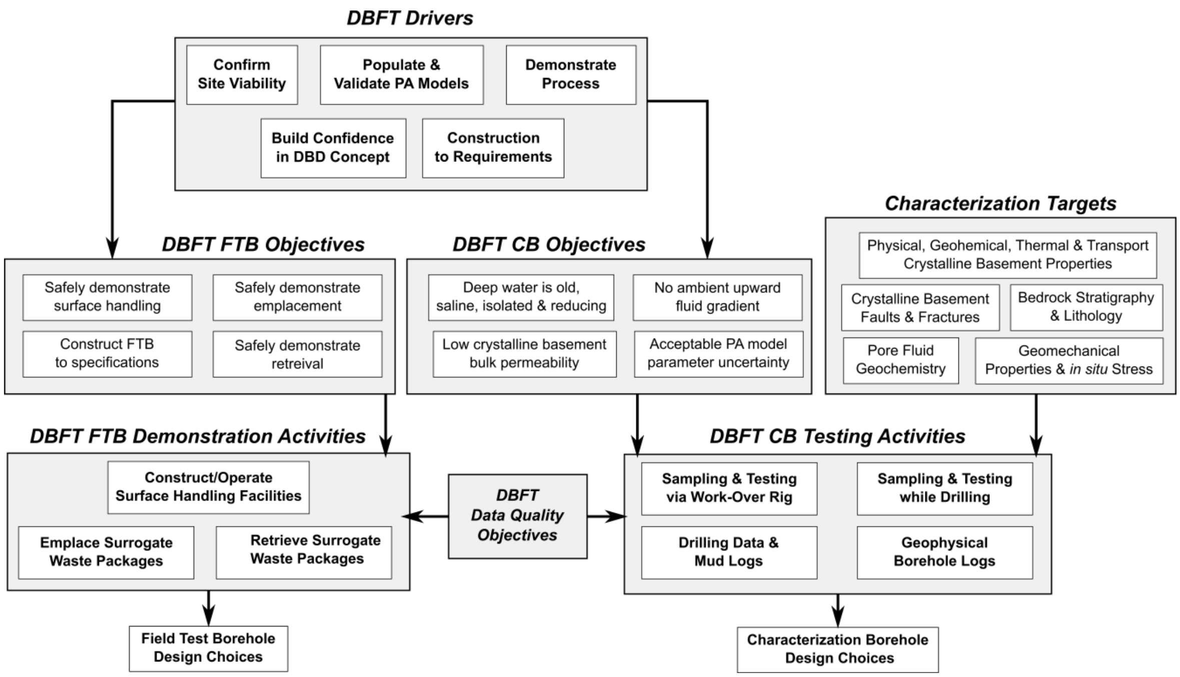

Figure 1. Conceptual relationship between borehole and casing design, testing and demonstration activities, and DBFT drivers.

There are five primary drivers for the DBFT (top level of Figure 1):

1. Confirm viability of a representative site (likely selected with limited deep crystalline basement information), including geological, geochemical, geomechanical, and geohydrological conditions at depth. Site selection requirements are specified in the DBFT RFP (DOE 2015b) and are not reiterated here.
2. Build confidence in DBD concept viability and robustness;
3. Demonstrate safe emplacement, retrieval, and surface-handling processes;
4. Provide engineering data needed to drill and construct a borehole to 5 km depth in crystalline basement to requirements (e.g., mud logging information, borehole deviation data, cementing specifications, and drilling parameters); and

5. Provide data necessary to demonstrate pre-closure and post-closure safety (i.e., populate performance assessment [PA] models) of the concept with site-specific data and validate process models against reality. DBD PA models have been developed for generic sites (Arnold et al. 2012, 2013) and reference designs (Arnold et al. 2011). These generic PA models will be parameterized using the characterization data collected at the DBFT site for the purposes of testing the post-closure DBD PA models.

Figure 1 shows how the CB and FTB portions of the DBFT each have four objectives or goals, which flow down from these five higher-level DBFT drivers.

1.3 CB DBFT Objectives

Based on the primary DBFT drivers, the four primary CB objectives (middle of Figure 1) are:

- Confirm deep groundwater in the crystalline basement is very old, saline, and reducing. Groundwater has been isolated from the surface environment for a long time, fluid density gradient is stable and opposes regional vertical circulation, and fluid geochemistry is rock dominated and associated with chemically reduced or reducing conditions (which generally decreases the solubility and mobility of radionuclides)
- Confirm no ambient fluid potential gradient exists to drive flow from the disposal zone to the shallow subsurface (i.e., over-pressured conditions are not present at depth, while under-pressured conditions in the crystalline basement would be favorable);
- Confirm bulk permeabilities of the host rock and the borehole disturbed rock zone (DRZ) are acceptably low (i.e., permeability at the borehole scale, rather than the core scale); and
- Reduce uncertainty to acceptable levels regarding host rock and DRZ parameter values used in site-specific numerical models (i.e., geochemical, thermal, geomechanical, geohydrological properties and constitutive laws).

There are data requirements related to achieving each of these objectives. The testing and sampling approaches used to collect the data themselves have limitations and requirements affecting the details of the drilling method, drilling mud type, and casing design.

The CB objectives of the DBFT must be considered in light of practical data quality objectives (DQOs) – see bottom middle of Figure 1. The DQOs serve two purposes: 1) they ensure data of appropriate types and sufficient quality are collected to answer the questions motivating the DBFT, and 2) they indicate when data have been collected that are “good enough” to satisfy the requirements. The DOE does not intend the DBFT to become an open-ended research project, but instead a demonstration of well-defined processes. DQOs will be considered explicitly in the drilling and testing plans. Further high-level discussion of DQOs is included in Section 5.5, where a distinction is made between the minimum set of data required from the CB and those data that are of secondary importance in achieving DBFT project goals.

If the DBFT science objectives are not met at a particular site due to unsuitable site geological conditions (e.g., recently recharged groundwater or significant upward hydraulic driving force) or formation instability (e.g., the borehole cannot be maintained open long enough to perform testing or demonstration activities), the drilling and completion of the subsequent FTB may be delayed, moved, or cancelled (the options will be detailed in the drilling and testing plans). In addition, the site chosen for the DBFT does not necessarily need to have conditions required for an actual disposal site for DBD; a site with characteristics not amenable to disposal operations could still prove useful for demonstration purposes (see bullets in Section 1.1).

1.4 FTB DBFT Objectives and Demonstration Activities

The objectives of the FTB are complementary to those of the CB. The FTB will be used to demonstrate emplacement and retrieval of test packages (SNL 2015; Hardin 2015a; Su & Hardin 2015). Surface and borehole test package handling and emplacement operations will be conducted to demonstrate safe handling and emplacement processes. Multiple borehole emplacement options are currently being considered, including wireline and drill pipe emplacement. The costs (Hardin 2015b) and risks (Sevougian 2015) associated with each emplacement method are being evaluated before choosing a final design. Regardless of the chosen emplacement and retrieval method, the borehole will be designed and constructed to maximize the likelihood of safe and efficient emplacement, thus increasing confidence in the DBD concept.

The FTB demonstration in the DBFT will not include radioactive materials, and therefore will have no radiological risk. However, the safe demonstration of completion and handling activities will be implemented as though radiological risk is present and therefore will be an important first step towards eventual implementation of the DBD concept.

The objectives for the FTB during the DBFT are to demonstrate borehole constructability and operational procedures (i.e., confidence building). The four primary FTB objectives are:

- Confirm the borehole can be drilled, constructed, and completed safely (i.e., involving monitoring and control of deviation, detection of borehole breakouts, selection of drilling fluid composition, and achievement of an acceptable penetration rate).
- Demonstrate surface handling procedures and facilities required for an actual DBD site with radioactive waste using test packages and non-radioactive components.
- Demonstrate safe and efficient emplacement of test packages from the surface to the disposal horizon portion of the FTB.
- Demonstrate safe and efficient retrieval of test packages from the disposal horizon portion of the FTB back to the surface. No seals or bridge plugs are planned to be installed in the DBFT.

In addition to these four primary objectives, some operational tasks will be conducted to understand the reliability, repeatability, and possible risks of operational tasks, including: lowering and raising one or more test packages down the borehole repeatedly, conducting simulated fishing operations with different test package designs or sets of hardware and couplings (Su & Hardin 2015), or cutting and removing casing or liner sections at depth. The DBFT does not currently include placing a permanent seal in the FTB above the disposal zone, so this aspect of the DBD emplacement process will likely not be tested *in situ* as part of the DBFT.

1.5 DBFT Characterization Targets and CB Testing Activities

This section discusses CB testing activities which flow down from DBFT Objectives. Tables 1 through 5 summarize the testing activities discussed in the following sections, grouping them by characterization target (middle-right in Figure 1). Table 6 summarizes the contents of Tables 1 through 5 in matrix form. Sections 5.1 through 5.4 discuss the testing activities in more detail.

1.5.1 Crystalline basement faults and fractures

Fractures and faults are typically the primary source of bulk permeability at depth (i.e., as opposed to core permeability determined from small unfractured samples) and therefore are primary characterization targets (Table 1) to ensure low bulk permeability of the basement rock. This key characterization target can also be related to the safe and efficient construction of the borehole or the quantification of parameters and their uncertainty for PA modeling.

Table 1. Activities to characterize faults and fractures

Method	**Reference**	**How**
Intermittent Coring	Section 5.2.1	Identify smaller fractures in cores, while larger fracture zones could affect core recovery.
Hydraulic Fracturing	Section 5.2.3	Estimate magnitude of *in situ* stress state components, and relate stress conditions to fracture sets and their permeability to flow.
Spontaneous Potential Log	Section 5.3.3	Identify fracture zones with different fluid salinity than borehole mud.
Induced Polarization Log	Section 5.3.4	Evaluate changes in formation mineralogy (clays, primary minerals) and indirect estimation of formation permeability.
Neutron Porosity Log	Section 5.3.5	Identify more porous rocks or fractured zones.
Density Log	Section 5.3.6	Identify more porous rocks or fractured zones.
Sonic Log	Section 5.3.7	Identify and characterize features such as fractures and fracture zones with different mechanical and flow properties.
Borehole Imaging and Caliper	Section 5.3.8	Map the locations and orientations of natural fractures and fracture zones intersecting the borehole. Map drilling-induced breakouts and tensile fractures.
Borehole Gravity Log	Section 5.3.9	Identify larger features such as through-going fault zones with different bulk density. Identify juxtaposition of different density formations across displaced faults.
Nuclear Magnetic Resonance Log	Section 5.3.10	Indirectly estimate formation permeability and tortuosity.
Vertical Seismic Profiling	Section 5.3.12	Identify fracture zones, providing indication of their lateral continuity or orientation away from borehole.
High-Resolution Temperature Log	Section 5.3.13	Identify flowing fractures and fracture zones; used in conjunction with borehole imaging.
Flowing Borehole Log	Section 5.3.15	Identify flowing fractures and fracture zones; used in conjunction with borehole imaging and high-resolution temperature logging.
High-Permeability Packer and Drill-Stem Pumping Tests	Section 5.4.3	Estimate hydraulic conductivity, compressibility, and static formation pressure in higher-permeability intervals (e.g., fracture zones), indicative of fracture connectivity.

1.5.2 Lithology and stratigraphy

The characterization of lithology and stratigraphy (Table 2) is directly related to most of the CB science objectives, because the lithology and stratigraphy will be strongly correlated with the geohydrological, geomechanical, geochemical, and thermal properties of the system.

Table 2. Activities to characterize lithology and stratigraphy

Method	Reference	How
Drilling Parameters Logging	Section 5.1.1	Provide semi-continuous record of drilling parameters, related to rock types and lithology changes encountered during drilling.
Drill Cuttings and Rock Flour Lithology Log	Section 5.1.2	Provide a semi-continuous vertical profile of overlying sediments and crystalline basement lithology, to correlate with geophysical log data.
Intermittent Coring	Section 5.2.1	Provide a discontinuous vertical profile from the base of the overlying sediments, across crystalline basement lithology, to correlate with geophysical log data.
Spectral Gamma-Ray Log	Section 5.3.1	Differentiate rock origins and sources of radioactivity (K, U, or Th) to characterize local ^{4}He sources.
Resistivity Log	Section 5.3.2	Provide data on pore fluid conductance, which can be correlated with lithology and pore fluid salinity.
Spontaneous Potential Log	Section 5.3.3	Provide data on variations in pore fluid composition, which can be correlated with lithology.
Neutron Porosity Log	Section 5.3.5	Provide data on porosity contrasts, in conjunction with density, sonic and other logs, to characterize lithology at a smaller scale than gravity data.
Density Log	Section 5.3.6	Provide data on porosity contrasts, in conjunction with neutron porosity, sonic and other logs, to characterize lithology at a smaller scale than gravity data.
Sonic Log	Section 5.3.7	Provide data on rock geomechanical properties, which can be correlated with lithology.
Borehole Imaging and Caliper	Section 5.3.8	Image natural foliation or fabric in rock, even where not cored. Identify transitions, discontinuities, and unconformities. Provide fracture distribution and orientation data to orient or corroborate core.
Borehole Gravity Log	Section 5.3.9	Provide data on rock density contrasts, related to differences in porosity and lithology, at a larger scale than density and porosity logs.
Vertical Seismic Profiling	Section 5.3.12	Identify stratigraphy and discontinuities, providing indication of their lateral continuity or orientation away from borehole.

1.5.3 Physical, chemical and transport parameters

Characterizing physical, geochemical, and transport parameters (Table 3) is directly related to developing input parameters for PA models and reducing uncertainty in these parameters.

Table 3. Activities to determine system physical, geochemical, and transport properties

Method	Reference	How
Drilling Parameters Logging	Section 5.1.1	Provide semi-continuous record of drilling parameters encountered (including borehole deviation), related to rock properties encountered while drilling.
Drilling Fluid Log (Liquid and Dissolved Gas Components)	Section 5.1.2	Provide semi-continuous information about changes in fluid inflow quality and quantity during drilling.
Intermittent Coring	Section 5.2.1	Provide samples for laboratory testing to estimate parameters such as sorption coefficients, bulk density, porosity, permeability, geomechanical properties, and thermal properties. Correlation with geophysical data.
Hydraulic Fracturing	Section 5.2.3	Determine magnitude of minimum horizontal stress; estimate maximum horizontal stress.
Resistivity Log	Section 5.3.2	Provide information about lithostratigraphy, fluid saturations, and groundwater salinity.
Induced Polarization Log	Section 5.3.4	Estimate fluid-formation interface properties; indirectly related to formation permeability.
Neutron Porosity Log	Section 5.3.5	Estimate porosity at smaller scale than gravity log.
Density Log	Section 5.3.6	Estimate formation bulk density and porosity at smaller scale than gravity log.
Sonic Log	Section 5.3.7	Provide data on rock geomechanical properties, which can be correlated with physical and chemical properties.
Borehole Imaging and Caliper	Section 5.3.8	Identify in-borehole vertical fluid potential gradient due to flowing fractures in conjunction with temperature logging.
Borehole Gravity Log	Section 5.3.9	Estimate host-rock bulk density and porosity, or possible mineral alteration at larger scale than density and porosity logs.
Nuclear Magnetic Resonance Log	Section 5.3.10	Estimate formation permeability and tortuosity independently and indirectly.
Vertical Seismic Profiling	Section 5.3.12	Estimate average rock geomechanical properties, and their lateral continuity and dip of discontinuities.
High-Resolution Temperature Log	Section 5.3.13	Measure geothermal gradient. In conjunction with borehole televiewer or formation micro-resistivity image log, identify flowing fracture zones where thermal anomalies are associated with fractures.
Fluid Density or Downhole Pressure Log	Section 5.3.14	Estimate fluid density, which also serves as a correction for other logs.
Low-Permeability Packer Pulse Test	Section 5.4.2	Estimate permeability, formation compressibility, and static formation pressure in lower-permeability intervals.

Method	Reference	How
High-Permeability Packer Pumping Test	Section 5.4.3	Estimate permeability, formation compressibility, and static formation pressure in higher-permeability fracture zones. Fluid samples are used to constrain density profiles.
Dipole and Single-Well Injection-Withdrawal Packer Tracer Testing	Section 5.4.4	Estimate advective porosity, dispersivity, sorption coefficient, dispersivity, and matrix diffusion rate. Estimate ambient groundwater flow during rest period after injection.
Waste Canister Mockup Electrical Heater Test	Section 5.4.5	Estimate bulk thermal conductivity, coefficient of thermal expansion, and confirm thermomechanical constitutive relationships.

1.5.4 Fluid geochemistry

Characterization of fluid geochemistry (Table 4) through profiles is the primary method to prove deep groundwater is old, isolated, saline, and reducing. The quantification and reduction of uncertainty in PA models is also related to these activities.

Table 4. Activities to characterize fluid geochemistry

Method	Reference	How
Drilling Fluid Log (Liquid and Dissolved Gas Components)	Section 5.1.2	Provide semi-continuous information about changes in water inflow quantity and quality during drilling.
Fluid Samples from Cores	Section 5.2.1	Provide water samples from lower-permeability rock for groundwater geochemistry testing and environmental tracer profiling.
Resistivity Log	Section 5.3.2	Provide pore-water quality data (e.g. salinity and ionic strength).
Spontaneous Potential Log	Section 5.3.3	Provide pore-water quality data (e.g. salinity and ionic strength).
Induced Polarization Log	Section 5.3.4	Estimate fluid-surface interface properties (e.g., clay distribution) through chargeability measurements.
Nuclear Magnetic Resonance Log	Section 5.3.10	Identify changes in formation fluid salinity or composition.
High-Resolution Temperature Log	Section 5.3.13	Identify flowing fracture zones as thermal anomalies.
Fluid Density or Downhole Pressure Log	Section 5.3.14	Wellbore fluid pressure and density profile.
Fluid Samples from High-Permeability Drill-stem and Packer Tests	Section 5.4.3	Provide water samples from higher-permeability fracture zones for groundwater geochemistry testing and environmental tracer profiling.
Packer Tracer Testing	Section 5.4.4	Sampling for introduced tracers will also provide data on pore or fracture zone fluid geochemistry.

1.5.5 Geomechanical parameters

Characterization of the geomechanical properties (Table 5) is related to safe and efficient construction of the borehole, as well as reduction of parameter uncertainty in PA models. Estimation of in situ stress state in the borehole will be important for borehole stability, affecting both the CB and FTB.

Table 5. Activities to characterize geomechanical properties

Method	Reference	How
Laboratory Geomechanical Tests on Core	Section 5.2.1	Estimate geomechanical characteristics (processes and properties for constitutive models).
Drill Stem Tests of Shut-In Pressure	Section 5.2.2	Estimate static formation pressure.
Hydraulic Fracturing	Section 5.2.3	Determine magnitude of least principal stress; estimate maximum horizontal stress.
Density Log	Section 5.3.6	Estimate rock bulk density and porosity.
Sonic Log	Section 5.3.7	Provide data on rock geomechanical properties based on seismic wave velocity propagation.
Borehole Imaging and Caliper	Section 5.3.8	Determine the location and nature of borehole breakouts and drilling induced-fractures, related to rock strength and *in situ* stress state.
Dipole Shear-Wave Velocity Log	Section 5.3.11	Estimate horizontal stress field anisotropy from apparent anisotropy in geomechanical properties.
Vertical Seismic Profiling	Section 5.3.12	Provide data on rock geomechanical properties, with data on lateral continuity and dip away from borehole.
High-Resolution Temperature Log	Section 5.3.13	Estimate location and orientation of flowing fracture sets in conjunction with borehole imaging.
Fluid Density or Downhole Pressure Log	Section 5.3.14	Provide wellbore fluid pressure correction to formation pressure measurements.
Low-Permeability Packer Pulse Test	Section 5.4.2	Estimate formation permeability, compressibility, and static formation pressure in lower-permeability intervals.
High-Permeability Packer Pumping Test	Section 5.4.3	Estimate formation permeability, compressibility, and static formation pressure in higher-permeability intervals (e.g., fracture zones).
Waste Canister Surrogate Electrical Heater Test	Section 5.4.5	Confirm thermomechanical constitutive relationships; confirm interactions between engineered system (packages) and geosystem (borehole and DRZ) under emplacement conditions.

Characterization methods in Tables 1 through 5 are summarized in Table 6, sorted by the number of columns associated with each method. Although inclusion or exclusion of a method from any given category may be subject to debate, this generally indicates which characterization methods have wide applicability and which have a more limited application. This matrix does not indicate dependence of tests on each other. For example, the flowing borehole log will be important for locating higher-permeability intervals for later packer tests (pumping, tracer, and heater), and ensuring no high-permeability intervals are missed.

Table 6. Matrix of characterization methods and characterization targets

Method	Fault & Fracture (Table 1)	Geology & Stratigraphy (Table 2)	Physical, Chem. & Transport Properties (Table 3)	Fluid Chemistry (Table 4)	Geomech. (Table 5)
Laboratory Core Testing	●	●	●	●	●
Borehole Imaging + Caliper	●	●	●		●
Hi-Res Temperature Log	●		●	●	●
Higher-Permeability Packer and Drill-Stem Tests	●		●	●	●
Vertical Seismic Profile	●	●	●		●
Density Log	●	●	●		●
Sonic Log	●	●	●		●
Spontaneous Potential Log	●	●		●	
Neutron Porosity Log	●	●	●		
Borehole Gravity Log	●	●	●		
Induced Polarization Log	●		●	●	
Nuclear Magnetic Resonance Log	●		●	●	
Fluid Density or Downhole Pressure Log			●	●	●
Hydraulic Fracturing	●		●		●
Resistivity Log		●	●	●	
Drilling Parameters Log		●	●		
Drilling Fluids Log			●	●	
Packer Tracer Test			●	●	
Waste Canister Mockup Electrical Heater Test			●		●
Low-Permeability Hydraulic Pulse Tests			●		●
Dipole Shear Velocity Log					●
Spectral Gamma-Ray Log		●			
Drill Cuttings and Rock Flour Lithology Log		●			
Flowing Borehole Log	●				

2. ENVIRONMENTAL TRACER TESTING

This section provides motivation and background related to environmental (i.e., non-introduced) tracers, which are an important component of characterization for both a future DBD site and the DBFT demonstration site. Vertical profiles of multiple tracer types, using samples collected by the drilling and testing contractor, will be used by the DBFT Technical Lead to build the case for site suitability and long-term confinement in a DBD system. The suite of environmental tracers will be constructed in conjunction with vertical profiles of temperature (i.e., geothermal gradient), physical water properties (i.e., density, over- or under-pressure), and water geochemistry (i.e., salinity, major cations and anions, pH, and redox potential) to build an understanding of the provenance and evolution of the geohydrologic system in the crystalline basement.

Environmental tracers are naturally occurring stable and radio-isotopes that can provide information on fluid flux, residence time, provenance, and flow path history. These tracers are measured in the fracture fluid, pore fluid, mineral grains, and fluid inclusions. These tracers can be used to understand the long-term history (i.e., past millions of years) of the regional groundwater system in the crystalline basement and quantify any interaction with shallow groundwater. Multi-tracer analysis allows inference of flow path, groundwater age, and mixing in water samples in complex subsurface systems, providing a picture of the long term evolution of the regional groundwater system, a fundamental component of site characterization and PA model parameterization.

The isotope tracer sampling program will be tailored to the specific site conditions (IAEA 2013). At a minimum it will include: detailed mineralogical and geochemical analysis of the mineral phases (both host rock and fracture infill); noble gas composition of fracture fluid, pore fluid, and mineralogical phases; and stable isotope composition of hydrogen and oxygen in water. Decay series and long-lived atmospheric tracers can be added if productive fracture zones are encountered.

Environmental tracers will be assessed in fluid samples collected *in situ* (i.e., downhole) from drill-stem tests and packer pumping tests in more permeable intervals encountered. Low-permeability and low-porosity intervals may only be sampled through pore-water extraction from cores, due to the difficulty in collecting representative *in situ* fluid samples from low-permeability formations at depth. The small size of fluid samples obtained from cores will restrict the types of analyses that can be performed (e.g., stable water isotopes and ^{4}He).

Effects of drilling method, drilling fluid, sampling and coring procedures should be quantified when possible (e.g., contamination or isotope fractionation). If these contributions cannot be quantified or controlled, they should be discussed in the drilling and testing plan to better quantify the final uncertainties in tracer data results.

2.1 Noble Gases

The full suite of noble gases and their isotopes including ^{4}He will be measured in the mineral grains, matrix pore fluid, and fracture fluid to provide a direct measure of the degree of equilibrium between these different sources. Helium-4 systematics can provide a direct analog to the prediction of containment. Helium-4 is produced *in situ* from U and Th decay. Radiogenic ^{4}He is stored in mineral grains, from where it migrates into fluids filling pores and fractures. The ^{4}He in each of these reservoirs can be measured to evaluate the degree of disequilibrium in the system, and this disequilibrium can be correlated to rates of fluid flux and diffusion in fractures, and the time since the last significant advective groundwater flow in the system. The total amount of ^{4}He observed in the system can be compared to the theoretical amount produced over geologic history, thereby estimating closure of the system and its ability to contain radioisotopes over long periods (IAEA 2013). In essence, the ^{4}He closure of the system can be measured.

Nucleogenic ^{21}Ne is produced slowly and has been used to determine the age of very old water (Lippmann-Pipke et al. 2011). Xenon isotopic composition has changed over geologic time due to fractionation processes in the atmosphere; Xe composition can therefore be related to age of recharge in very old waters (Holland et al. 2013). The noble gas isotopic water analyses must be complemented with mineralogical analyses.

Required sample sizes for noble gas analyses depend on the phase being sampled and the expected amount of noble gases in the particular phase. For fracture zones where a modest amount of fluid can be pumped, typical fluid sample sizes are around 20 ml of water collected in leak-tight copper tubes (Weiss 1968). Downhole collection methods can be employed which preserve *in situ* pressure. Equilibrium head-space samples can also be taken, further reducing the need to pump fluid (Gardner & Solomon 2009). Mineralogical phase noble gas content and matrix pore water gas content requires core samples. The size of core sample needed depends on the amounts of noble gases expected and the detection limit of the analytical method. For example, for a full suite of noble gases from pore fluid in core, the total sample size can be estimated from v_{Cu}/ϕ_m where v_{Cu} is the volume of water in a copper tube sample and ϕ_m is the matrix porosity. A matrix porosity of 1% would require a core sample of approximately 2 liters. For many applications in deep geohydrology the He composition alone is enough. Given expected He enrichments in deep porewater in excess of 10^4, core sample sizes on the order of 1 ml would likely provide enough He. Most sub-coring techniques for noble gas analysis produce sub-cores on the order of 50 ml depending on the original core diameter, so He concentration in pore water should be measurable using traditional methods (Osenbrück et al. 1998). Mineralogical concentration of He can also be used to estimate the pore fluid concentration and advective flux. These require around 100 g of rock for analysis (Smith et al. 2013).

2.2 Stable Water Isotopes

Stable isotope composition of water (i.e., hydrogen and oxygen) is affected by long-term climatic and tectonic changes. Vertical profiles of the stable isotope composition can thus be used to infer the effect of climatic and geologic processes on the fluid flow system at depth. The amount of isotope exchange between the water and rock is a function of fluid flux and can give further information on the amount of long term fluid flux in the system. Stable isotopes only require small fluid sample sizes (i.e., milliliters), and can therefore be derived from core samples, drill-stem tests (DSTs), or packer pumping tests.

2.3 Atmospherically Derived Radioisotope Tracers

Other long-lived atmospherically derived radioisotope tracers could provide information on fluid residence times in these systems (e.g., ^{81}Kr, ^{129}I, and ^{36}Cl). The water need for analysis of ^{81}Kr has been reduced by advances in the atom-trap trace analysis technique, now feasible for fractured rock systems (Jiang et al. 2012; IAEA 2013). The analysis of ^{129}I and ^{36}Cl by accelerator mass spectrometer allows determination of concentrations using fluid sample volumes possible in deep borehole environments (Bentley et al. 1986). These radioisotope samples require volumes of water from 1 to 100 liters and thus will only be possible in higher-permeability portions of the borehole, pumped *via* downhole packer.

2.4 Uranium Decay Series

Decay series can be used to provide evidence of fluid-rock interaction and fluid residence times. For example, the difference in aqueous concentrations of ^{234}U and ^{238}U due to the alpha recoil effect can provide information on the rate of fluid flux and water-rock interactions. The transfer of natural ^{234}U from the rock matrix to groundwater is faster (on an atom-by-atom basis, corrected for overall abundance) than the transfer of ^{238}U, because the ^{234}U has been subject to alpha-recoil effects. Depletion of the local rock-water system in ^{234}U indicates active water movement on the time scale of the ^{234}U half-life (2.48×10^5 years). The U-series isotopic composition can provide information on the amount of fluid flux through the rock, and the time since the last fractionation (fluid flux) event. Uranium sample masses of at least a few nanograms are needed for analysis by thermal ionization mass spectrometry. Because of the low concentrations of U in many natural waters, sample volumes of tens to hundreds of milliliters may be required, although smaller volumes may suffice if the requisite mass is obtained.

2.5 Strontium Isotopic Ratios

Strontium-87/strontium-86 ratios are useful in determining water sources, in particular for water which has been in contact with radiogenic rocks. These ratios can be used to distinguish water which has not been in contact with the crystalline basement for long time periods, to identify meteoric and/or shallow water sources and determine mixing ratios between crystalline brine and meteoric waters (McNutt et al. 1984, 1990). Strontium-87 is a daughter product of ^{87}Rb which is found in higher concentrations in rocks with higher U and Th concentrations, while ^{86}Sr concentrations do not vary with time (McNutt 2000). Strontium samples generally require 1 liter of water (Harrington 2014), and therefore will be restricted to permeable fracture zone fluid samples.

3. RELEVANT HISTORIC DRILLING AND TESTING

This section summarizes relevant historical projects and studies for both the CB and FTB activities.

3.1 Relevant Drilling and Characterization Efforts

One of the goals of the DBD concept is to use existing technology and hardware, but drilling into crystalline basement rocks at great depth can be difficult. Several previous scientific deep crystalline drilling projects (e.g., KTB, Cajon Pass, Gravberg, and Kola boreholes) are being used to guide expectations for drilling, sampling, and testing conditions in the DBFT. Previous summaries of deep crystalline drilling and characterization of fractured crystalline rock are available (Boden & Eriksson 1988; Rowley & Schuh 1988; SKB 1989; NRC 1996; Harms et al. 2007; Stober & Bucher 2007; Beswick 2008; Arnold et al. 2012). Table 7 summarizes key statistics from each of the deep (>3 km [9,840’] total depth) drilling (as opposed to coring only) projects mentioned in the following paragraphs.

Although none of these projects have completed a borehole the size of the FTB to their total depth, the main KTB borehole had a diameter of 37.5 cm [14¾”] to a depth of 6,018 m [19,700’] and was a diameter of 31.1 cm [12¼”] from this depth to a depth of 7,790 m [25,600’] (Engeser 1996; §C.2.2.1).

The Kola project included drilling the 21.6-cm [8½”] diameter SG-3 borehole to a total depth of 12.2 km [40,000’] in the former Soviet Union. Scientific and technical findings from the project (1970-1992) are discussed in two conference proceedings books dedicated to the project (Kozlovsky 1987, Fuchs et al. 1990).

The Fenton Hill project included drilling three boreholes (22.2 cm [8¾”] and 25.1 cm [9⅞”] in diameter) as part of an enhanced geothermal project to total depths of 3 km [9,840’], 4.2 km [13,800’], and 4.6 km [15,100’] near Los Alamos, New Mexico (Fehler 1989; Brown 2009).

The Urach-3 borehole was a 14-cm [5½”] diameter enhanced geothermal project borehole to 4.4 km [14,400’] depth in southwestern Germany. The borehole was originally drilled to 3.3 km [10,800’] total depth in 1978, then it was deepened multiple times (Stober & Bucher 2000; 2004; 2007).

The Gravberg borehole was a 16.5-cm [6½”] diameter wildcat natural gas borehole drilled to 6.6 km [21,700’] depth in the Siljan Impact Structure in central Sweden. A summary of the data collected during drilling (1986-1987) is given by SKB (1989).

The Cajon Pass borehole was a 15.9-cm [6¼”] diameter borehole to 3.5 km [11,500’] depth near the San Andreas Fault in Southern California. Scientific findings from the project (1987-1988) are featured in a different special section of Journal of Geophysical Research (Zoback & Lachenbruch 1992).

The KTB project included coring a 15.2-cm [6”] diameter borehole to 4 km depth and drilling a 16.5-cm [6½”] diameter borehole to 9.1 km [29,900’] depth in southeastern Germany. The KTB project (1987-1994) is summarized by Bram et al. (1995) and scientific and technical findings from the project are featured in a special section of Journal of Geophysical Research (Haak & Jones 1997).

The Soultz-sous-Forêts GPK geothermal project drilled three 24.4 cm [9⅝"] diameter boreholes to 5.1 km [16,700'] and 5.3 km [17,400'] depth in northeastern France (Sanjuan et al. 2015).

The San Andreas Fault Zone Observatory at Depth (SAFOD) project included drilling 22.2-cm [8¾"] diameter vertical pilot borehole to 2.2 km [7,220'] depth and drilling a deviated 21.6-cm [8½"] diameter borehole to 4 km [13,100'] total length (borehole drilled 1.5 km [4,920'] vertical, then 60° deviation) in central California (Zoback et al. 2011). The SAFOD project (2002-2005) is summarized by Harms et al. (2007), and scientific and technical findings from the project are featured in a special section of Journal of Geophysical Research (Hickman et al. 2004). This borehole was not entirely completed in crystalline rocks, but dealt with difficult drilling conditions at and around the San Andreas fault.

The Deep Heat Mining Project drilled a 21.6-cm [8½"] diameter borehole to 5 km [16,400'] depth in Switzerland (Häring et al. 2008). The Basel-1 borehole was completed through 2.4 km [7,870'] of sedimentary overburden and 2.6 km [8,530'] of granitic basement. Hydraulic stimulation efforts in the borehole below 4.6 km [15,100'] depth triggered significant microseismic activity and a >3-magnitude earthquake (Mukuhira et al. 2013).

Table 7. Some Notable Deep (>3km) Drilled Boreholes in Crystalline Rock

Site	Bores	Location	Years	Depth [km]	Diam* [inch]	Purpose
Kola SG-3	1	NW USSR	1970-1992	12.2	8½	Geologic Exploration + Technology Development
Fenton Hill	3	New Mexico	1975-1987	3, 4.2, 4.6	8¾, 9⅞	Enhanced Geothermal
Urach-3	1	SW Germany	1978-1992	4.4	5½	Enhanced Geothermal
Gravberg	1	Central Sweden	1986-1987	6.6	6½	Gas Wildcat in Siljan Impact Structure
Cajon Pass	1	California	1987-1988	3.5	6¼	San Andreas Fault Exploration
KTB	2	SE Germany	1987-1994	4, 9.1	6, 6½	Geologic Exploration + Technology Development
Soultz-sous-Forêts GPK	3	NE France	1995-2003	5.1, 5.1, 5.3	9⅝	Enhanced Geothermal
SAFOD	2	Central California	2002-2007	2.2, 4	8½, 8¾	San Andreas Fault Exploration
Basel-1	1	Switzerland	2006	5	8½	Enhanced Geothermal

*borehole diameter at total depth

3.2 Relevant Borehole Construction, Handling, and Emplacement Efforts

Woodward-Clyde (1983) prepared an engineering study on radioactive waste emplacement in a deep borehole disposal system via drill pipe (i.e., using a drill rig). Drill pipe package emplacement is one of the options being considered for the DBFT, along with wireline emplacement. More discussion of the Woodward-Clyde design and a discussion of the potential risks and costs of these two emplacement options are presented in SNL (2015), Hardin (2015b), and Sevougian (2015).

A demonstration of handling, emplacement, and retrieval of spent nuclear fuel through large-diameter surface boreholes (to a mined drift 420 m [1,380’] below the surface) was conducted via wireline at the Nevada Test Site (Patrick, 1986). The Spent Fuel Test-Climax was conducted from 1978 to 1983 at what is now the Nevada Nuclear Security Site. SNL (2015) provide more details of this test, indicating its relation to the current DBFT demonstration design.

From 1984 to 1986 Standard Oil drilled and completed (Minge et al., 1986) the ultra-deep gas well L.W. Magoun No. 1 in Concordia, Parish, Louisiana to a depth of 7.6 km [25,015’] in sedimentary rocks. During the completion process, the well was drilled to an intermediate depth of 3.8 km [12,455’] at a diameter of 66 cm [26”]. A world-record size string of 50.8 cm [20”] diameter C-95 casing was successfully installed and cemented to this depth (Pejac and Fontenot, 1988).

4. BOREHOLE DESIGN

This section presents the nominal design for the CB and FTB components of the DBFT, prior to any site-specific information or refinements to the design. Once a site and site management contractor has been chosen as part of the RFP process (DOE 2015b), a detailed site-specific drilling and testing plan will be prepared.

4.1 Characterization Borehole

The five primary testing activities and their individual testing components are discussed in Sections 5 through 5.4; they can be related to three primary requirements for CB drilling and well completion (Section 6):

1. Representative crystalline basement fluid and rock sampling;
2. Representative *in situ* crystalline basement hydraulic, geomechanical, geochemical, and thermal testing;
3. Minimal casing or liner in the crystalline basement interval to increase the interval available for later packer testing *via* work-over rig.

To the extent possible, testing and fluid sampling will be conducted after borehole completion, and after releasing drilling equipment that is no longer needed, to reduce the cost of rig time and increase the likelihood of success. The only sampling to be conducted from drill-stem completions during drilling of the borehole will be for zones that will be cased or lined (with or without cementing) in the completed borehole. This includes the overburden and possibly any zones in the crystalline basement that are cased or lined to ensure borehole integrity. At least one of the in situ hydraulic fracture stress measurements will be completed before reaching total depth in the CB, to provide information for decision points in the FTB procurement and construction process.

The DBFT science objectives are presented in Sections 5.1 through 5.4 to aid selection of the proper drilling method, drilling fluid type, and casing/liner design to maximize the likelihood for success in meeting the DBFT CB science objectives (Figure 1).

Figure 2 illustrates a conceptual design of the CB for a generic site. Overburden here refers to the non-basement portion of the material encountered in the borehole (see labels on right side in Figure 2). The crystalline basement interval is the focus of most testing in the CB and the DBFT. The preferred geology in the crystalline basement is igneous intrusive, crystalline rock. Nominally, the crystalline basement will be older (i.e., Paleozoic or pre-Cambrian), while the overburden will consist of younger sedimentary rocks. Other site configurations are allowable as part of the site selection process (DOE 2015b).

The site selection requirement related to depth to crystalline basement specifies: 1) The borehole must be 5 km total depth, and 2) at least 3 km of the borehole must be crystalline basement (possibly more). It is viable for crystalline basement to extend to the surface (no sedimentary overburden), but drilling costs would be higher and drilling would likely be slower through 2 km of overlying additional crystalline basement, rather than 2 km of sedimentary rocks.

Conductor casing will be set to prevent caving and possible inflow from shallow deposits. Surface casing will then be set to approximately 460 m m [1,500’] (see discussion below). An intermediate liner will then be set across the remainder of the overburden and will penetrate into the top of the crystalline basement (a few meters or tens of meters), until competent basement rock is encountered. Figure 2 illustrates a design with two casing/liner diameters across the overburden. If drilling conditions in the overburden require further telescoping of casing diameter, then the intermediate borehole and casing diameters will be selected to maintain the capability for 8.5-inch bottom-hole diameter. If crystalline basement is encountered at 1 km depth, the intermediate casing will only extend that deep.

To maximize access to the crystalline basement for testing purposes, minimal casing will be used in the crystalline basement interval. A common oilfield technology is to grout casing and then use shot-perforating to access the formation. For the CB, however, shot-perforated sections would not provide representative fluid samples or support representative flow testing. Casing and shot-perforation strategies should be used only as a last resort, if no other viable completions can be implemented for a given interval. Geophysical logging, drill-stem fluid shut-in pressure testing, and sample collection should be considered before grouting any part of the crystalline basement.

Borehole and casing schedule (recommended diameters and depths) for the generic CB (shown in Figure 2) are:

Conductor (50.8 cm [20”] casing in 66 cm [26”] hole): The conductor is usually set to a depth of 15 to 30 m [50’ to 100’] and cemented to the surface. Often the conductor borehole is drilled with a separate drilling rig and installed as part of the location construction.

Surface (34 cm [13⅜”] casing in 44.5 cm [17½”] hole): Maximum depth of the surface casing is controlled by requirements on blow-out preventer equipment. The total depth will be as deep as regulatory agencies allow drilling without well control (assumed 460 m [1,500’] in Figure 2). This casing is cemented to the surface and if required will have a blow-out preventer installed after cementing.

Intermediate (24.4 cm [9⅝”] liner in 31.1 cm [12¼”] hole): This liner runs from the bottom of the surface casing to the base of the overburden (approximately 2 km in the nominal design) and far enough into the crystalline basement to reach competent rock; the annulus behind this liner is cemented along its entire length.

Crystalline Basement (unlined 21.6 cm [8½”] hole): This unlined borehole extends from the bottom of the intermediate liner to total depth.

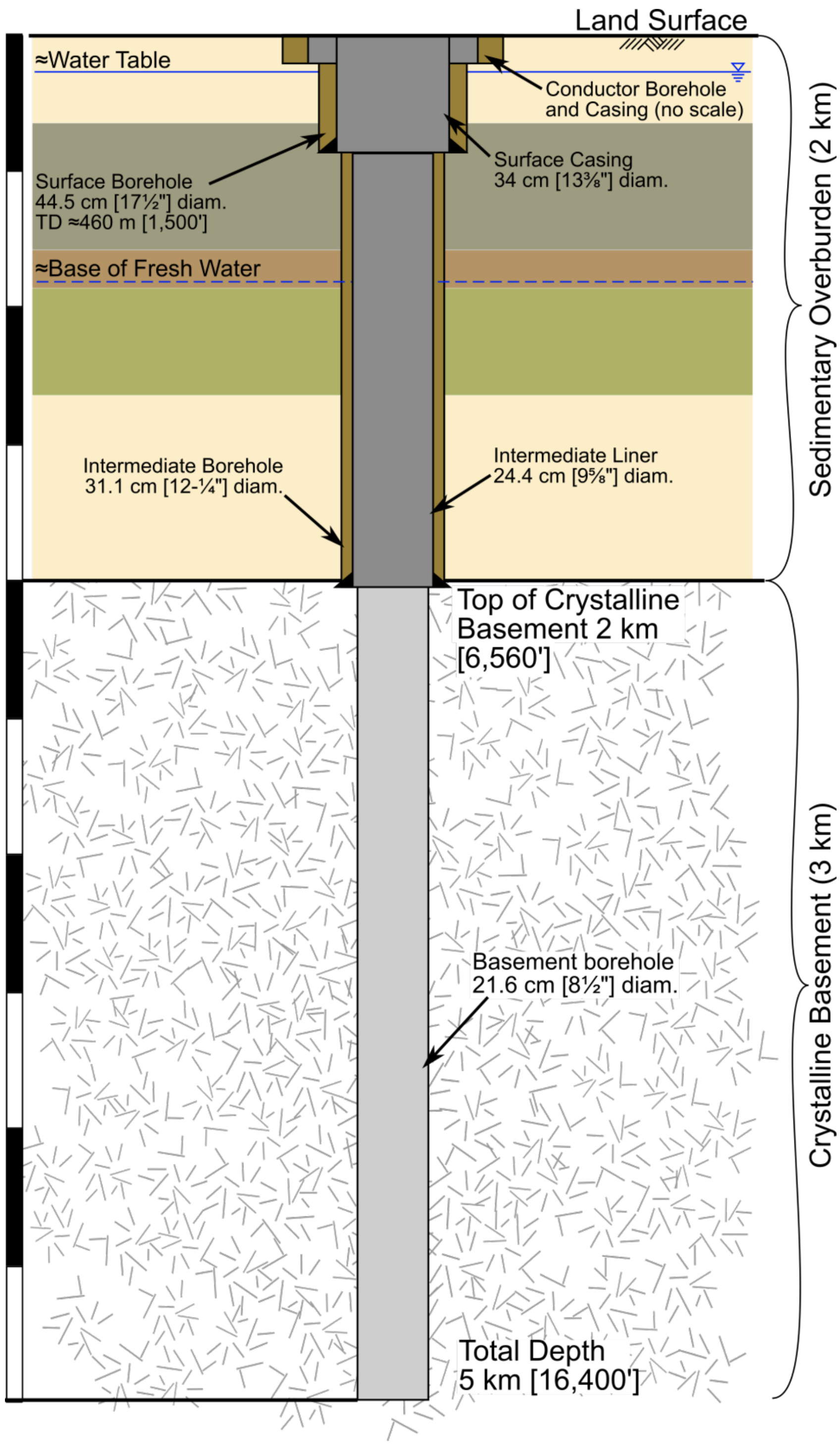

Figure 2. Characterization Borehole (CB) schematic. Dark gray represents permanent casing or liner, olive represents cemented annulus, light gray represents uncemented borehole.

4.2 Field Test Borehole

In contrast to the CB, the primary objectives of the FTB are 1) to drill and construct a 43.2-cm [17”] borehole to 5 km [16,400’] total depth, and 2) to safely and reliably conduct the emplacement and retrieval demonstrations. The FTB will demonstrate larger diameter drilling, and will be completed consistent with a reference concept for actual disposal boreholes. It will also be used for confirmatory characterization activities, and for emplacing and retrieving test packages. A conductor borehole and cemented casing will first be installed (Figure 3). Then a surface borehole, cemented steel casing, and blowout preventer will be constructed using a large drill rig, to similar depths (but larger diameters) as the characterization borehole. Then a smaller, intermediate borehole and fully cemented steel liner will be constructed through most of the overburden to stabilize the sedimentary section. The diameter will step down and another intermediate borehole and partly cemented liner will be constructed through the remaining overburden and the top 1 km of the crystalline basement. This liner will be hung from the intermediate liner above, and cemented only in the lower part of the interval using a port collar (just above 3 km depth), to support hanging of uncemented casing in the disposal interval below. Finally, a smaller diameter 43.2 cm [17½”] borehole will be constructed in the crystalline basement disposal zone (3 to 5 km depth). A perforated steel guidance liner will be hung in the disposal zone, then a guidance tieback casing will be hung from the top of the surface casing to the top of the disposal zone (from 0 to 3 km). In this way guidance casing of constant diameter will run from the surface to total depth, providing a path for emplacing test packages. The seal zone near the top of the crystalline basement (at 2 to 3 km depth) will remain mostly uncemented so that the liner there could be removed, exposing open hole for final sealing.

Borehole and casing schedule (recommended diameters and depths) for the generic FTB (shown in Figure 3) are largely consistent with the DBD reference design (Arnold et al. 2011) specifically:

Conductor (102 cm [40”] casing in 122 cm [48”] hole): The conductor is usually set to a depth of 15 to 30 m [50’ to 100’] and cemented to the surface. Often the conductor borehole is drilled with a separate drilling rig and installed as part of the location construction.

Surface (76.2 cm [30”] casing in 91.4 cm [36”] hole): Maximum depth of the surface casing is controlled by requirements on blow-out preventer equipment. Similar to the surface casing in the CB, the total depth of the FTB surface casing will be as deep as regulatory agencies allow drilling without well control (assumed 460 m [1,500’] in Figure 3). This casing is cemented to the surface and if required will have a blow-out preventer installed after cementing.

Intermediate (61 cm [24”] casing in 71.1 cm [28”] hole): This casing runs from the land surface (for attaching to a smaller-diameter BOP, if needed) to a depth of between 1.5 and 2.0 km. The final design of this casing will depend on site-specific conditions, including depth to basement and borehole stability in the sedimentary overburden above the top of the crystalline basement. The annulus behind this casing is cemented along its entire length. This cemented casing may extend into the crystalline basement until competent crystalline basement is reached, or may end 500 m [1,640’] above the top of crystalline basement. The basement seal zone will extend to the base of this casing after removal of the temporary casing there.

Upper Crystalline Basement (47.3 cm [18⅝”] liner in 55.9 cm [22”] hole): This liner runs from the bottom of the intermediate casing (500 m [1,640’] above the top of crystalline basement for the nominal case of 2 km depth to basement), to a depth of 1 km into the crystalline basement (base of the DBD seals zone). This liner has a port collar installed approximately 160 m [525’] above the bottom, allowing cement to be circulated out of the annulus during emplacement. For DBD (but not necessarily for the DBFT), this liner is then removed above the port collar after emplacement operations, to allow emplacement of seals against the crystalline basement from the top of the port collar to the base of the intermediate casing.

Lower Crystalline Basement (34 cm [13⅜”] perforated casing in 43.2 cm [17”] hole): This perforated guidance liner runs from the bottom of the upper crystalline basement liner to the total depth. The casing is set on the bottom of the borehole, and will be the interval where test package emplacement is demonstrated. This casing is not retrieved.

Guidance Tieback Casing (34 cm [13⅜”] casing): This casing is the same diameter as and is connected to the perforated guidance liner in the disposal interval of the borehole. The guidance tieback casing extends to the surface to provide a constant-diameter pathway for emplacement operations. This casing will be retrieved after emplacement operations (before removing the upper crystalline basement casing above the port collar).

As with the CB, the final site-specific design will be made once a site is chosen. The FTB design will also likely be further refined or modified after the completion of the CB, to incorporate site-specific information about the sedimentary overburden and crystalline basement.

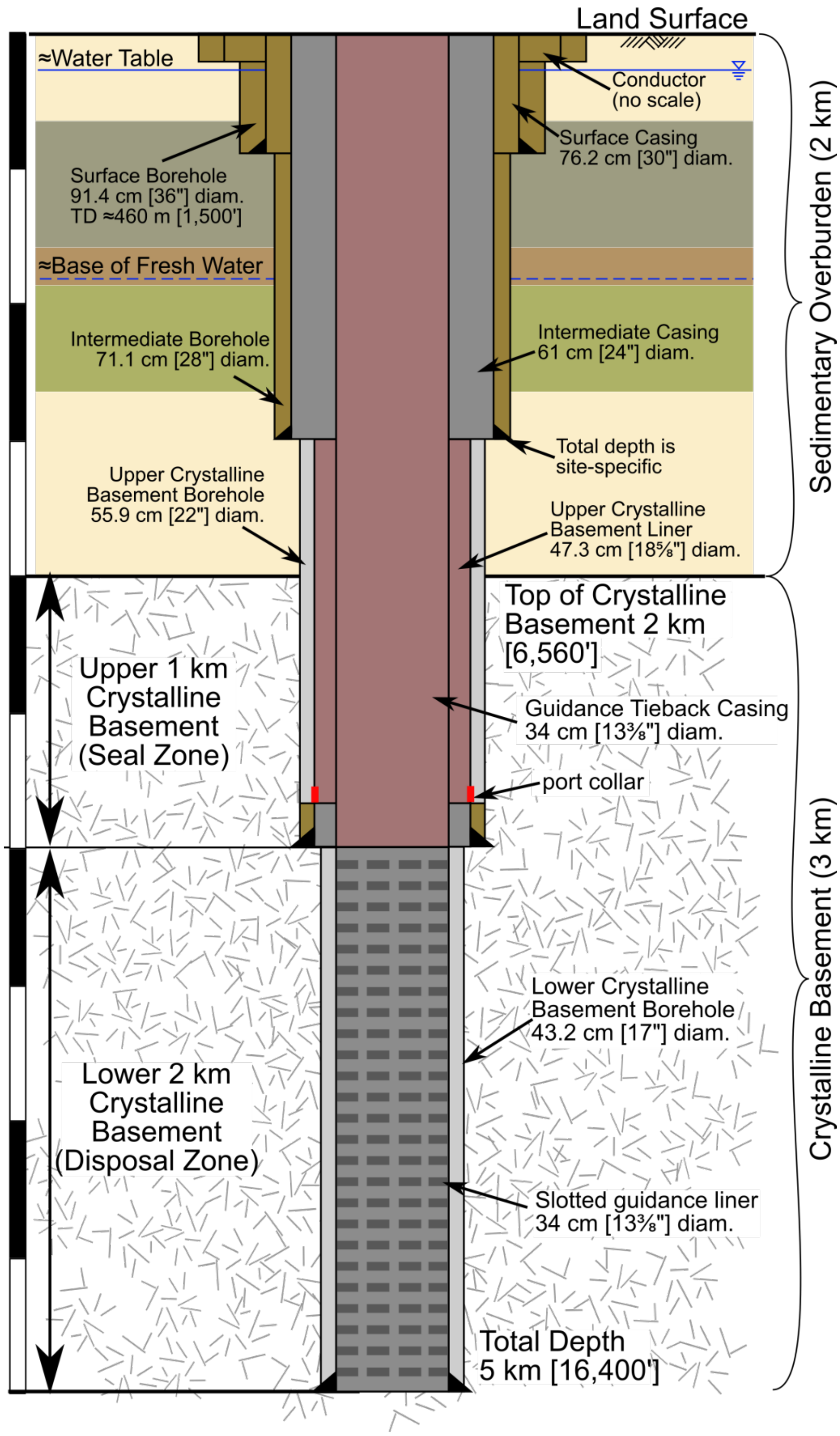

Figure 3. Field Test Borehole (FTB) schematic. Dark gray represents permanent casing/liner, pink represents casing/liner to be removed, olive represents cemented annulus, light gray represents uncemented annulus. Seal and Disposal Zones refer to Arnold et al. (2011) design; no permanent seals or radioactive waste will be included in the DBFT.

5. CONCEPTUAL DESIGN OF CHARACTERIZATION BOREHOLE

The primary focus of the CB is effectively characterizing the in situ conditions encountered in the crystalline basement at the DBFT site. A secondary focus of the CB is the demonstration of in situ testing activities in crystalline basement rock, at depths and conditions relevant to DBD.

5.1 Drilling Characterization

The drilling contractor will monitor the process of drilling, as part of their scope of work to ensure the safety of the borehole. Surveys and logging during drilling will likely include several methods.

5.1.1 Drilling Parameters Logging

The drilling contractor will monitor parameters related to the drilling rig and the drill-pipe string, including: penetration rate, bit weight, hook load, rotary speed, rotary torque, mud circulation rate, deviation, and mechanical, hydro-mechanical, and drilling specific energies. These data will be recorded and saved, to be used to assist in determination of lithology changes with mud, fluid, and cuttings logging (Section 5.1.2). Some drilling parameters (e.g., weight on bit, torque, and vibrations) can be measured at the bit (i.e., measurement while drilling) and either transmitted to the surface or stored and retrieved with the bit.

Deviation logs are important to keep track of the amount the borehole deviates from both vertical and a straight line; sometimes these can be compensated for or over-drilled to fix. Deviation will also be monitored while drilling using standard directional drilling technology (e.g., magnetometers and accelerometers). These data are mostly for engineering requirements of the borehole, but the data are also required data for interpreting and designing subsequent testing.

5.1.2 Drilling Fluid Logging at Surface

The type of drilling fluid (i.e., mud) used will depend on the drilling method and will strongly impact sample collection and testing (Section 7.1.4).

Standard logging of drill cuttings provides a semi-continuous vertical profile of rock type, stratigraphy, 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. Drill cuttings samples will be stored for possible future geochemical and petrophysical analysis.

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

Indications of significant water inflow during drilling from mud logging and measurement while drilling may be used as the basis to stop drilling and attempt to sample formation water through a drill stem test (Section 5.2.2).

5.1.2.1 Logging drilling fluid physical properties

Cuttings samples collected at 3-m intervals, provide a semi-continuous vertical profile of crystalline basement lithology. Basic lithologic information from the borehole is central to interpreting the geology and geologic history of the site, and providing information relevant to groundwater flow and radionuclide transport, such as porosity and sorption characteristics.

Rock flour samples centrifuged from drilling fluid can be analyzed onsite using X-ray fluorescence and X-ray diffraction to quantify variation in mineral and rock composition (Emmermann & Lauterjung 1990). High-frequency data on drilling fluid physical properties measured at the surface or possibly downhole (e.g., flowrate, density, viscosity, and electrical conductivity) can be used to augment cuttings and rock flour samples.

5.1.2.2 Logging drilling fluid chemical properties

The general mineral and general physical properties (e.g., temperature, pH, redox potential, major anions and cations, or total dissolved solids) of the liquid component of drilling fluid will be monitored at a high frequency during drilling to qualitatively determine inflow and outflow zones, including changes in groundwater geochemistry. Drilling fluid composition will be tested and logged (i.e., mud logging) before it is recirculated with makeup water (Section 5.1.2.4) back into the borehole. Geochemical logging includes monitoring concentration of any added tracers (Section 5.1.2.4).

5.1.2.3 Logging dissolved drilling fluid gases

Along with major atmospheric gases (i.e., N_2, O_2, and CO_2), concentrations of noble gases (particularly He, Ne, and Ar) and hydrocarbons (at least methane) should be monitored in the drilling fluid to provide additional information for constructing geochemical profiles of environmental (non-introduced) tracers (Section 2). This logging is conducted to further qualitatively determine inflow and outflow zones, including changes in crystalline basement bulk permeability and groundwater geochemistry.

5.1.2.4 Logging and tracing makeup water

Additional drilling fluid (i.e., water or oil) is added to the drilling fluid system to maintain the required mud system volume as cuttings are removed. The chemistry of added makeup fluid will be monitored, and tracers will be added.

The quantity and timing of addition of tracers to the drilling fluid and makeup fluid will be logged, to maintain and document a relatively uniform concentration of tracers in the drilling fluid system. Conservative (non-sorbing and non-reacting) drilling fluid tracers that will not significantly alter drilling fluid chemistry will be used.

Tracers will be used to 1) indicate contamination of formation water samples pumped from higher-permeability crystalline basement portions of the borehole, and 2) indicate fluid invasion and contamination in cores. Two candidate drilling fluid tracers for water-based mud are fluorescein dye (very easy on-site determination of contamination during sampling, but may sorb to clays and organics) and deuterated water (requires more complex analysis than fluorescein dye, but is completely conservative).

For oil-based mud systems, appropriate tracers should be chosen to achieve the objectives. Air drilling may be possible, but it would change the mud logging system significantly. As long as the objectives are met, the chosen drilling fluid and tracers are flexible, although a drilling method and circulation fluid choice must be agreed upon between the contractor and the DBFT Technical Lead early in the design process.

5.1.3 Downhole Monitoring

Some drilling fluid systems can transmit data from bit-mounted sensors to a drilling-fluid pressure sensor at the surface *via* pressure pulses up the liquid in the drill pipe. This technology only allows low baud rate (approximately 10 bits/second), but is simple and provides some information while drilling (i.e., logging or measurement while drilling). Wired drill pipe (allowing a continuous electrical circuit from the bit to the surface) can accommodate much higher data transfer speeds, but may not be compatible with all drilling methods and would likely be very expensive.

Drilling fluid pressure, temperature, and resistivity should be monitored near the drill bit to provide information on fluid loss to and production from formations as they are encountered. The exact suite of downhole instrumentation to be used is dependent on the drilling method, balanced with costs. The first priority is directional drilling, which requires some down-hole data collection. Additional data (fluid resistivity and temperature) may be acquired if the drilling system allows. Drilling fluid resistivity can be related to salinity, and therefore inflow of fresher or more saline water to the bottom of the borehole can be noticed immediately, rather than waiting for subtle changes in fluid chemistry to circulate to the surface while mixing *en route*. Changes in temperature during drilling can also be related to significant inflow of warmer or cooler formation water. Fluid pressure changes can be related to encountering highly over- or under-pressurized zones, which may also be related to changes in rock bulk permeability (e.g., fractured zones).

5.2 Downhole Sampling and Testing during Drilling

Downhole sampling and testing will include intermittent (5%) advance coring, hydraulic fracturing stress measurements, and drill-stem testing (DST). Core and fluid sampling will be used to obtain vertical profiles of natural tracers to verify effective hydrologic isolation of the disposal zone (Figure 2 and Section 2). Downhole sampling during drilling increases rig standby time and poses risks of damage to the borehole or stuck tools, but should be carefully planned and executed to collect the key core and fluid samples. Thus, a minimum but necessary scope of testing and sampling should be planned to achieve the project's scientific characterization goals. All drilling and completion activities should be planned to support downhole testing and sampling (Figure 1). Much of the open-hole sampling and testing in the basement interval will be conducted using a work-over rig after drilling is complete (Section 5.4).

Core and fluid sampling depths should be planned prior to drilling, but additional sampling locations may be identified during drilling. Drilling and coring activities should be designed to minimize sample contamination as discussed in Section 6.

5.2.1 Intermittent Coring

Advance coring will target recovery of 50 m [164'] of core per 1 km [3,280'] of basement (i.e., 5% of crystalline basement interval). Coring methods may require wireline retrieval to be cost effective for the large amount of core and intermittent core points (i.e., depths where coring begins). Coring activities will be coordinated, to the extent practical, to coincide with bit changes and other activities when drilling is stopped. Core points will be chosen to maximize the ability to interpret environmental tracers (Section 2) and other core data. The majority of the core will be collected from the basement rock, with some coring in the overburden as necessary to help improve the ability to interpret the vertical profile of environmental tracers. When possible, coring should sample changes in crystalline basement lithology or character, with the secondary target of recovering some core from each major crystalline basement lithology encountered. Core may be required from intervals other than those initially planned, based on fulfilling the science objectives of the DBFT. Percussion or rotary sidewall coring can be used as a contingency if advance core retrieval is poor or if important intervals are not advance cored and only identified after drilling.

The overburden-basement interface is of special interest to hydrological, mechanical, and thermal assessments, and thus should be cored. The initial core point should be at (e.g., within a few meters) the overburden-basement interface. The nature of the interface will likely be sharp (i.e., an unconformity), and therefore the choice of core point for optimal characterization should be chosen carefully. Picking the initial core point during drilling may be difficult due to uncertainty in the depth of the interface. Coring should occur as least as soon as crystalline basement is encountered, if some before, as confirmed by mud logging, cuttings, or indications from drilling behavior (Section 5). Once the transition to the basement crystalline rock is identified, it will be cored at a rate determined by the characteristics of the rock. If the top of crystalline basement is missed in the CB, it may be possible to core the interval in the FTB.

Coring equipment and methods will be chosen to maximize recovered core diameter given other constraints. Core diameter must be commensurate with planned laboratory testing requirements (Section 5.2.1.2). The largest feasible diameter core will be collected to maximize the volume of rock cored for both extraction of pore water and gases for geochemical assessments (Mazurek et al. 2011) and to provide representative rock samples for laboratory-based thermal, geohydrologic, and mechanical properties testing. Oriented core will allow determination of absolute fracture orientations, but may add complications for core collection and retrieval, and the scribe tool itself can initiate fractures. If oriented core is not collected, plans for obtaining absolute fracture orientations should be presented (e.g., using image log data). Any sidewall coring must be planned to meet the scientific sampling and testing requirements of the project as much as possible even though the amount and diameter of sidewall core is much less.

5.2.1.1 Pressurized coring

One pressurized core sample will be collected in the lower 2 km of the borehole (i.e., in the disposal zone – Figure 2). High quality core and fluid samples are an objective of the DBFT, to enable assessments of *in situ* environmental tracers (Section 2). Pressurized core will be used to assess the efficacy of securing cores in pressure vessels after bringing them to the surface. Natural tracers from pore fluids (including dissolved gases) will be extracted from core samples in the laboratory (e.g., *via* centrifuge extraction, aqueous leaching, high-pressure squeezing, vacuum distillation, isotope diffusive-exchange, and noble gas core outgassing; Mazurek et al. 2011). Coring and core handling must minimize core damage, preserve core fluids, and prevent contamination of core fluids during drilling. Three processes generally cause damage to and modification of core and influence the results of the core analyses: 1) fluid invasion into the core during drilling; 2) drilling and coring related fracturing, possibly due to fractures propagated in front of the drill bit, and are associated with weight-on-bit issues, and pressure-release effects from drilling and coring activities; and 3) loss of entrained gases as the core is brought to the surface.

The first line of defense against fluid invasion is low-invasion coring, where the drill bit is designed with cleaning nozzles that direct the drilling fluid and cuttings away from the core. Additionally, some systems inject a non-reacting gel around the core as it is cut to displace any drilling fluid and protect the core from invasion (Neaimi et al. 2014). A sponge liner can be used to protect the core as it is being cut and while being brought to the surface. Gel and sponge coring methods are both available with low-invasion coring, but only downhole pressure vessels will capture exsolved core gases.

Reservoir or elevated pressure core systems allow for the core to be brought to the surface with minimized drilling fluid infiltration and gas or liquid loss. True pressure core methods collect core samples at reservoir conditions in a pressure vessel, which is transported to the surface, maintaining full reservoir pressure. Pseudo-pressure core systems bring core to the surface in a system of vessels retaining all liquids and gases in the core. Collection of drilling mud should be minimized to avoid contamination of core samples. In both true and pseudo pressure-core systems, core fluids are captured and available for surface preservation and analysis.

Sidewall coring systems have also been developed that can obtain and maintain several samples at reservoir pressure (e.g., 3.8-cm [1.5”] diameter and 6.1-cm [2.4”] length at up to 172 MPa [25,000 psi]; Halliburton, 2015). Options for true and pseudo-pressure core vary for core diameter and coring intervals, which may affect material available for core testing. Pressure coring systems may have limitations for total depth and ability to drill in crystalline rock (Neaimi et al. 2014).

5.2.1.2 Core handling

On-site core handling should be minimized, but will include activities necessary for sample preservation and any required immediate characterization (i.e., for making decisions about drilling, continued coring, and testing). The majority of the 150 m [492’] of core will be left in the inner core barrel or sleeve for protection during transport to an offsite laboratory for further core processing and analysis. Core depths will be marked on the core barrel or sleeve in the field. Coring depths should be carefully confirmed with mud loggers, rig operators, and drilling engineers. Depth marks will be made at locations on the core barrel where the core will be cut into smaller lengths (approximately 0.9 m [3’]) for packaging and shipment. The cut sections will be sealed to stabilize the core and prevent dry-out or biological activity. Insulated containers for containing the cut core sections and freezing some of the cores using liquid nitrogen should be considered as part of the core stabilization and preservation methods. Depth marking procedures should be systematic and documented in the field test plan. Assumptions used to estimate depths should be documented (e.g., any loss of core was at the bottom of the length of the core and not at the top). Cutting should be done so the core can be unambiguously pieced back together; cuts should be “island-cut” instead of a smooth straight cut. Core should be carefully handled to maximize the ability to reassemble the core and obtain fracture orientations (Lorenz & Hill 1992). Correction to core depths will be made using geophysical logging, such as correlation between core and borehole gamma-ray logs or borehole imaging logs.

Coring will be conducted to provide samples for laboratory testing (Section 5.2.1.3). Recovered core will be physically divided up, following a standard custody-tracking protocol for shipment to storage or analysis labs. Special core handling may be required on-site, and thus a core handling facility should be available (e.g., a trailer with good lighting to protect workers from inclement weather). A portion of the core will be preserved using helium-tight canisters

(Osenbrück et al. 1998, Rübel et al. 2002, Heath 2010, Gardner et al. 2012) to preserve noble gases in core pore fluids. The technique involves immediate placement of samples of fresh core, as soon as the core reaches the surface, into stainless steel canisters with helium-tight metal-to-metal seals, flushed with ultra-high purity nitrogen gas to remove atmospheric gas from canisters. The noble gases are then allowed several weeks or longer to degas from the core samples, followed by laboratory noble gas isotopic analysis. Once this preserved core has been tested for environmental tracers, it should be returned for storage and geologic description with the other cores. A downhole true- or pseudo-pressure core (Section 5.2.1.1) will be collected to compare whether critical noble gases will be adequately contained in cores first sealed at the surface. Further transfer of pressure core or gases from the pressure core into helium-tight core canisters on-site may be necessary.

Any sub-sampling of core on-site should be carefully documented, including photography and marking of sample depth locations while stabilizing the remaining core. This may involve removal of core from the cut sections of core. Core will be preserved against drying and biological activity using methods like sealing in wax or ProtecCore. A combination of preserved core, pressure core, and core in helium-tight canisters will be necessary to obtain the appropriate suite of samples for assessing the geohydrological, mechanical, and thermal properties of the disposal zone and one or two key lower sections of the overburden.

5.2.1.3 Planned laboratory core testing

The core testing outlined in Table 8 will be performed separately, and will be managed by the DBFT Technical Lead. It will not be conducted by the drilling contractor or site management contractor as part of the drilling contract. These types of tests are mentioned here to motivate the collection of quality core and quantify the science objectives for the core.

Table 8. External core testing requirements

Core testing	**Motivation**	**Sampling Requirements**
Petrophysical Properties	Density, spectral gamma & fracture distribution for comparison and correlation with cuttings, geophysical logs and testing intervals	Core preservation to prevent dry-out and inhibit biological activity; proper core depth marking and handling
Fracture Characterization	Fractures are primary source of permeability in crystalline basement	Careful handling and reassembly; core orientations should be obtained or deduced from logs.
Hydraulic Properties	Water saturation, porosity & permeability for comparison with drill-stem and packer testing results. Hydraulic testing should be done at a range of confining pressures, up to the *in situ* stress state at sampling depth.	Large enough diameter samples for representative testing (i.e., several crystals or grain across). Core preservation to prevent dry-out and inhibit biological activity.
Geologic Characterization	Texture, rock type, mineral makeup, fracture filling materials, fluid inclusions & X-ray diffraction for correlation with physical, geohydrological, geochemical and geomechanical properties; electron and optical petrography	Representative cores from each major crystalline bedrock formation or lithology encountered
Geochemical Properties	Pore fluid extraction and analysis for construction of geochemical and isotopic profiles, to supplement sampling *via* drill-stem and packers.	Core preservation to prevent dry-out and inhibit biological activity; noble gas samples require pressurized sample handling in He-tight

		containers
Geomechanical Properties	Stress-strain relationship, elastic parameters, anisotropy, and frictional strength; determine mechanostratigraphy for weak and strong facies and correlate to geophysical logs	Large enough diameter samples for representative and directional testing. Core preservation to prevent dry-out and inhibit biological activity.
Thermal Properties	Thermal conductivity, heat capacity, non-linearity of properties for parameterizing performance assessment models	Core preservation to prevent dry-out and inhibit biological activity.

5.2.2 Drill-Stem Testing

Drill stem testing (DST) provides three basic pieces of information on the host formation: formation fluid pressure, formation bulk permeability, and water geochemistry. DST equipment consists of a packer or tool to isolate the bottom of the borehole, down-hole pressure sensor, flow control valves that can be controlled from the surface, and a down-hole sampling device.

Extended testing will be conducted using a set of at least two packers to isolate an interval, and will utilize a work-over rig after drilling and borehole construction is complete (Section 5.4). Testing and sampling *via* DST will be limited to intervals that will eventually be cased or cemented as part of the completion of the borehole, since they will not be available for later testing *via* work-over rig.

DST intervals will generally involve:

1. Estimating shut-in/static formation pressure (identification of under- and over-pressure zones);
2. Slug withdrawal testing to estimate permeability of the near-borehole region; and
3. Pumping an interval to obtain representative fluid samples.

This sequence of testing is conceptually similar to that conducted *via* work-over rig (Section 5.4), but work-over rig testing will include multiple packers, be of longer duration, and will include tracer and heater testing components.

Depending on the availability of nearby shallow wells and the uncertainty associated with the local geology overlying the crystalline basement, DST may be performed on lower portions of the overburden before setting casing or liner, to better characterize the flow system.

For example, if the overburden formation immediately above the basement is a poorly characterized brackish reservoir, sampling and testing may be warranted. Aquifers that can be sampled from nearby wells would not warrant sampling in the CB, due to the existence of data or ready access otherwise.

5.2.2.1 Drill-stem shut-in testing

Ambient fluid pressure in the formation surrounding the borehole is estimated from the shut-in pressure. After the drill-stem packer is inflated to isolate the test interval at the bottom of the borehole, a control valve is opened to allow equilibration of fluid pressure within the drill stem and the formation. Formation fluid pressure is monitored downhole until it stabilizes, as it may have been altered during drilling and the equilibration process must allow such anomalous pressures to dissipate.

Accurate estimates of ambient formation pressure are necessary to determine vertical hydraulic gradients in the system and to develop an overall conceptual model of groundwater flow in the hydrogeological system. Vertical profiles of fluid pressure and factors that affect fluid density (primarily temperature and salinity) are used to calculate the overall fluid potential. Vertical fluid potential gradients are the driving force for fluid movement in the system. Over-pressured conditions would indicate the long-term potential for upward migration of groundwater containing dissolved radionuclides from a DBD system. Hydrostatically stable or under-pressured conditions are thus favorable natural conditions for the long-term safety of the DBD system.

5.2.2.2 Drill-stem slug testing

Drill stem slug or pulse tests are conducted for shorter periods of time than pumping tests and in lower-permeability intervals which will not support pumping. Both pumping and slug tests are used to estimate the geohydrologic properties of crystalline basement and near-borehole DRZ. The formation properties that will be estimated from the drill-stem slug test include rock permeability, rock and matrix compressibility (i.e., storage properties), and any spatial variability or anisotropy of these properties vertically along the borehole or possibly radially away from the borehole (e.g., borehole damage or skin).

5.2.2.3 Drill-stem sampling

If more permeable intervals are encountered during drilling, samples will be collected *via* drill stem using downhole pumping. Water samples from drill-stem testing will be collected and tested for similar analytes as packer-testing (Section 5.4). Drill stem sampling will be performed sooner than packer-based workover rig testing, before the drilling fluid has had a long time to possibly invade the formation, but without the luxury of extended sampling time, which is available after drilling when using the work-over rig.

Drill-stem sampling will be conducted to compare against later packer sampling and to sample intervals before they are cemented or cased/lined.

5.2.3 Hydraulic Fracturing Stress Measurement

Hydraulic fracturing tests will be performed in the crystalline basement interval while drilling to determine the magnitude of the minimum horizontal stress at depth. They will be used in conjunction with other indications of rock fabric and stress orientation (e.g., formation micro-resistivity image log, borehole televiewer, and anisotropic shear wave velocity log) to describe the orientation and magnitude of stress through the entire basement interval.

A drill-stem packer tool will be placed at the current bottom of the borehole, and pressure in the interval will be monitored downhole while applied fluid pressure and flowrate are monitored during an increase in pressure. Data will be collected from at least two repetitions of the hydraulic fracturing cycle, to collect information on the formation breakdown pressure, the fracture propagation pressure, the instantaneous shut-in pressure, and the fracture closure pressure.

Hydraulic fracturing stress measurements will be conducted in relatively low-permeability rock (degree of fracturing may be confirmed by coring, borehole televiewer, etc.) so that fluid pressure build-up can reach the breakdown pressure. To ensure proper seating of the packers, borehole breakouts cannot be too significant in the test interval.

5.3 Borehole Geophysics

Borehole geophysical characterization methods measure characteristics of the drilling fluid filled borehole, the rock formations intersected by the borehole, and the pore fluids saturating the DRZ and far-field rock. They will be relied upon extensively to provide essential data about the stratigraphy and lithology in the CB for the DBFT. Some geophysical tools and methods may not be effective in the large-diameter FTB (43.2 cm), and therefore must be done in the narrower CB (21.6 cm). There are three basic types of borehole geophysical methods: cross-hole testing, surface-to-borehole methods, and in-hole methods. During and right after drilling of the CB, only the latter two methods are applicable and in-hole testing (geophysical logging) is the primary means of acquisition for most types of data. Cross-hole testing and surface-to-borehole testing are common for seismic data acquisition (e.g., vertical seismic profiling [VSP], check-shot or velocity surveys) used to help characterize geophysical properties away from a single borehole or between two boreholes. VSP is particularly useful for imaging mechanical properties tens to hundreds of meters away from the borehole, albeit at lower resolution than in-hole methods. VSP can be utilized in the basement interval after completion of the borehole; cased intervals and especially multiple casing strings may not give useful data. Cross-hole testing methods, could be used after completing the FTB and are beyond the scope of this report.

A suite of wireline geophysical logs will be obtained after the CB reaches total depth, as summarized in Table 9 (also see Tables 1 through 5 for indication of how geophysical methods can be used with other methods, for characterization). Most geophysical logs will also be obtained at intermediate depth to characterize the overburden rock prior to emplacement of the surface and intermediate casings/liners. A description of the data to be collected from the suite of geophysical logs is given after Table 9.

Information gained during wireline logging, drill stem testing, and the flowing borehole log is absolutely critical to the success of the packer test program (Section 5.4).

Table 9. Borehole geophysical methods

Borehole Log	Interval or Frequency	Purpose
Deviation Survey	Entire borehole	Borehole azimuth and inclination measurements compliment continuous downhole measurements during drilling and help ensure the hole is kept within design limits. One of main drilling parameters (Section 5.1.1)
Borehole Imaging (Formation Micro-Resistivity Imaging, Borehole Televiewer, and Acoustic Caliper)	Entire borehole	Determine minimum principal stress orientation from breakouts and drilling-induced tensile fractures. Determine location, orientation, spacing, and aperture of natural fractures. Determine orientation of bedding and foliation of rock fabric. Provide map of fractures for orienting cores.
Borehole Caliper	Entire borehole	Locate borehole breakouts; assess borehole stability and clearance for setting casing. Confirms and compliments borehole imaging logs.

Borehole Log	Interval or Frequency	Purpose
Gamma-Ray	Overburden portion of borehole	Identify lithology, can operate through casing and cement (often run with other wireline logs to assist in depth correction for cable stretch)
Spectral Gamma-Ray	Basement portion of borehole	Identify lithology and discern radioactive sources (K, Th & U)
Resistivity	Entire borehole	Identify lithology and pore fluid salinity. Downhole drilling fluid resistivity measurements during drilling can locate fluid inflow zones
Spontaneous Potential	Entire borehole	Identify lithology, mineralization, and pore fluid salinity
Nuclear Magnetic Resonance	Basement portion of borehole	Estimate formation porosity and tortuosity, which can be used to infer permeability. Sensitive to formation fluid geochemistry.
Induced Polarization	Basement portion of borehole	Estimation of formation chargeability, a function of the solid-liquid interface and can be related to permeability. Sensitive to formation fluid geochemistry.
Gravity	Entire borehole	Estimate density and therefore porosity at lower resolution but over larger volumes than neutron porosity
Neutron porosity	Entire borehole	Estimate water or hydrocarbon content and therefore porosity at high resolution over smaller volumes than gravity
Temperature	Entire borehole	Estimate geothermal gradient and temperature correction for other logs
High-Resolution Temperature	Basement portion of borehole	In conjunction with borehole imaging, locate groundwater inflow and outflow
Dipole Shear Wave Velocity	Basement portion of borehole	Estimate horizontal stress anisotropy from shear seismic waves
Density	Entire borehole	Estimate formation bulk density and porosity
Sonic	Entire borehole	Estimate rock hydromechanical properties from compressional seismic waves

5.3.1 Spectral Gamma-Ray

Gamma-ray logging measures naturally occurring gamma radiation, which varies by lithology. The most common emitters of gamma radiation are ^{40}K, ^{232}Th, ^{238}U, and their daughter products. A spectral gamma-ray log will determine the relative abundance of Th and U, which are typically of sufficient concentration to be important sources of ^{4}He, a key component in the geochemical profile. Gamma-ray logging can be conducted in both open borehole and through steel casing and annular cement, though the steel and cement will absorb much of the gamma radiation and reduce logging rates (for comparable resolution).

5.3.2 Resistivity

Resistivity is a fundamental material property which represents how strongly a material impedes the flow of electrical current. Most rock materials are essentially insulators, while the saline pore fluids are conductors.

Resistivity logs measure electrical current flow in the formation, produced by electrodes spaced along a sonde (e.g., normal or lateral arrays), or by induction coils (e.g., laterolog tools). The induction tools use coils and magnetic fields to develop currents in the formation whose intensity is proportional to the conductivity of the formation. Induction devices provide resistivity measurements regardless of whether the drilling fluid in the borehole is air, bentonite mud, oil-based mud, or water, and are therefore most generally applicable to conditions in the CB. The electrode arrays and contacting electrode tools rely on an electrically conductive borehole drilling fluid to facilitate current injection and voltage measurement.

Drilling fluid resistivity logging can also be done during drilling (Section 5.1.3) or in conjunction with a formation micro-resistivity image log or a high-resolution temperature log to locate flowing fractures (i.e., fresher or saltier water flowing into the borehole).

5.3.3 Spontaneous Potential

Spontaneous or “self” potential measures the difference in electrical potential between two electrodes in the absence of an applied current. One electrode is grounded at the surface and the other is set at the target location in the borehole. Spontaneous-potential logs provide information on lithology, the presence of high permeability beds or features, the volume of shale in permeable beds, the formation water resistivity, and pore water quality (e.g., salinity, ionic concentration). Water-saturated rock and electrically conductive liquid-filled boreholes are required to conduct the current between the electrodes (i.e., the method does not work with oil-based drilling fluid). When drilling fluids 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.

5.3.4 Induced Polarization

Induced polarization passes a low-frequency alternating current through the formation in one set of electrodes, while observing the variation in voltage from another set of electrodes. The frequency-dependent resistivity (i.e., complex resistivity) of the formation can be estimated from the log, which is an indication of the rock surface-fluid interactions in fractures and pores. The results of the induced polarization log can be related to formation clay content, composition of formation fluids, and rock matrix permeability using petrophysical assumptions. Induced polarization logging can be performed equally well in water or oil-based drilling fluids.

5.3.5 Neutron Porosity

Fast neutrons emitted by the radioactive source in the tool interact with the nuclei of surrounding materials *via* elastic collisions and lose energy at a thermal level and are then detected by the sensor. Fast neutrons are converted to thermal (or epithermal) neutrons most efficiently by collisions with hydrogen nuclei. Logging tools consist of a fast neutron source and sensors for detecting thermal or epithermal neutrons. The neutron porosity tool thus effectively measures the hydrogen concentration, or formation fluid content, within about 20 cm of the borehole wall.

Porosity values must be corrected for borehole diameter, drilling fluid characteristics, rock type, salinity of the pore fluid, and presence of casing material. Neutron porosity logging would be useful for estimating the porosity of the crystalline basement in conjunction with borehole imaging.

5.3.6 Density Log

Density logging uses a radioactive source in the borehole to emit gamma rays into the formation, which are scattered and measured in the tool's detector. The formation's electron density and composition control the observed response; the observed response is then related to the formation bulk density and ultimately porosity.

5.3.7 Sonic Logging

The sonic logging tool is often integrated with dipole shear logging. Sonic logging determines the formation's seismic travel time over a fixed distance. The compressional velocity is a function of bulk modulus and density and varies with lithology as well as other rock properties such as fractures, porosity and fluid content. Full-depth coverage by sonic logs is used to constrain interpretation for other seismic methods such as VSP.

5.3.8 Borehole Imaging

Multiple methods are available and in common use for mapping the inside of the borehole wall. These methods allow determination of borehole diameter and shape due to breakouts, washouts, and tensile fractures (caliper), as well as analysis of existing rock fabric, layers, and fractures (formation micro-resistivity image log and borehole televiewer). Because of the importance of good borehole imaging data to the characterization of the borehole, and the complementary nature of the methods (borehole televiewer measurements are more influenced by rock properties, while micro-resistivity imaging is more sensitive to fluid properties), all three approaches should be used if hole conditions are appropriate (Zoback 2010, Davatzes & Hickman 2010).

5.3.8.1 Formation micro-resistivity imaging

Formation micro-resistivity imaging uses surface resistivity measurements to construct an oriented image of the electrical surface resistance of the rock exposed along the borehole wall. Measurements are made with multiple electrode pads pressed against the borehole wall in a borehole filled with conductive drilling fluid (oil-based micro-resistivity image logging tools are available for oil-based drilling fluids). The tool configuration is self-centralizing.

The resulting image consists of discontinuous vertical stripes, but can be used to determine stratigraphic strike and dip, foliation, borehole breakouts, and fracture orientations, filling, and apertures. Natural and drilling-induced fractures can usually be distinguished from one another on formation micro-resistivity image logs.

5.3.8.2 Borehole televiewer

Acoustic or ultrasonic televiewers scan the borehole wall with a focused ultrasound beam, resulting in a continuous image of the borehole wall. Both amplitude and travel time are recorded. The amplitude log indicates the borehole wall roughness, while the travel-time log indicates borehole diameter changes and is sensitive to breakouts and open fractures. This type of borehole log can be conducted equally well in a borehole with water or oil-based drilling fluid. The borehole televiewer must be centralized in the borehole. This borehole log may have depth limitations that restrict its use to the sedimentary overburden sequence.

5.3.8.3 Borehole caliper

Borehole calipers measure the diameter of the borehole using a multi-finger caliper that measures several diameters on the same horizontal plane simultaneously, thus physically measuring the irregularity of the borehole. Borehole caliper logging will be used to determine the integrity of the borehole and to confirm borehole imaging (i.e., identifying larger fractures).

5.3.8.4 Sonic caliper

Sonic or acoustic logging tools can be used to estimate the shape of the borehole, in a manner similar to the borehole televiewer (i.e., an acoustic caliper log). The sonic caliper log is better suited to pressure and temperature conditions expected at significant depth. The method can also be used to inspect quality of casing and cement, depending on the frequency of acoustic signal used.

5.3.9 Borehole Gravity

Borehole gravity logging makes measurements of the acceleration due to 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 tens of meters into the rock. In combination with information on rock grain density and fluid density, borehole gravity logging results can be used to estimate total porosity, averaged over a similarly large volume. Rock grain density can be measured on core samples and fluid density would be determined from groundwater samples.

Estimates of porosity from borehole gravity logging apply further into the rock formation than those from neutron logging. Borehole gravity logs are relatively expensive and can be difficult to interpret, requiring an inverse solution using a model of rock density distribution around the borehole.

5.3.10 Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) can be used to estimate both the water content (absolute value of response) and the distribution of free water in the rock surrounding the borehole (t_2 relaxation time). In water-saturated rock, the NMR response to hydrogen is proportional to water content. When using oil-based drilling fluid, interpretation must account for the effects of hydrocarbons. Similar to neutron porosity logs, the absolute NMR response can be used to estimate rock porosity. The relaxation time distribution can be used to estimate the tortuosity (i.e., mean free path of water molecules). These two components can be related to permeability using petrophysical assumptions.

Based on oilfield experience, NMR logs in oil-based borehole fluids are often more useful than those made in water-based fluids. The interaction of oil-based fluids with the water-wet rocks must be taken into consideration in the NMR log interpretation.

5.3.11 Dipole Shear-Wave Velocity

Dipole shear-wave velocity logging measures the velocity of circumferentially polarized shear waves that travel axially along the borehole wall, as a function of azimuthal direction to the travel path. Anisotropy in the shear-wave velocity can be related to differential horizontal stress, rock fabric orientation (e.g., bedding or foliation), and fracture orientations. Rock micro-fractures oriented parallel to the maximum horizontal compressive stress tend to be more open than micro-fractures parallel to the minimum horizontal stress. Shear wave velocity tends to be greater when the direction of particle motion corresponds with the direction of maximum 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 tensile fractures.

5.3.12 Vertical Seismic Profiling

Vertical Seismic Profile (VSP) is a borehole seismic measurement method used to correlate with surface seismic data. In the most common type of VSP geophones or accelerometers are located in the borehole to record reflected seismic energy originating from a surface seismic source. VSP provides a high-resolution map of the seismic-sensitive rock properties along the length of the borehole.

5.3.13 High-Resolution Temperature

Temperature logging records fluctuations in borehole fluid temperature with depth. Temperature data are usually acquired after drilling, but continuous measurements during drilling are also possible (Section 5.1.3). If the borehole is allowed to equilibrate thermally after completion, periodically repeated temperature logs can be recorded to observe the decay of the temperature perturbations caused by drilling and construction activities (Freifeld & 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 will be used to calculate fluid viscosity and density, and apply thermal corrections to other geophysical logs. Temperature logs can be used to identify zones of inflow and outflow from the borehole and determine intra-borehole flow.

When used in conjunction with borehole imaging (Section 5.3.8), high-resolution temperature logging can be used to estimate inflow locations. These inflow locations can also be correlated with specific fractures or fracture zones, and the orientation of those features can be evaluated to look for trends in the orientation of flowing fractures (Barton et al. 1995, Ito & Zoback 2000). High-resolution temperature logging will be used in conjunction with the flowing borehole log (Section 5.3.15).

5.3.14 Fluid Density or Downhole Pressure

Vertical profiles of fluid pressure or differential pressure are related to the fluid density in the borehole. These measurements can be used to correct formation pressure measurements and identify inflow, outflow, or changes in salinity within the borehole.

5.3.15 Production Profile

The open crystalline basement portion of the borehole will be tested *via* a flowing or pumping log to ensure all higher-permeability regions of the borehole have been identified. The entire borehole (or a section of borehole isolated using a packer) will be pumped at a low constant flowrate, while a tool is moved slowly through the entire open-hole portion of the borehole. Either solute dilution or heat-pulse methods can be used to monitor flow in the borehole (Paillet et al. 2010). Heat-pulse methods move a tool comprising a small wire heater and surrounding thermistors along the borehole, observing the direction heat is advecting away from the heat source. The salinity dilution log involves replacing the borehole fluid with that of a known initial salinity (this will be a significant volume of water in a very large deep borehole), followed by monitoring the evolution of salinity for a few days along the length of the borehole.

These production logs will compliment and confirm the combination of high-resolution temperature log and imaging logs in identifying flowing fracture zones. Some fracture zones may not produce water under non-flowing conditions, so the high-resolution temperature log and the production log will complement one another in finding the higher-permeability regions of the borehole.

If one or more high permeability regions dominate flow into and out of the borehole, the production logs may not be sensitive to minor flows through less permeable fractures. The tests may be re-run after isolating high permeability intervals with packers to better resolve the presence of intermediate-permeability zones in the borehole.

The production log will take the place of exhaustive hydraulic testing of every interval in the 3 km crystalline basement portion of the borehole (e.g., 100 adjacent hydraulic tests using a 30-m packer tool). The point of conducting the production profile is to identify any higher-permeability zones for further packer testing, geochemical sampling, and tracer testing. Low-permeability portions of the borehole will not be the focus of the hydraulic testing.

5.4 Borehole Packer Testing

Borehole packer testing is similar to drill-stem testing (Section 5.2.2), but conducted in the completed borehole via workover rig. Packer testing involves multiple packers (both above and below the target interval – straddle packers, possibly) with guard packers and allows more accurate determination of the thermophysical and geochemical conditions than the short-term tests afforded by DST and wireline logging.

Formation micro-imaging, borehole televiewer, and caliper logging (Section 5.3.8) can provide information on the condition of the borehole, and the associated risk from packer testing in the open disposal-zone interval. The production log (Section 5.3.15) may be used to select several intervals for testing *via* packers.

Packer testing will involve mechanical displacement pulses and slugs which do not add or remove water from the test interval (rather than sustained pumping or injection). Minimal foreign water should be introduced into packer intervals to reduce the possibility of compromising future samples. Previously produced formation water may be saved to be used when filling tubing or chasing tracers during tracer testing (Section 5.4.4) to minimize contamination.

5.4.1 Zonal Isolation

A packer testing tool isolates an interval between packers or sets of packers (in the case of guard zones on each end of a straddle interval). The tool can be designed to test a single interval, and repositioned for successive tests, or a multi-interval packer tool can be installed in the borehole with all intervals completed simultaneously, with access to individual intervals *via* valves in the deployment system.

Zonal isolation in the open borehole environment requires packer systems that seal against the rough wall and any breakouts that remain after the drilling process. Standard oilfield-style packer designs will not provide effective isolation in an uncased borehole in crystalline rock. The ideal packer for sealing and retrievability in open intervals is an external casing packer (ECP), which allows for the use of gland elements that can be up to 6 meters long. ECPs can be fabricated with mechanical deformable metal backing slats that aid survivability of the gland element when set against voids and breakouts. ECP may be retrieved reliably using several methods.

Limitations and problems of ECP deployments (Gai & Elliot 1997) require careful design and operation to lower the risk profile of the borehole completion process. Some consideration should be given to: (1) deployment of redundant gland systems at each isolation interval, (2) utilization of long seal glands with metal reinforcement, (3) the use of permanent set valve bodies for inflation and (4) an inflation fluid less prone to leaking than water. Tradeoffs in ECP design will be considered. The use of a permanent set valve body will require the destruction of the gland element within the packer through the use of a perforation charge. In such a case the packer will be single-use only. While ECPs are normally fabricated on tubular mandrels similar to tubing strings, instrumentation using control lines requires the use of mandrels incorporating pass-through to allow required control lines. Given a projected 21.6 cm [8½”] drill bit size for the open-hole portion of the CB, an ECP string can be run-in-hole using a 7.3 cm [2⅞”] tubing string. A typical run-in diameter for such an ECP would be 19.4 cm [7⅝”]. The ECP can be built on a custom mandrel with the required pass-through for numerous control lines that will provide flexibility in instrumentation options.

Packer inflation requires special attention at great depths. Packer inflation procedures and the proper sizing of lines and pumps must consider the significant depth required for some crystalline basement tests. The packer inflation pressure must be sufficient to expand the packer gland against the borehole wall.

5.4.2 Packer Pulse Testing

Lower-permeability intervals will not support pumping or sampling and will only be hydraulically tested using pulse or slug tests (NRC, 1996; Chapter 5). The most reliable method for acquiring geochemical samples from lower-permeability intervals may be pore water extracted from cores.

Laboratory methods for fluid extraction from cores depend on the type of test being conducted on the fluid samples and include: centrifuge extraction, distillation (only for isotopes), flushing cores with deionized water (good for isotopes and trace elements, but may cause some mineral dissolution), high-pressure destructive squeezing, and crush and leach. Destructive methods (squeezing and crushing) will lead to dissolution of minerals not originally present in fluid samples, and should only be used if other methods are not viable.

The borehole monitoring system consists of downhole tools and measurement systems. Downhole tooling includes the tubular elements, packers, and valves that facilitate the isolation and access to different testing zones (Section 5.4.1). Downhole tools also allow application of a mechanical pulse (i.e., slug) or specified pumping rate to the interval, depending on its permeability. Measurement systems monitor flowrate (if any), downhole fluid pressure, fluid temperature, borehole closure, and some downhole chemical properties (e.g., electrical conductivity, pH, and redox potential).

After inflating the packers on a test interval the static formation pressure will be monitored, followed by a pulse test, which will monitor the decay or buildup in pressure after a mechanical pulse is applied to the formation.

Several low-permeability intervals will be identified from geophysical logs and the flowing production log to estimate the general variation in crystalline basement permeability, rock compressibility, and static formation pressure with depth.

5.4.3 Packer Pumping Tests and Sampling

Packer pumping tests are targeted at several specific higher-permeability borehole intervals as identified by the production log (Section 5.3.15). Identification and characterization of any relatively higher-permeability intervals will be important for characterization of any site for DBD.

The borehole monitoring system described under packer pulse testing (Section 5.4.2) will be used for pumping tests on more permeable intervals, but additionally downhole flowrate will be monitored and samples will be collected. While pumping, geochemical parameters will be monitored downhole to identify changes that indicate when fluids being produced are representative of the formation or if drilling fluid is still being produced.

Pumping tests will be conducted to estimate formation permeability, compressibility, hydro-geomechanical response (Schweisinger et al. 2009), and porosity. The pumping tests will be conducted in zones with higher permeability (as identified in the flowing log), but the ability of the system to test very transmissive regions (e.g., fracture or shear zones) may be constrained by the downhole flow system (e.g., rate and pressure output limit of pump, friction losses in the supply line).

After inflating the packers on a relatively higher-permeability test interval the static formation pressure will be monitored, followed by a discharge test, which will monitor the decay in pressure while the interval is pumped at a specified rate.

At the end of packer pumping tests, samples of formation fluid will be collected for laboratory analyses. Collecting representative environmental tracer samples of sufficient volume is a key component of the DBFT project, and these tracers have specific sampling requirements (Section 2), which must be considered when determining whether samples are representative of the formation water, or are still contaminated by drilling fluid and atmospheric air.

The pumping test and sampling event will be followed by monitored recovery.

5.4.4 Tracer Testing

Once the flow properties of the borehole are characterized, two higher-permeability intervals will be picked for tracer testing. The borehole seal interval (Figure 2) will be tested to understand the nature of transport through the DRZ surrounding the borehole. An additional tracer test will be conducted near the bottom of the disposal interval, to determine if transport properties and processes change significantly across the crystalline basement portion of the borehole.

Tracer testing will involve a tool consisting of two adjacent packed-off borehole intervals using three packers (Figure 4). Injection of previously produced formation water will occur into one interval and recirculation pumping will occur from the other interval (Roos 2009). Solute transport occurs vertically through the DRZ between the injection interval and the pumping interval and around the intervening packer interval in the borehole. *In situ* transport properties of the rock mass will be estimated from the breakthrough curve of the tracer in the pumped interval. The vertical dipole tracer test will also interrogate the solute transport characteristics of the borehole DRZ immediately adjacent to the packed borehole, which in a disposal borehole is a potential pathway for the vertical migration of radionuclides from the disposal zone (Figure 2).

A push-pull (i.e., single-well injection-withdrawal) tracer test will be conducted in conjunction with the vertical dipole tracer test. Before beginning the recirculation tracer test, a unique tracer will be injected into the withdrawal interval and chased with formation water obtained from the packer interval. There will be a short rest period before beginning pumping for the dipole test, which will allow estimation of ambient flow conditions. Different tracers will be used in the push-pull and vertical dipole tracer tests, to allow interpretation of both tests independently.

Multiple tracers may be used simultaneously in each of the tracer tests to investigate effects of any sorption or rock-fluid interactions.

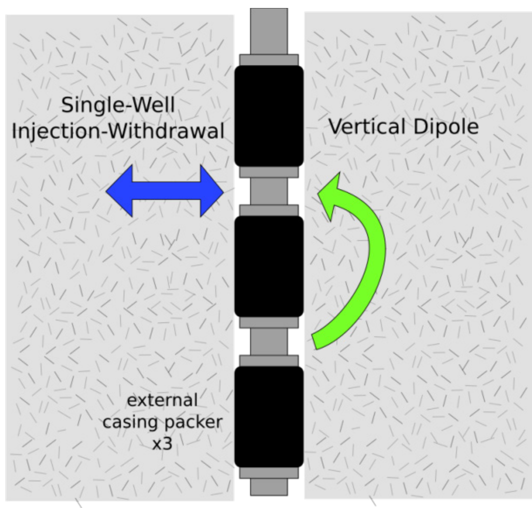

Figure 4. Schematic diagram of tracer test configuration.

The design, construction, and use of the tracer testing tool will be done in close conjunction with the DBFT Technical Lead.

5.4.5 Test Package Electrical Heater Test

A borehole heater test will be conducted in a lower-permeability interval of the borehole to simulate the effects of heat generated from radioactive decay that would be expected in an emplaced waste package. A 5-m long test package (narrow enough for the CB bottom-hole diameter of 21.6 cm) containing a 5 kW electrical heater will be emplaced in a manner similar to waste packages, including emplacement working fluids, perforated casing, and any borehole plugs and seals deemed important for testing. Temperatures, fluid pressures, borehole closure, and mechanical strain will be monitored in the emplacement zone. Chemical tracers may be added to the emplacement zone working fluid and monitored for potential migration past borehole seals. The heater test will nominally be run for two months.

To minimize complicating effects of free convection in the borehole fluid (i.e., make conduction more important than convection), a backfill material may be added in the annular space between the heater and borehole wall. A backfill material should be chosen to allow retrieval of the heater test tool, and provide uniform well-characterized material properties to aid in interpretation of the test results.

The go-ahead decision for a heater test, and its design and implementation will be done in close consultation with the DBFT Technical Lead.

5.5 Data Quality Objectives and DBFT Project Success

There are many types of tests that could be conducted and data that could be collected in the CB, as discussed in the previous sections. Data quality objectives (DQOs) will be developed in detail in the drilling and testing plans, which will indicate critical data types, qualities, and quantities which should be required to consider the data collection phase of the DBFT in the CB a success.

The data discussed in the previous sections are grouped according to a combination of likelihood for success and importance associated with each data type for the DBD safety case.

5.5.1 Minimum or Base Set of Test Data Required

Data indicating and supporting long residence time of pore water at depth in the crystalline basement and isolation from shallow groundwater are central to the DBD concept and are one focus of characterization in the DBFT. These data are summarized below. Of the geochemical methods available to indicate long residence time of pore water, we plan to rely principally on those that can be applied to smaller water sample volumes that can possibly be extracted from cores. It will be more challenging to acquire representative *in situ* water samples from very low permeability crystalline basement rocks, so methods that need larger water sample volumes will be used as a secondary set of confirmatory analyses. In fact, some of the investigations will be to evaluate the utility and efficiency of a variety of methodologies as input to developing efficient and sufficient characterization programs for potential future disposal sites. Successful demonstration of isolating conditions in the DBFT (to provide adequate bases to support a defensible safety case) relies on high-quality geochemical profiles for the principal data sets with depth. Note that even if this facet of the DBFT does not result in such data, this would not affect the potential success of other aspects being evaluated within the DBFT.

5.5.1.1 Minimum required for success

For a successful DBFT the testing and data collection should ensure:

- good quality core must be collected and adequately preserved (see discussion of core handling procedures in Section 5.2.1.2),
- quality geophysical borehole logs must be conducted,
- repeatable hydraulic fracture stress measurements must be made, and
- high-quality hydraulic pulse testing (requiring adequate packer seals and a leak-free testing system) must be conducted.

More specifically, we will collect high-quality data profiles of the following constituents and conditions to build a safety case for the DBD concept:

- Helium-4 will be sampled from headspace of He-tight canisters, into which cores would be loaded at the surface (Section 5.2.1.2). Also headspace from pressurized core collected at reservoir conditions (Section 5.2.1.1) would be sampled for He. Since He is generated in the crust (especially in granites with high U and Th content), it is expected to be at elevated concentrations in an isolated system in the crystalline basement, allowing small sample sizes. He profiles from both water and rock samples will provide information on the ability of the crystalline basement to contain He (a very small and inert molecule) over geologic time scales, and may allow quantification of the rate at which constituents may leave the isolated system.

- Stable water isotopes (e.g., D, ^{3}H, and ^{18}O), which only require very small sample sizes, because they are isotopes of the constituents in water itself (Section 2.2). Profiles of these isotopes can give information about origins/provenances of water at depth.

- Major pore water anion/cation concentrations and rock/mineral chemical composition from cores. The degree of fluid-rock equilibration is affected by the duration of water-rock reaction, the degree of isolation from advective flux supplying disequilibrium fluids, and the physiochemical conditions (e.g., pressure, temperature) at depth. In addition, drilling-fluid logs (both downhole and at the surface) can be used to support core mineralogy and pore fluid compositions, and may provide supporting information regarding the relationships between depths and changes in pore fluid geochemistry.

- Equilibrium fluid/rock borehole temperature. The drilling process will perturb the existing geothermal gradient near the borehole wall in both the crystalline basement and overburden. High-resolution temperature profiles will be recorded at early time (under static non-pumping conditions), as part of the geophysical borehole logging performed immediately after drilling to determine the location of high-permeability zones (Section 5.3.13). These same measures will be repeated after the borehole has had time to re-equilibrate. Measured temperatures and geothermal gradient will be used as indicators of possible regional groundwater flow.

- Borehole physical/mechanical conditions, including natural and induced fractures will be collected and analyzed (Section 5.3.8). Borehole geophysical imaging techniques (i.e., caliper logs, formation micro-resistivity imaging, borehole televiewer, and sonic logging) will be used to reconstruct both the original fracture sets and fracture zones –existing in the rock before drilling – and the drilling-induced breakouts and tensile fractures which may occur during drilling the borehole due to the stress state of the rock. Both the natural conditions and induced feature datasets are critical for understanding the crystalline basement *in situ* stress state, interpreting geophysical logs, determining the orientation of flowing fracture sets, orienting and locating core, and mapping geologic contacts.

- Standard electromagnetic (i.e., resistivity, spontaneous potential, induced polarization, and NMR), radioactive (i.e., neutron porosity, density and gamma), gravity, and seismic-based (i.e., sonic, dipole shear-wave velocity and VSP) borehole geophysics will be conducted. The profiles of data provided by these logs will be used jointly with laboratory results from tests on core and packer-based testing profiles to understand the geological, lithological, geochemical, physical, and geomechanical properties with depth in both the overburden and crystalline basement.

- *In situ* stress measurements will be made (Section 5.2.3). Hydraulic fracture tests will be conducted at multiple depths in the crystalline basement. Tests will be repeated multiple times at each depth to help understand the in situ state of stress in the crystalline basement, and to better prepare for drilling the larger-diameter FTB after the CB.
- Bulk Permeability and static formation pressure will be determined from packer tests (Section 5.4). These model parameters will be estimated from data collected during pulse tests in low-permeability intervals, and/or from pumping/flow tests conducted in higher-permeability fracture zones or intervals. Permeability will be needed to parameterize the flow models used in performance assessment, and static formation pressure will be required to assess whether any intervals are over- or under-pressurized.
- Laboratory tests on cores (Table 8) to determine properties for model parameterization. These tests include petrophysical (e.g., lithology, mineralogy, grain size), hydraulic, geochemical, geomechanical, and thermal rock properties, as well as fracture characterization.

5.5.1.2 Additional data

Additional data would further support the safety case, would test applicability of potential alternative characterization methods at future sites, and typically involve samples or tests with a lower level of confidence in success.

- Geochemical profiles requiring larger sample sizes (Section 2). These profiles would require *in situ* sampling from packer-based intervals, which may be difficult to obtain in a reasonable time period (i.e., less than a few weeks per sample interval) without contamination from drilling fluid.
    - Noble gases other than He (especially Ne, Ar, Kr and Xe);
    - Atmospherically derived radioisotope tracers (e.g., ^{81}Kr – also radiogenic from U and Th rock constituents, ^{129}I, and ^{36}Cl);
    - Uranium and strontium isotopic ratios.
- Geochemical data that will be challenging to collect uncontaminated at depth include:
    - redox potential (due to the drilling process which introduces large amounts of metal and air-saturated fluid into the disturbed borehole environment); and
    - pH (the drilling fluid will likely alter the temperature and pH of the fluid in the crystalline basement rock, making representative in situ testing difficult).
- *In situ* tracer testing (single-well injection-withdrawal and dipole), which may be difficult to conduct at significant depth in low-permeability crystalline basement rock. The primary flow path may be along the borehole wall, due to poor sealing of the packers. The primary focus of the test would be determining the flow and transport properties of the DRZ surrounding the borehole, which is considered the primary pathway for flow under long-term disposal performance.
- *In situ* heater testing (single package installed and heated for two months), which may be difficult to conduct at significant depth in low-permeability crystalline basement rock. It may be difficult to set packers to effectively isolate the heated interval, which may allow

heated fluid to quickly escape up the borehole, rather than into the DRZ and surrounding rock mass.

6. CONCEPTUAL DESIGN OF THE FIELD TEST BOREHOLE

The primary focus of the FTB in the DBFT is the safe and efficient demonstration of the emplacement and retrieval of test packages (without radioactive waste). The test package, emplacement, and retrieval options for a generic site are discussed in Su and Hardin (2015), Hardin (2015a), and SNL (2015); these details will not be reiterated here. Prior to the choice of a particular site, the design of the borehole is consistent with the generic DBD reference design (Arnold et al. 2011). A final site-specific design will be prepared after a site is chosen through the RFP process (DOE 2015b).

6.1 FTB Characterization

Once drilling begins on the FTB, most of the characterization will have already been conducted in the CB, or will be conducted concurrently in the CB while FTB drilling progresses. Some level of minimal characterization will be carried out in the FTB, primarily to monitor deviation and quantify the similarity in conditions encountered in the larger borehole. Any data collection in the FTB will be confirmatory in nature, since rig time for the larger borehole will be expensive compared to the CB.

6.1.1 Logging while drilling

The drilling mud will be logged to monitor fluid inflows during drilling, and the cuttings will be logged to get confirmation of geology encountered while drilling the FTB.

6.1.2 Advance coring

The exact location of the overburden/crystalline basement interface will likely not be well known before drilling the CB. It is likely the interface will not be cored in advance, unless site-specific information regarding the exact depth to crystalline basement is available.

It may be deemed necessary to core the overburden/crystalline basement interface in the FTB, since the exact location of it in the CB will be determined from borehole geophysics. This will likely be the only interval which may need to be sampled via advance coring in the FTB.

6.1.3 Borehole Geophysics

The geophysical borehole logging done in the FTB is a small subset of that conducted in the CB. Some electromagnetic geophysical tools would not work effectively in a large-diameter borehole, so the borehole geophysics planned to be conducted in the crystalline basement will include gamma, neutron porosity, sonic log and borehole televiewer logs.

These logs will help pick exact depths of geologic contacts (gamma, neutron, and sonic log) and will be used to map the location and orientation of existing fractures and borehole breakouts in the FTB (borehole televiewer).

6.2 FTB In Situ Testing

Packer-based in situ testing is not expected in the FTB, since this testing will be the focus of the CB. Hydraulic flow and pulse testing, hydraulic fracturing testing, tracer testing, and heater tests are not planned in the FTB. The larger borehole diameter, compared to the CB, will make packer-based testing more difficult. This is one of the primary reasons for constructing the smaller-diameter CB, and conducting testing in the CB.

6.3 Cross-Borehole Testing

Although it is not part of the current plan for the DBFT, the possibility for cross-borehole testing between the CB and FTB exists. This type of testing would likely be very informative, due to the ability to place source and receiver at depth (for borehole geophysics, or similar for borehole hydraulic testing), nominally separated by only a few hundred meters. Interrogation of the larger rock volume surrounding the boreholes would be scientifically interesting, but is not one of the primary focuses of the DBFT. This type of testing would be a good candidate for follow-on work in the boreholes, after the DBFT is complete.

7. BOREHOLE CONSTRUCTION

The construction of the CB and FTB includes the drilling, casing, and cementing involved in completing the borehole to target total depth (5 km) and diameter (21.6 cm [8½”] for the CB and 43.2 cm [17”] for the FTB). The FTB will also include surface facilities required to demonstrate the safe handling of radioactive materials. These surface-handling facilities are not discussed in this report; their conceptual design is presented in Hardin (2015a) and SNL (2015).

The choice of drilling method and drilling mud type will have significant impact on the ability of the DBFT to achieve its objectives in both boreholes (Figure 1). This section discusses some of the generic (non-site specific) options and conditions which may need to be considered before the drilling method and mud type are chosen. Once the RFP process (DOE 2015b) is complete and a site and drilling management contractor are chosen, the site-specific detailed drilling and testing plans will be prepared.

The CB and FTB should be drilled and constructed following current petroleum and geothermal industry best practices (e.g., API 2006; Finger & Blankenship 2010). The 5 km total depth at 21.6 cm [8½”] diameter for the CB is not exceptional, as projects in Australia (Beardsmore 2007), France (Genter et al. 2009), and the United States (Duchane & Brown 2002) have recently drilled 4.5 to 5 km total depths in granite at bottom-hole diameters up to 24.4 cm [9⅝”]. The 43.2 cm [17”] diameter for the FTB at 5 km depth will be pushing the boundaries of drilling capability but is considered achievable. Current geothermal practice is relevant because geothermal resources are usually found in hard, igneous rock and because the flow rates in geothermal production often require large-diameter holes.

7.1 Drilling Requirements and Considerations

Several factors will be monitored and reported along with other drilling-related parameters (Section 5.1.1) to assist in the drilling of a CB and FTB that complies with the deviation specification. A key uncertainty in planning the drilling programs is whether the specification can be met for the selected DBFT field site using conventional drilling practices, or whether measures such as downhole motors and survey-while-drilling are needed.

7.1.1 Drilling Method Choice

For a generic borehole (no site selected yet), several candidate drilling methods may be considered, including:

1. **Direct rotary drilling**: where drilling fluid is circulated down drill pipe and mud and cuttings rise up in the annular space between the drill stem and the borehole wall. This is the most common drilling method for this type of borehole. An important distinction among rotary drilling rigs is those with kelly drive (torque applied at rig floor) vs. top-head drive (torque applied at top of drill string). A top-head drive can be important in difficult drilling conditions that require rotation while pulling up.
2. **Reverse rotary drilling**: where drilling fluid and cuttings are forced up the drill pipe and the recirculated drilling fluid is pumped down the annulus. This method can produce more depth-specific cuttings and drilling fluid, which can improve mud logging.
3. **Downhole hammer-drilling:** can have fast penetration rates and good sample recovery, using either water or air as the working fluid. Modern air and water- or mud-based hammer drilling technologies have reached depths approaching 5 km, with very high penetration rates. This technology is less widely used, and fewer contractors will have

access to the equipment or expertise required to drill with this technology.

Key criteria for selecting a suitable drilling rig in addition to borehole depth, diameter, and rock type include the expected weight of the drill string and the weight of casing/liner to be installed. Oil-field drilling rigs are available up to 4,000 horsepower size with lifting capacities up to 900 metric tons (Beswick 2008). Within the range of available land-based rigs, there are several rigs that could be suitable for drilling the CB and FTB to 5 km in crystalline basement rock.

Conventional rotary drilling (either direct or reverse circulation) in the crystalline basement would likely be performed using a hard-formation, tungsten-carbide insert, journal bearing, roller-cone bit. A downhole turbine drill motor could be fitted with diamond-impregnated bits.

The choice of drilling method, and the selection of specific bits and operating parameters (rotary speed, bit weight, and mud hydraulics), will be driven by the experience of the drilling contractor and rock characteristics at the DBFT site. Rotary drilling with conventional circulation would be consistent with the scientific goals of the CB.

Whatever drilling methods are selected, core will be collected at regular intervals totaling about 5% of the total depth (Section 5.2.1). Core drilling will likely require that the rotary string is tripped out. The coring method can significantly affect the speed of the process and quality of the core. Coring may be done *via* wire-line retrieval methods (core is retrieved up the center of the drill pipe without tripping out of borehole) to speed up core retrieval at depth, or it may be performed using a more traditional core barrel on the end of a drill string.

Less sampling and testing will occur during drilling in the overburden compared to the basement rock; the primary goal in the overburden section will be to safely and quickly reach the crystalline basement, while preserving the capability to achieve the desired diameter at total depth (21.6 cm [8½”] at 5 km). Some DSTs and coring will be conducted in the overburden section, particularly to characterize the overburden-basement interface.

7.1.2 Drilling Process Efficiency

Drilling in crystalline rock will be slow, with penetration rates possibly as low as 1 meter per hour on average. Hard crystalline basement rock (especially rocks with high silica content like granite) will typically lead to limited drilling bit life. Frequent bit changes will increase the number of trips in and out of the borehole. Coupled with the large diameters, this means that drilling costs are somewhat uncertain.

When drilling deep boreholes in hard rock, the amount of time spent tripping drilling and testing equipment in and out of the borehole (e.g., to change the drill bit, retrieve core samples, conduct a drill-stem test, or perform hydrofracture tests) can be a significant portion of the total time. This can be minimized by using longer drill pipe sections, longer-life drill bits, alternative drilling methodologies, and wireline coring methods.

Using a top-drive rig that has the capacity to handle multiple sections of drill pipe simultaneously would be consistent with the goals of the CB and the depth and conditions expected.

7.1.3 Borehole Deviation

While the exact causes of drill bit deviation are not always known, it is generally agreed deviation is caused by a combination of one or more of several factors:

- Heterogeneous nature of rock formation (e.g., rock fabric dip angle);
- Drill string characteristics, specifically the makeup of the bottom hole assembly;
- Stabilizers used in drilling, including location, number, and clearances;
- Applied weight on bit;
- Hole-inclination (i.e., angle from vertical);
- Drill-bit type and mechanical design;
- Hydraulics related to drilling fluid and cuttings removal at the bit;
- Improper borehole cleaning.

Both boreholes have horizontal deviation requirements, which specify the maximum horizontal deviation away from the starting location. This deviation requirement is primarily needed for spacing boreholes in a grid, where providing adequate separation from adjacent boreholes is critical. In the DBFT, with only two boreholes planned and no waste disposal, the chance of the two boreholes impacting each other is small.

Dogleg severity specifies the maximum angle the borehole curvature can make at any point, and presents a more stringent requirement than maximum deviation. Dogleg severity is important for the test package emplacement demonstration to be conducted in the FTB as part of the DBFT, and less so for characterization testing to be conducted in the CB. Although the requirements for a characterization borehole at a future disposal site may be different from those for a disposal borehole, the deviation requirements for the CB in the DBFT will be the same as those for the FTB to allow possible re-use of the CB for package emplacement demonstration. A dogleg severity specification of 3 degrees per 30.5 m [100'] is being used the package emplacement demonstration in the FTB (with the additional constraint of 2 degrees per 30.5 m [100'] in the upper 1 km [3,281'] of the borehole), and will be applied to the CB.

7.1.4 Drilling Fluid

The fluid circulation system is composed of pumps, connections to the drill string, fluid recovery equipment, and surface equipment for fluid makeup and removal of cuttings. Mud is a general term for the fluid circulated during the drilling process. Depending on the drilling method it can be composed mostly of water, oil, or air. Its functions are to cool and lubricate the bit, lubricate the drill string, flush cuttings from the borehole, condition the hole to limit sloughing and lost circulation, and control downhole pressure. Drilling fluid or mud often has a significant impact on the cost of the borehole, particularly when the borehole has large diameter or lost circulation. Drilling fluid composition will be closely monitored at the surface and downhole as part of drilling and characterization (Section 5.1.2). A water-based polymer drilling fluid (of similar design to that used for the KTB project (Emmermann & Lauterjung 1990; Born et al. 1997)) would be consistent with the scientific goals of the CB.

Airlifting is a commonly used drilling technique to lift drilling fluid and cuttings to the surface from depth. Airlifting involves injecting compressed air into the return side of the circulation path. Airlifting or drilling with air as the drilling fluid could significantly modify the chemistry of the drilling fluid and any dissolved formation gases it contains, which in turn could impact the quality of dissolved gas samples and estimation of *in situ* fluid geochemistry (e.g., redox potential, pH, and temperature). Drilling without any airlifting would be consistent with the scientific goals of the CB.

The drilling fluid used in drilling the overburden section of the borehole will be selected to efficiently maintain a stable borehole across the overburden (e.g., water- or oil-based fluid with bentonite). Depending on the geology of the overburden, and the potential for clay sloughing or swelling, some sections of the hole may require oil-based fluid (e.g., for swelling clays) or brine (e.g., where evaporate minerals are present). The drilling fluid type will affect mud logging data collection (Section 5.1.2) and borehole geophysical methods (Section 5.3).

After the overburden section is drilled, and logging and sampling are complete, casing will be set across the entire section (Figure 2). The drilling fluid used for the overburden section will be circulated out and replaced with a water-based polymer drilling fluid or equivalent, including added tracers (Section 5.1.2.4). Tracers will not be required while drilling the uppermost portions of the overburden section. The selection of drilling fluid type for the crystalline basement is important because of potential impacts on sampling and testing. The drilling fluid will be selected to optimize formation sampling while limiting contamination (including possible quantification of contamination level), and maintaining safety and stability of the borehole.

7.1.5 Cementing

Cementing operations are important for ensuring the stability of casing strings and liners. In addition, cementing may also be used to seal permeable zones and fractures during drilling, where lost circulation is encountered and other methods are not successful. The CB and FTB present depth, temperature, and chemical challenges to successful cementing.

A cement bond log will be performed in cemented, cased intervals of the completed boreholes to confirm proper cement placement. Extended leak-off tests can be conducted at the bottom of cased intervals to verify cement performance, and could be done in conjunction with hydraulic fracturing measurement (Section 5.2.3).

8. CHRONOLOGY

The CB and FTB will be drilled to a depth of 5 km [16,400’] as part of the DBFT. The DBFT will not involve handling or emplacing radioactive waste, but instead will confirm scientific and technological readiness to execute the Deep Borehole Disposal (DBD) concept in the future at a different site.

8.1 Characterization Borehole Construction and Testing

The CB will be the primary location for activities to: (1) demonstrate the ability to evaluate site suitability, (2) populate performance assessment models with required model parameters, (3) collect required borehole construction data, and (4) build confidence in the DBD concept (Figure 1).

The upper portions of the CB will be sized to accommodate a bottom-hole diameter of 21.6 cm [8½”]. The drilling method, drilling fluid and additives, borehole diameter, and casing schedule will be chosen to maximize likelihood of collecting representative and uncontaminated cores and water samples, as would be done for characterizing an actual DBD site.

8.1.1 Construction and Testing Chronology

The following sequence summarizes, at a high level, the envisioned sequence for drilling, testing, and completion activities in the CB for the DBFT (Figure 5).

1. Drill conductor borehole and set conductor casing (often drilled with an auger rig);
2. Mobilize drilling rig;
3. Drill surface borehole (44.5 cm [17½”] diameter) to approximately 460 m [1,500’] depth while collecting physical and chemical drilling fluid properties and logging cuttings;
4. Geophysically log surface borehole
5. Install 34 cm [13⅜”] diameter surface casing to surface;
6. Drill intermediate borehole (31.1 cm [12¼”] diameter) into crystalline basement (nominally 2 km [6,560’] depth, but possibly shallower).
7. Geophysically log open borehole and perform drill-stem testing and sampling in any overburden zones identified before setting casing.
8. Install 24.4 cm [9⅝”] diameter liner to base of surface casing;
9. Switch from drilling fluid used in overburden sequence to polymer and water-based drilling fluid and begin including tracers in drilling-fluid and makeup water;
10. Beginning at the overburden-basement contact, core 5% of crystalline basement portion of borehole;
11. Drill upper half of basement portion of borehole (2 to 3.5 km depth);
12. Perform hydraulic fracturing stress measurements in the disposal zone and seal zone (at least one hydraulic fracture test will be performed before the decision point halfway through the crystalline basement);
13. At halfway through the crystalline basement, a decision will be made whether or not to move forward with procurement process associated with drilling the larger FTB.

14. Finish drilling lower half of basement portion of borehole (3.5 to 5 km depth);
15. Geophysically log open portion of borehole;
16. After receipt of geophysical logs, a final decision will be made to begin drilling the larger FTB;
17. Clean out cuttings and drilling fluid from borehole;
18. Demobilize non-essential drilling rig equipment;
19. Conduct flowing log of open borehole to locate permeable zones;
20. Isolate several lower-permeability zones, estimating formation hydraulic properties and static formation pressure;
21. Conduct packer pumping tests in several isolated higher-permeability intervals, followed by sampling and recovery analysis;
22. Perform tracer testing (push-pull followed by vertical dipole) in two higher-permeability intervals;
23. Perform heater test;
24. Demobilize work-over rig.

This high-level sequence indicates the order in which tests will likely be conducted, but the exact design, order and nature of testing and sampling will be resolved by the DBFT Technical Lead, the drilling contractor, and other parties. The drilling and testing program may be modified as these activities progress.

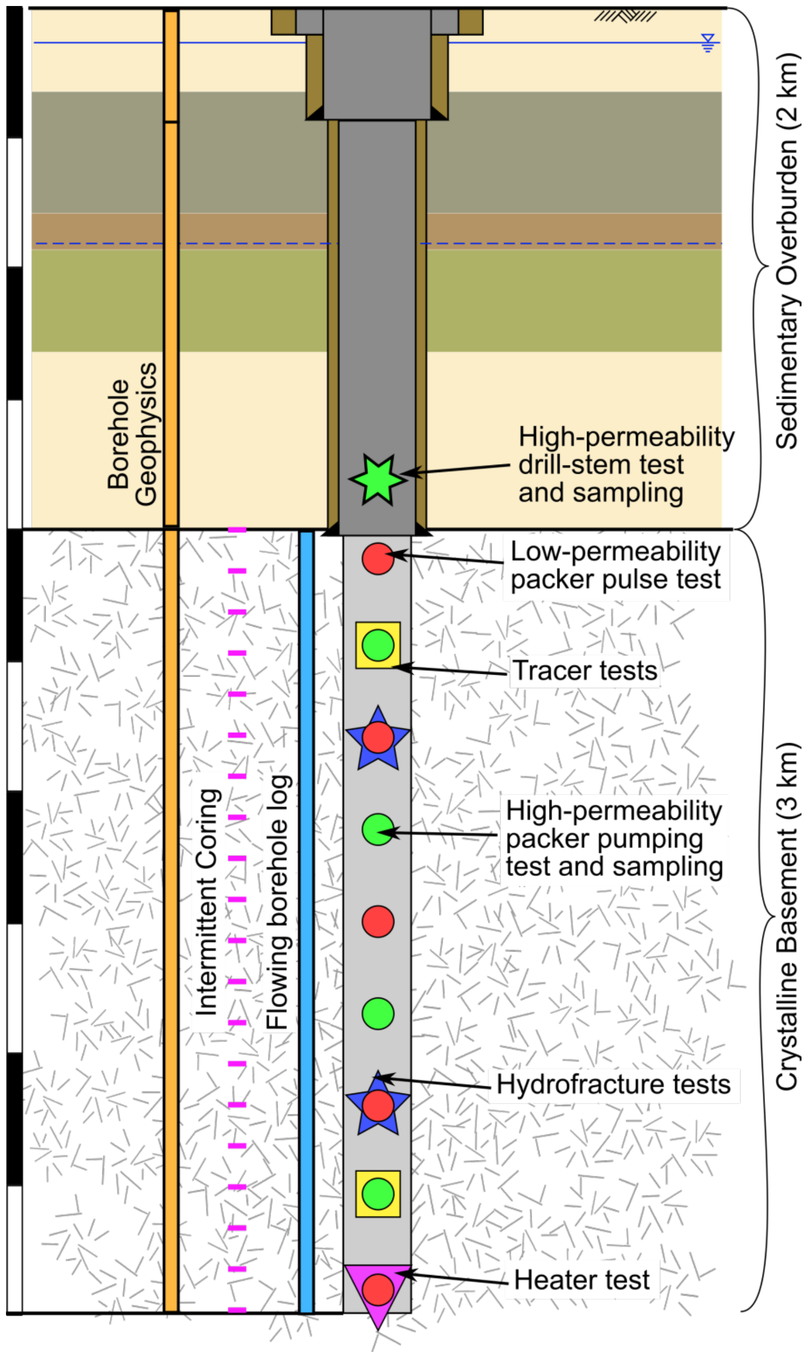

Figure 5. CB schematic with nominally located tests and samples; casing, liner and borehole details given in Figure 2

8.1.2 CB Data Required for FTB Decisions

The two decisions to be made regarding continuing with the larger FTB are decision points related to the following undesirable downhole conditions which may preclude drilling the FTB at the same site as the CB. The first preliminary decision point will be made after drilling through 50% of the crystalline basement (nominally at 3.5 km depth); a decision at this point will be made to cease or move forward with the FTB procurement process. The second decision point to decide whether or not to proceed with drilling the FTB will be after geophysical logs are run in the completed borehole.

Characteristics found while drilling the CB which may prevent continuation with the FTB include:

1. Significantly different rock type or depth to crystalline basement than was predicted or expected for the site (e.g., an over-thrust situation, where crystalline basement overlies sedimentary rocks at depth);
2. Unfavorable in situ stress and rock strength conditions at depth, resulting in very difficult drilling; and
3. Significantly elevated geothermal gradient, resulting in hotter than expected bottom-hole conditions. Drilling under very hot (i.e., geothermal) conditions involves additional risk and complications the project would rather avoid, if possible.

The depth to crystalline basement and the nature of the upper portion of the crystalline basement will be known by the primary decision point 50% of the way through the drilling of the crystalline basement rock (nominally at 3.5 km depth – see point 13 in CB chronology presented in Section 8.1.1).

In situ stress conditions and rock strength may change significantly with depth, but conditions in the upper crystalline basement in the CB will provide some indication of likely success for the FTB. The preliminary decision point is only to continue with the procurement process; the procurement process for the FTB drilling can be initiated before all CB characterization activities are complete. The final decision to begin drilling the FTB will wait until total depth is reached and the geophysical logs are collected across the entire crystalline basement interval. These logs will include temperature profiles and borehole imaging logs. Along with the experience gained from drilling the CB (drilling penetration rates, locations and types of problems encountered while drilling, unusually hot downhole conditions, and any previously unforeseen rock or borehole issues), the geophysical logs will provide significant assurance a successful FTB demonstration can be conducted.

Presence of high-permeability fracture zones or faults in the disposal interval of the CB would preclude construction of a disposal borehole at a DBD site, but would typically not preclude the demonstration activities planned at the FTB. If the high-permeability feature is related to borehole stability problems, there may be valid reasons to forgo continuation with the FTB portion of the DBFT, and conduct modified demonstration activities in the CB.

8.2 Field Test Borehole Construction Chronology

The FTB will be where the downhole emplacement and retrieval demonstration activities will be carried out. The procurement process that will precede FTB drilling and completion process will be ongoing as drilling in the CB progresses through half the total thickness of the crystalline basement. The final decision to proceed will occur after drilling is complete in the CB and the geophysical borehole logs have been conducted and reported to the Technical Lead.

The geophysical borehole logging done in the FTB is a small subset of that conducted in the CB, including gamma, neutron porosity, sonic log and borehole televiewer logs.

Once drilling of the FTB has been deemed safe and necessary, the following general sequence of events is envisioned.

1. Drill conductor borehole and set conductor casing (often drilled with an auger rig);
2. Mobilize drilling rig;
3. Drill surface borehole (91.4 cm [36”] diameter) to approximately 460 m [1,500’] depth;
4. Geophysically log surface borehole;
5. Install 72.6 cm [30”] diameter surface casing to surface;
6. Drill intermediate borehole (71.1 cm [28”] diameter) to just above the crystalline basement;
7. Geophysically log intermediate borehole;
8. Install 61 cm [24”] diameter intermediate casing to base of surface casing;
9. Drill upper crystalline basement borehole (55.9 cm [22”] diameter) to a total depth of 3 km (1 km into the crystalline basement);
10. Geophysically log upper crystalline basement borehole;
11. Install 61 cm [24”] diameter upper crystalline basement liner. Only lower portion of this liner is cemented (up to the port collar placed 160 m [525’] from the bottom);
12. Drill lower crystalline basement borehole (43.2 cm [17”] diameter) to total depth of 5 km.
13. Geophysically log lower crystalline basement borehole
14. Install 34 cm [13⅜”] diameter perforated guidance liner on bottom of open borehole.
15. Install 34 cm [13⅜”] diameter guidance tieback casing from top of perforated guidance liner to surface.
16. Demobilize non-essential drilling rig equipment;
17. Perform borehole emplacement and retrieval demonstrations in guidance liner casing.
18. Demobilize equipment used for emplacement and retrieval demonstration (i.e., wireline or drill pipe handling equipment at surface).

9. DIFFERENCES BETWEEN DBD AND DBFT

This document has primarily described the planned activities for the DBFT. The DBFT is being conducted to support the DBD concept, but there are some key differences. These differences stem from several primary sources:

- The DBFT is a five-year demonstration exercise planned in two boreholes without any use of radioactive waste or installation of permanent seals. DBD may include an array of boreholes, and will include handling and disposal of radioactive waste and emplacement of a system of borehole seals.
- Activities that would permanently change the borehole environment (e.g., installation of vertically extensive permanent borehole seals or cement plugs in the disposal interval) will not be conducted in the DBFT, to maximize the utility of the boreholes for later follow-on work.
- The DBFT has been designed primarily as a demonstration of activities at critical technology readiness levels (TRLs):
    - In the CB, in situ characterization of low-permeability and low-porosity crystalline basement at 5 km depth and possibly elevated temperatures,
    - In the FTB, drilling and completion of a large-diameter borehole to 5 km in crystalline basement rock, and
    - In the FTB, test package emplacement and retrieval demonstration.

  Some activities required for DBD have a high TRL and therefore do not require explicit demonstration in the DBFT. To focus resources on key activities needed to build confidence in the concept, these high-TRL activities are not included or in some cases minimally included.
- The DBFT is utilizing a competitive RFP process to procure a test location, and site management contractor (DOE 2015a; 2015b). Future repositories or DBD sites will likely be selected following a consent-based siting approach (BRC, 2012).

The following set of activities would be planned for a DBD site, but are not currently planned as part of the DBFT.

9.1 Characterization Differences

Drilling and constructing the CB and FTB as part of the DBFT will likely identify further characterization activities that may be required or suggested for future DBD.

9.1.1 Surface Geophysics

Extensive exploratory surface geophysics are not planned prior to the start of drilling due to a combination of 1) the procurement process being used to acquire the DBFT site, , and 2) the relatively high TRL associated with surface geophysics.

9.1.2 Overburden Coring and Sampling

Collecting cores and performing packer-based sampling and testing in shallow overburden formations are commonly conducted in the hydrology and oil and gas industries. These tasks have a high TRL and could significantly increase the time required for testing in the CB, delaying schedules and increasing costs.

9.2 DBD Closure Activities

The steps involved in sealing and closing a disposal borehole do not plan on being demonstrated as part of the DBFT. These steps are discussed in Arnold et al. (2011), and the final details of the design will be site-specific.

9.2.1 Installation of Plugs or Packers

To reduce the axial load on packages placed in the lower portions of a disposal borehole during emplacement, cement plugs or annular packers (or a combination of the two) will be emplaced in the perforated liner above bridge plugs. These seals will not be installed as part of the DBFT, since they would preclude simple retrieval of test packages placed below the bridge plug without drilling or other invasive processes.

9.2.2 Removal of Guidance Casing

The portions of the casing in the FTB indicated in red in Figure 3 would be removed as part of the DBD closure process, to allow construction of seals against the crystalline basement. It is currently not planned to remove the guidance casing as part of the DBFT.

9.2.3 Installation of Borehole Seals In Basement

The borehole seals will not be installed as part of the DBFT against the crystalline basement (and possibly any sedimentary overburden, depending on the site-specific design and final depth of the intermediate casing). Installation of seals would preclude access to the deepest parts of the borehole for later testing. Testing of sealing processes and mechanisms are not currently planned to be demonstrated as part of the DBFT, with these activities currently planned to be conducted in the laboratory at representative pressures and temperatures.

9.2.4 Installation of Borehole Seals In Casing

The borehole seals will not be installed in the cased intervals within grouted casing. This activity would preclude access to the deepest portions of the borehole for other testing activities, and this type of plugging is standard procedure (high TRL) in oil and gas drilling.

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