DRILLING AND TESTING IN THE DEEP BOREHOLE FIELD TEST

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The Deep Borehole Field Test (DBFT) is a planned multi-year project led by the US Department of Energy's Office of Nuclear Energy to drill two boreholes to 5 km total depth into crystalline basement in the continental US. The purpose of the first characterization borehole is to demonstrate the ability to characterize in situ formation fluids through sampling and perform downhole hydraulic testing to demonstrate groundwater from 3 to 5 km depth is old and isolated from the atmosphere. The purpose of the second larger-diameter borehole is to demonstrate safe surface and downhole handling procedures. This paper details many of the drilling, testing, and characterization activities planned in the first smaller-diameter characterization borehole.

I. INTRODUCTION

Deep Borehole Disposal (DBD) of high-level radioactive wastes has been considered an option for permanent geological isolation for many years. Recent advances in drilling technology have decreased costs and increased reliability for straight large-diameter (i.e., ≥50 cm [19.7"]) boreholes to depths of several kilometers [1,2]. These advances have therefore also increased the feasibility of the DBD concept [3,4], and the DBFT will demonstrate these advances.

The DBFT includes drilling two boreholes to 5 km [16,400'] total depth, in a region where crystalline basement is expected to begin at less than 2 km depth [6,560']. The characterization borehole (CB) is the smaller-diameter borehole (i.e., 21.6 cm [8.5"] diameter at total depth), and will be drilled first. All geologic, hydrogeologic, geochemical, geomechanical and thermal testing will take place in the CB. The field test borehole (FTB) is the larger-diameter borehole (i.e., 43.2 cm [17"] diameter at total depth). Surface handling and borehole emplacement of test packages (no nuclear waste will be used in the DBFT) will be demonstrated using the FTB to evaluate engineering feasibility and safety of disposal operations [5].

Preliminary performance assessment calculations have been conducted for the DBD concept [6]. The nominal (i.e., undisturbed) post-closure release scenario includes short-duration thermally induced upward advective flux through borehole seals and the disturbed rock zone (DRZ), followed by longer-term slower diffusive transport.

II. BOREHOLE DESIGN AND DRILLING

The primary CB testing activities can be related to three primary requirements for CB drilling and completion. The DBFT objectives include:

- Representative crystalline basement fluid and rock samples;
- Representative downhole hydraulic, mechanical and geochemical test results in the crystalline basement;
- Minimal casing or liner in the crystalline basement interval to increase the depth interval available for later packer-based testing via workover rig.

II.A. CB Design

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 standby time and increase scheduling flexibility. During drilling, collected samples will include drilling fluids, rock flour and cuttings, and coring of ~5% of the crystalline basement. The only formation fluid sampling to be conducted during drilling will be from a wireline-conveyed packer system in zones that would be cased or lined in the completed borehole (Figure 1). Such sampling targets include the basal overburden aquifer and the uppermost interval of crystalline basement that is cased for borehole integrity. At least one *in situ* hydraulic fracture stress measurement, an extended leak-off test, and one estimate of static formation pressure will be completed in the target crystalline basement section during drilling, to provide information for completing the CB and for the FTB procurement and construction process.

Borehole and casing generic design (recommended nominal diameters and depths) for the CB (Figure 1) 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 [50-100'] and cemented to the surface. Commonly the conductor borehole is drilled with a separate drilling rig and installed as part of the site construction, including possible sub-grade completions required for drilling fluid plumbing and electrical connections to the drilling rig used for the crystalline basement section.

• 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 required by regulatory agencies for well control (assumed 460 m [1,510’] in Figure 1). This casing is cemented to the surface. If required by local regulations, it will have a blow-out preventer installed after cementing.

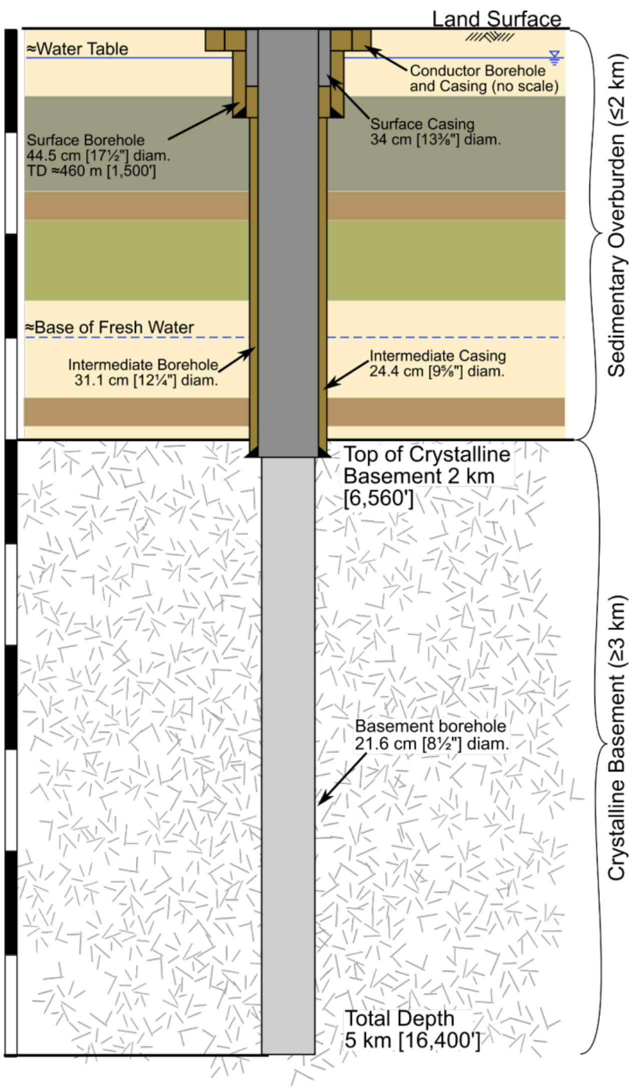

Figure 1. Generic CB Design. Dark gray is permanent casing or liner, olive is cemented annulus, light gray is open borehole

• Intermediate (24.4 cm [9⅝”] liner in 31.1 cm [12¼”] hole): This liner runs from the bottom of the surface casing through the base of the overburden (2 km in the nominal design) and far enough into the crystalline basement to reach competent rock; the annulus behind this liner is cemented at least up into the surface casing, and possibly all the way to the surface.

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

II.B. CB Drilling

The site-specific design for the DBFT will be developed with the CB drilling and site management contractors in a detailed drilling and testing plan. From the perspective of achieving the scientific goals of the project, the drilling fluid will likely be water-based, with salt added for similar density and chemical composition to formation fluid, and with minimal other additives (e.g., viscosifiers, rust inhibitors, biocides). Drilling fluid will be made up from consistent and clean makeup water sources and consistent, new additive materials. The DBFT will avoid recycled or produced brines as makeup water, which may vary significantly and could introduce unneeded complexity to the drilling fluid composition, especially with respect to trace metals and hydrocarbons.

In the target crystalline basement interval, drilling fluid will include conservative tracers (e.g., iodide or fluorescein). Tracers will be compatible with drilling fluid additives, and will allow on-site quantification.

Top-drive rotary drilling in crystalline basement would likely be performed using a hard-formation, tungsten-carbide insert, journal bearing, roller-cone bit connected to a rotary steerable system (RSS) for automatic directional control. This drilling system could alternatively be fitted with hybrid roller-cone/polycrystalline diamond compact (PDC) bits. The DBFT should take advantage of and explore the feasibility of recent advances in drilling technology (i.e., PDC or hybrid PDC/roller-cone bits), but the DBFT will not be relying on experimental approaches unless the consequences of failure for these approaches are acceptably low.

In low-strength sedimentary rocks the mud window during drilling (i.e., difference between the least principal stress where hydraulic fracture occurs and the fluid pressure where inflow of formation fluid or gas occurs) may be very narrow, requiring complex telescoping casing design and significant weight and filter-cake additives to minimize breakouts and formation fluid invasion/production, and to deter possible well collapse. When drilling through stronger crystalline rocks like granite, less benefit may be derived from maintaining high hydrostatic fluid pressure in the borehole than is seen in weaker sedimentary formations. It would likely be advantageous to the project if drilling were conducted in a slightly underbalanced manner, to allow fluid production from the formation, and to minimize the infiltration of drilling fluid into the formation. Traditional filter cake, as developed in porous sedimentary rocks, is notably less effective in low-porosity fractured crystalline rocks.

III. CHARACTERIZATION BOREHOLE DRILLING AND TESTING SEQUENCE

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.

III.A. Drilling and Logging Sequence

The following sequence summarizes drilling, logging, and completion activities in the CB for the DBFT (Figure 2).

D1. Drill conductor borehole and set 50.8 cm [20"] diameter conductor casing to 15-30 m [50-100'] depth.

D2. Mobilize main drilling rig.

D3. Drill surface borehole (44.5 cm [17½"] diameter) to approximately 460 m [1,500'] depth while collecting drilling performance information, logging cuttings, and analyzing rock flour by X-ray diffraction (XRD) and X-ray fluorescence (XRF).

D4. Collect geophysically logs in uncased portion of surface borehole (Table 1).

D5. Install and cement 34 cm [13⅜"] diameter surface casing from the bottom to the surface.

D6. Conduct extended leak-off test to estimate magnitude of least principal stress at 460 m depth.

D7. Drill intermediate borehole (31.1 cm [12¼"] diameter) through most of the remaining overburden, to ≤150 m [500'] of expected depth to basement.

D8. Conduct vertical seismic profile (VSP) to better constrain depth to crystalline basement, to increase likelihood of coring overburden/basement interface. If depth to basement is well-constrained from existing geophysics or nearby boreholes, VSP would not be necessary.

D9. Drill intermediate borehole (31.1 cm [12¼"] diameter) to within ½ core barrel length from expected top of crystalline basement.

D10. Core across overburden/basement interface.

D11. Collect geophysical logs in open borehole to identify candidate unit of overburden (basal unit if sufficiently permeable) for hydraulic testing.

D12. Perform hydraulic testing and fluid sampling using wireline-based packer tool on selected higher-permeability unit of overburden (estimate hydraulic properties and static formation pressure, and collect water quality samples for laboratory analyses).

D13. Drill intermediate borehole deeper into crystalline basement until competent crystalline rock is encountered.

D14. Collect geophysical logs in any additional section of borehole drilled, including a high-resolution temperature log of the upper crystalline basement (to be cased) and the lower sedimentary overburden (where hydraulic testing was done), to determine distribution of flowing units and fractures.

D15. Perform hydraulic testing and fluid sampling using wireline-based hydraulic packer-isolated interval testing tool near top of crystalline basement (higher-permeability location identified by high-resolution temperature log), in the uppermost basement interval that will be cased and cemented.

D16. Collect any desired rotary sidewall cores via wireline from to-be-cemented intervals of interest identified from geophysical logging.

D17. Install 24.4 cm [9⅝"] diameter casing from the surface to top of competent crystalline rock in the upper basement.

D18. Cement the annulus behind the 24.4 cm [9⅝"] diameter casing, from the bottom up to at least 150 m [500'] into the surface casing.

D19. Conduct extended leak-off test to estimate magnitude of least principal stress at 2,000 m depth.

D20. Switch from the drilling fluid composition used in the overburden, to drilling fluid including tracers selected for the crystalline basement section. Exchange all drilling fluid and use only traced drilling fluid throughout basement section.

D21. Drill and core (at ~5% frequency) the 21.6-cm [8½"] borehole through the upper half of the basement interest section (nominally from 2 to 3.5 km depth), while logging and sampling drilling fluid liquid, dissolved gas, and cuttings and performing XRD/XRF analysis on rock flour.

D22. Image a lower interval of the borehole to find optimal location for hydraulic fracture stress measurement and packer-based testing (estimating static formation pressure).

D23. Perform hydraulic testing and fluid sampling, if sufficient permeability, using the wireline-based hydraulic packer-isolated interval testing (HPIT) tool.

D24. Set wireline-based HPIT tool on a low-permeability interval and conduct hydraulic fracturing stress measurement.

D25. Collect image log of the interval where hydraulic fracturing stress measurement was conducted to determine orientation of induced fractures.

D26. Provide CB data and analysis to support the decision point to move forward with the procurement process associated with drilling the FTB.

D27. Drill and core (~5%) the 21.6-cm [8½”] borehole through the remaining lower half of the basement section (nominally from 3.5 to 5 km depth), while logging and sampling drilling fluid liquid, dissolved gas, and cuttings and performing XRD/XRF analysis on rock flour.

D28. Collect Geophysical logs (Table 1) in the open part of the borehole (the entire crystalline basement section).

D29. Provide additional CB data and analysis as needed to support the decision point to move forward with the FTB.

D30. Flush cuttings and drilling fluid from borehole, and swab if necessary. Replace drilling fluid with workover/testing fluid selected to provide long-term chemical stability and well control during subsequent testing.

D31. Based on geophysics, locate and drill any additional intervals with rotary sidewall coring via wireline tool.

D32. Demobilize non-essential drilling rig equipment before workover rig testing.

III.B. Workover Testing Sequence

The following sequence summarizes in situ testing and post-completion activities in the CB for the DBFT, which follow demobilization of non-essential drilling and completion rig equipment.

T1. Conduct dynamic flowing temperature or dilution log of open borehole to locate permeable zones.

T2. Isolate, hydraulically test, and sample four ~9.1-m [30’] higher-permeability zones using packer tool. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating higher permeability zones). Pump formation fluid from interval to surface using either submersible or surface-based pump.

T3. Isolate and hydraulically test four ~9.1-m [30’] lower-permeability zones using packer tool. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating lower permeability zones).

T4. Isolate and perform injection-withdrawal tracer test on two ~9.1-m [30’] higher-permeability zones using packer tool. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating higher permeability zones). Locate interval where successful high-permeability hydraulic tests were conducted (T2 above), if possible.

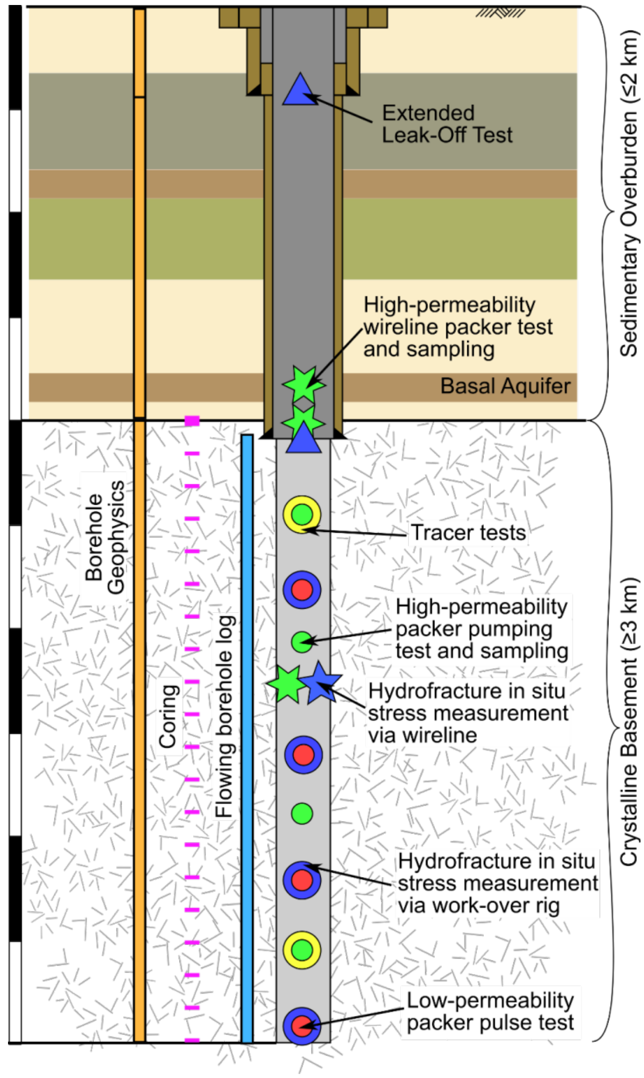

Figure 2. CB schematic with nominally located tests and samples. Circles represent tests conducted with workover rig. Polygons represent tests conducted during drilling.

T5. Isolate and hydraulically test one ~18.2-m [60’] lower-permeability zone using three-packer hydromechanical testing tool. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating lower permeability zones).

T6. Isolate and conduct sequence of hydraulic fracture stress measurement tests on four ~4.6-m [15’] low-permeability regions of the borehole. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating lower permeability zones).

T7. Demobilize testing equipment (i.e., workover rig) from borehole.

These drilling and testing sequences indicate 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 (Sandia National Laboratories), the CB Drilling Contractor, and the Site Management Contractor.

IV. GEOPHYSICAL BOREHOLE LOGGING

Borehole geophysical characterization methods measure characteristics of the drilling-fluid filled borehole, the rock formations intersecting the borehole, and the formation fluids saturating the DRZ and far-field rock. They will be relied upon extensively to provide vertically continuous data about the stratigraphy and lithology in the CB. Some geophysical tools and methods may not be effective in the large-diameter FTB (43.2 cm [17”]), and are therefore planned for the smaller-diameter CB (21.6 cm [8½”]). The choices of wireline logs and logging tools are also constrained by borehole temperatures or pressures. Table 1 lists the wireline geophysical methods planned to be conducted in the uncased crystalline basement portions of the CB.

Table 1. Geophysical Methods Planned for the CB

Borehole Log	Purpose
Deviation Survey	Borehole azimuth and inclination help ensure the hole is kept within design limits.
Borehole Imaging	Estimate horizontal stress orientations from breakouts and hydraulic fracturing. Orient core.
Gamma-Ray	Identify lithology.
Spectral Gamma-Ray	Identify radioactivity sources (K, Th & U).
Resistivity	Input for interpretation of lithology and calculation of formation fluid salinity (using formation factor).
Spontaneous Potential	Identify lithology, mineralization, and formation fluid salinity.
Nuclear Magnetic Resonance	Estimate formation porosity and tortuosity, which can be used to infer permeability.
Induced Polarization	Estimate formation chargeability, a function of the solid-liquid interface; related to permeability.
Photoelectric Factor	Mineral composition for advanced lithology logs.
Gravity	Estimate density and porosity.
Neutron Porosity	Estimate water or hydrocarbon content and porosity.
Temperature	Estimate geothermal gradient and temperature corrections for logs.
High-Resolution Temperature	Locate inflow and outflow features from small-scale variations in borehole fluid temperature.
Gamma Density	Estimate formation bulk density and porosity. Input for design of VSP survey.
Full Waveform Sonic	Estimate porosity and rock hydromechanical properties from compressional seismic waves.
Borehole Radar Polarimetry	Estimate depth and extent of borehole breakouts and near-borehole fractures (both natural and drilling induced).

V. DOWNHOLE TESTING

Limited wireline-based packer testing will be conducted during the drilling phase, to obtain information from intervals that will ultimately be cased or cemented during borehole completion. Most hydraulic and geomechanical in situ testing will be conducted with packers using a workover rig (i.e., packers set on tubing, rather than wireline).

V.A. Flowing Borehole Log

The flowing borehole production profile is an important survey for identifying high-permeability inflow or outflow intervals for later packer testing. The production profile tests the entire open borehole, or sections of the open borehole, in an integrative manner. In this test, the open crystalline basement portion of the CB will be mapped via a flowing or pumping log to identify higher-permeability features. The method relies on repeated surveys using one or more methods: 1) salinity logging, 2) high-resolution temperature logging, and/or 3) on-station high-resolution measurements of axial flow. Modern high-resolution flow meter tools are based on solute dilution or heat-pulse time-of-flight principles [7].

Fluid flows into and out of the borehole through permeable features, under natural head conditions driven by differences in head between the formation and the borehole. Simply logging the borehole may reveal temperature or salinity anomalies that indicate inflow and outflow. These anomalies can be further investigated using a calibrated borehole flow meter to make point measurements of axial flow. For better resolution, the borehole can first be flushed with fluid that is colder or less saline, or both, to set up a transient condition that is monitored by repeated logging, as it is modified by inflow and outflow. Finally, the borehole can be pumped during repeated logging to increase the strength of temperature or salinity transients, and to produce flow from additional features of the host formation.

The production profile survey will conceptually take the place of a much more resource intensive program of longer-duration tests in many intervals isolated by packers. For example, in the 3-km open interval 100 adjacent hydraulic tests could be performed using a 30 m packer tool, roughly doubling the overall duration of testing in the CB. The objective of the production profile survey is to identify higher-permeability zones for focused packer testing, geochemical sampling, and tracer testing.

V.B. Hydraulic Packer Tests

Hydraulic packer testing will be done to obtain three critical pieces of information on the host formation: formation static fluid pressure, formation bulk permeability, and in situ formation fluid geochemistry (in higher-permeability intervals that allow pumping). Packer testing equipment consists of a packer or tool to isolate a section of the borehole, down-hole pressure sensor, flow control valves that can be controlled from the surface, and a pump which brings fluids to the surface along with possible down-hole pressurized sampling devices.

Hydraulic testing of packer-isolated intervals will involve:

1. Estimating shut-in/static formation pressure (i.e., identification of any under- and overpressure zones that deviate significantly from hydrostatic pressure);
2. Slug, pulse, or constant-head hydraulic testing to estimate permeability and storage properties of fracture zones and the near-borehole region;
3. Pumping an interval to obtain representative in situ fluid samples (when permeability of intervals is high enough to allow pumping); and
4. Monitoring enough recovery to improve estimates of static formation pressure.

V.C. Hydraulic Fracturing Stress Measurements

A hydraulic fracturing stress measurement test will be performed via wireline in the crystalline basement interval while drilling to estimate the horizontal principal stresses, and to evaluate the variation of in situ stresses with depth. Several more hydraulic fracturing stress measurements will be made via workover rig. They will be used in conjunction with geophysics and observations of borehole breakouts and drilling-induced tensile fractures (e.g., formation micro-resistivity image log, borehole televiewer, and anisotropic shear wave velocity log) to create a profile of the orientation and magnitude of stress through the entire basement interval.

Hydraulic fracturing stress measurements are a common diagnostic tool in geomechanical testing [8]. Although based on the same principal as hydrofracture well stimulation used in the oil and gas industry, hydraulic fracturing stress measurements are only performed to determine the properties of the rock and *in situ* stress, not to create a large stimulated volume of rock. Hydrofracture well stimulation is a high-flowrate, high-pressure, high-volume method that includes a mixture of chemicals and proppant to maximize subsequent production from the stimulated region. Hydraulic fracturing stress measurements are high-pressure, low-flowrate, low-volume tests run with a small pump, and only use water. The types of tests planned for the CB are called “mini-fracs” when performed in the oilfield to estimate *in situ* stress.

Extended leak-off tests will also be conducted after surface and intermediate casing annuli have been cemented. The borehole is drilled deeper (typically 3 to 6 m [10-20’]) and the open borehole is pressurized to the point of hydraulic fracture, allowing estimation of the least principal stress.

V.D. Injection-Withdrawal Tracer Tests

Tracer injection/withdrawal (push/pull) tests will be conducted across identified high-permeability fracture zones to help estimate the density and spatial distributions of fractures, and interrogate fracture surface area. The use of suites of geochemically reactive and conservative tracers can provide insight into changes that have occurred in the exposed reactive fracture surface area due to drilling, and the surface area of rock matrix porosity, in fractured rock systems. The interaction of tracers with newly exposed surfaces will lead to preferential retention via sorption or ion exchange processes that may have complex kinetics and long-tail behavior [9,10]. Hence, analysis of pumped flow-back formation fluids promises to yield useful information on the type and magnitude of new exposed surfaces.

Two of the high-permeability intervals used for hydraulic testing and sampling will be used to perform injection-withdrawal tracer tests. This involves pumping fluid from a packer-isolated interval, then injecting traced water into the interval, a rest period, and finally a pumping phase with both downhole and surface fluid sampling for added tracer constituents. These tests will elucidate the roles that primary fractures and microfractures in the rock matrix play in solute transport through the borehole DRZ.

V.E. Hydromechanical Packer Test

A three-packer hydromechanical test is proposed to explore the role of the DRZ in flow up the borehole, and the effect of applying normal stress to the borehole wall (with a middle packer, simulating the effects of a plugging material with swelling properties). The three-packer hydromechanical test will be conducted, with the middle packer inflation pressure controlled separately from the outer two packers. This test will perform and observe pulse flow tests between two adjacent packed-off intervals, with the inflation of the intermediate packer changing between repetitions of the test.

A pulse hydraulic test will be performed before inflating the middle packer, with both intervals acting together as a single interval. Additional tests will be conducted in both intervals, as pressure is increased stepwise in the middle packer (keeping the packer inflation of the outer two packers constant). Pulse testing will be done from the upper interval, observing in the bottom interval, and vice-versa. After stepping up the middle packer inflation pressure beyond the packer inflation of the outer two packers (up to the potential swelling pressure of bentonite, 20 MPa above the borehole fluid pressure, if equipment allows), the inflation pressure will be decreased on the middle packer in a stepwise manner while repeating pulse testing and observation in both test intervals.

This test will explore the hydromechanical coupling *in situ* and will possibly obtain data for characterization of strain-permeability constitutive models. Independent measurement of mechanical strain in the borehole (rather than just packer inflation pressure) during testing would provide data useful for interpreting the test results. The tool should have minimal storage in the testing interval, to increase the tool's sensitivity to the storage properties of the formation. The hydraulic testing should be able to discern a positive or negative wellbore skin that may exist in the packer interval, and how this changes with packer inflation pressure. A coupled hydro-mechanical numerical model will be used to interpret the test results.

VI. SAMPLE TYPES AND ANALYTES

Here we briefly indicate the types of analyses to be performed on different samples collected during the DBFT. Detailed descriptions of these proposed tests, including quantification objectives and identification of contamination or loss potentials are given in the SNL report "Deep Borehole Field Test Laboratory and Borehole Testing Strategy" [11].

VI.A. Liquid Samples

Many laboratory analyses will be conducted on liquid samples from various parts of the drilling and testing activities planned. There will be some high-frequency field analyses (i.e., temperature, pH, Eh, electrical conductivity, specific gravity, and drilling fluid tracer concentration), but the majority of precisely quantified testing will be done at off-site laboratories.

VI.A.1. Liquid Sample Types

Liquid samples of groundwater will be used to characterize *in situ* formation fluids, and will include samples of:

1. Drilling fluid makeup water source;
2. Drilling fluid with additives before circulation;
3. Drilling fluid and formation water after circulation;
4. Produced water from higher-permeability packer-isolated intervals, pumped to the surface;
5. Fluids extracted from cores (i.e., through centrifugation, vacuum distillation, squeezing, and crush and leach); and
6. Formation fluids pumped to the surface during injection / withdrawal tracer tests.

The frequency of these samples will be dictated by the scientific needs and available budget of the DBFT.

VI.A.2. Liquid Sample Analytes

Not all samples will be tested for every analyte. Small-volume samples may not provide large enough samples sizes for all analyses, and added tracers will only be tested where they are expected to be found. The primary suite of liquid sample analytes consists of the following natural tracers and constituents of interest:

1. Major anions/cations (e.g., Na^{+}, Cl^{-}, Ca^{++}, SO_4^{--});
2. Trace elements (e.g., Li, Sr, U);
3. Stable water isotopes (e.g., ^{2}H, ^{18}O);
4. Dissolved and total inorganic carbon;
5. Isotopic ratios of major species (e.g., C, N, S);
6. Fission product species (e.g., ^{36}Cl, ^{129}I);
7. Cosmogenic and anthropogenic tracers (e.g., ^{4}He, tritium, ^{21}Ne, ^{81}Kr);
8. Drilling fluid tracer (e.g., fluorescein or iodide); and
9. Tracer test tracers (e.g., uranine, fluorinated benzoic acids, amino-G acid or Cs salts)

VI.B. Solid Samples

The solid samples of rock will mostly be collected during drilling; wireline-based sidewall coring may also be conducted after drilling is complete. The DBFT provides a unique opportunity to obtain rock samples from great depth, in what will likely be very old crystalline basement rocks.

VI.B.1. Solid Sample Types

Solid rock samples will be a primary means of understanding the water-rock interactions that may dominate in situ formation fluid chemistry. Samples will come from:

1. Core collected across approximately 5% of the target crystalline basement interval (mostly 10 cm [4"] diameter advance core, but some small-diameter sidewall core may be collected as a contingency);
2. Cuttings recovered at the surface during drilling for geological characterization;
3. Rock flour centrifuged from drilling mud for XRD and XRF mineralogical analysis.

Cores will be oriented and depth-corrected through use of image log data. These samples will have the highest degree of positional certainty, but will only be collected across 5% of the crystalline basement. Cuttings come continuously to the surface during drilling and allow high-frequency sampling, but there is higher uncertainty about their origin location, due to mixing and spalling during drilling fluid circulation. Centrifuging rock flour from drilling fluid is an alternative approach to obtain rock compositional data that are less prone to depth-location errors that affect cuttings [12]. Rock flour testing requires rinsing and onsite XRD/XRF instruments.

VI.B.2. Solid Sample Analytes/Testing

Solid samples (especially cores) will have extensive testing performed on them, for geochemical, hydrological, geomechanical, and thermal parameterization. Laboratory testing will generally include:

1. Compositional XRD & XRF analysis of rock flour;
2. Geological characterization of cores and cuttings (e.g., quantitative imagery, thin-section analysis, and scanning-electron microscopy), including analysis of fracture fill materials;
3. Geochemical whole-rock characterization of core and cuttings samples (e.g., He content of quartz crystals, whole-rock isotopic ratios and elemental abundances: Li, Sr & U);
4. Geomechanical characterization of cores (e.g., compressive strength vs. confinement, Brazilian indirect tension tests, triaxial loading tests with pore pressure, normal and shear compliance of pre-existing fractures, and anelastic strain recovery analysis of cores); and
5. Hydrological and thermal characterization of cores (e.g., Hg porosimetry, nuclear magnetic resonance pore characterization, hydraulic testing at representative confining stress, thermal conductivity and heat capacity testing, thermal expansion coefficient testing, and Biot coefficient estimation).

VI.C. Gas Samples

Gas samples will be collected to more fully characterize the *in situ* geochemical environment. Major gas components dissolved in the formation fluid will likely exsolve at the surface spontaneously, whereas minor components will require extraction using a gas-permeable membrane. Gases exsolved from vacuum-preserved cores will also be monitored over weeks and months to estimate a profile of the dissolved gas ratios *in situ* (especially the noble gases He and Ar).

VI.C.1. Gas Sample Types and Analytes

Gas sampling requires careful handling and effective isolation from the atmosphere. Gas components of formation fluids will be sampled from:

1. Drilling fluid after circulation to the surface. Major gas components analyzed via onsite gas chromatograph (e.g., N_2, O_2, Ar, CO_2, He, Ne, CH_4);
2. Formation fluids pumped to the surface from higher-permeability intervals. A dissolved-gas extraction membrane may be used at the surface to capture minor gases (e.g., ^{81}Kr and ^{85}Kr) that do not spontaneous exsolve; and
3. Core subsamples will be sealed in helium-tight vacuum canisters, after purging atmospheric gases and flooding the samples with high-purity N_2 gas. The head space gases that evolve will be monitored over several weeks, to give an indication of ratios of the in situ gases in equilibrium with the formation fluids.

VII. CONCLUSIONS

The planned CB testing effort described here involves conducting downhole *in situ* testing and sample collection from great depths at elevated temperatures and pressures. Portions of the borehole will likely have breakouts, which may complicate obtaining a good seal when setting packers. The deeper portions of the borehole may have a stress state that leads to discing when coring (i.e., short, hockey-puck shaped core fragments). Obtaining uncontaminated solid, liquid, and gas formation samples from low-permeability low-porosity crystalline rock will be a challenge.

The characterization effort proposed will not be trivial, but the purpose of conducting the DBFT is to demonstrate and explore the feasibility of the outlined characterization steps. The purpose of the DBFT is not primarily to exhaustively investigate a single site. The strategy of characterization effort at the DBFT is to test the technical readiness level of various approaches that might be used at future DBD sites.

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