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Field Test to Evaluate Deep Borehole Disposal

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Summary

The U.S. Department of Energy (DOE) has embarked on the Deep Borehole Field Test (DBFT), which will investigate whether conditions suitable for disposal of radioactive waste can be found at a depth of up to 5 km in the earth's crust. As planned, the DBFT will demonstrate drilling and construction of two boreholes, one for initial scientific characterization, and the other at a larger diameter such as could be appropriate for waste disposal (the DBFT will not involve radioactive waste). A wide range of geoscience activities is planned for the Characterization Borehole, and an engineering demonstration of test package emplacement and retrieval is planned for the larger Field Test Borehole. Characterization activities will focus on measurements and samples that are important for evaluating the long-term isolation capability of the Deep Borehole Disposal (DBD) concept. Engineering demonstration activities will focus on providing data to evaluate the concept's operational safety and practicality. Procurement of a scientifically acceptable DBFT site and a site management contractor is now underway.

The concept of deep borehole disposal (DBD) for radioactive wastes is not new. It was considered by the National Academy of Science (NAS 1957) for liquid waste, studied in the 1980's in the U.S. (Woodward–Clyde 1983), and has been evaluated by European waste disposal R&D programs in the past few decades (for example, Grundfelt and Crawford 2014; Grundfelt 2010). Deep injection of wastewater including hazardous wastes is ongoing in the U.S. and regulated by the Environmental Protection Agency (EPA 2001). The DBFT is being conducted with a view to use the DBD concept for future disposal of smaller-quantity, DOE-managed wastes from nuclear weapons production (i.e., Cs/Sr capsules and granular solid wastes). However, the concept may also have broader applicability for nations that have a need to dispose of limited amounts of spent fuel from nuclear power reactors. For such nations the cost for disposing of volumetrically limited waste streams could be lower than mined geologic repositories.

1. Deep Borehole Disposal Concept

DBD safety relies on emplacing wastes in competent crystalline rock well below the extent of naturally circulating groundwater. Whereas movement in groundwater is practically the only means for migration of radionuclides, if the groundwater has not moved for millions of years, then transport is limited to the mechanism of aqueous diffusion, a slow process. Diffusion-limited transport is the principle of isolation for mined repositories proposed at depths of 500 m in clay or shale, and salt. However, DBD would be situated at 3 to 5 km depth (Figure 1) in low-permeability granite or schist and therefore the radionuclide migration path distance would be at least an order of magnitude greater than for mined repositories (e.g., 1,000 m in the crystalline basement vs. 150 m in clay or shale). Hence, DBD offers the potential for exceptional waste isolation because the time for diffusive release to the biosphere is proportional to the square of distance.

The key to proving the potential effectiveness of DBD is to carefully analyze the environment at depth, to determine the origin and residence time of deep groundwater, and to understand why it has remained isolated. Natural cosmogenic tracers with long half-lives such as Ar-isotopes and

Kr-81 could be helpful because they can be used to estimate or bound the average time since a groundwater sample was at the earth's surface. Other tracers originate in the solid earth: accumulation of radiogenic He, and U-series equilibria, are indicators of long groundwater residence time. The Characterization Borehole will use state-of-the-art methods to characterize chemical and isotopic tracer signatures for interpretation of groundwater provenance and apparent age (SNL 2015a).

Another aspect of deep groundwater isolation pertains to the chemical composition of such waters, which are typically concentrated chloride brines with density from 2.5% (seawater) to more than 30% greater than pure water. Types of brine range from sodium chloride to calcium and magnesium chloride at higher density. The density gradient (fresh near the surface, concentrated at depth) is stabilizing and inhibits vertical flow or mixing. The inhibitive effect is well known where seawater invades near-surface groundwater aquifers. Density stratification would tend to limit the effects from future perturbations to hydrologic conditions such as climate change, or from early borehole heating by the waste. For example, ancient brines have been found in crystalline basement rock over a large area of the northern plains of North America, an area subjected to glaciation during the Pleistocene epoch.

Several causes have been proposed for deep brines: water-rock interaction (leaching), infiltration of cryogenic brines from large-scale freezing of seawater, and dissolution of evaporites (where present). The cause and age for specific occurrences may be inferred from their composition (e.g., Bottomley et al. 1999) or they may be undetermined. The simple existence of concentrated chloride brines in the crystalline basement is a general indicator of great age, especially when no evaporites are present in the geologic setting.

The presence of ancient, saline water in the basement suggests that waste isolation in deep boreholes may not depend critically on borehole seals above the waste disposal interval. Within the borehole and the disturbed rock zone (DRZ) within a few feet of the borehole, the permeability will be low and the potential radionuclide pathway will be long, limiting the rate of diffusion-dominated transport to the biosphere above. During the thermal period (a few decades to hundreds of years depending on waste type) there is the possibility for thermally driven buoyant convection which seals could help to mitigate. After cooldown, with fluid of similar composition in the borehole and formation re-establishing density stratification, the upward hydraulic gradient is likely to be very small or nonexistent regardless of the seals. Radionuclide transport under such conditions would be diffusion dominated and limited to long pathways and low permeability.

The DBFT will evaluate methods for sampling and testing in the Characterization Borehole to determine groundwater provenance and apparent age at the test site. The capability for safe handling and emplacement of waste in deep boreholes will be demonstrated, and borehole sealing materials and technologies will be evaluated.

2. Deep Borehole Field Test (DBFT)

Previous Investigations

The National Academy of Sciences (NAS 1957) identified deep injection as a promising method for disposal of liquid radioactive or mixed wastes. This was followed in the 1960's by a campaign of injection of cementitious waste slurries into shale, near Oak Ridge, TN. The Oak

Ridge disposal site was shallower (about 300 m) than proposed for deep boreholes. It was discontinued in the 1980's but continues to be monitored (DOE 2000).

A number of disposal options for radioactive waste were investigated in the 1980's in the U.S., including deep borehole disposal of commercial spent nuclear fuel (Woodward–Clyde 1983). That study was the first to propose a means for emplacing strings of waste packages, threaded together, using a drill rig (drill-string emplacement). Later studies evaluated drill-string emplacement for the Swedish waste program (SKB 1992). R&D programs for deep borehole disposal have been ongoing for several years in the U.S. and the U.K. (Sapiie and Driscoll 2009; Beswick et al. 2014). Technical leadership for the DBFT is provided by Sandia National Laboratories for the U.S. DOE, and builds on Sandia's DBD R&D activities which were started in 2009 (Brady et al. 2009).

There have been hundreds of deep-injection wells for wastewater and liquid hazardous waste in the U.S., licensed by the U.S. Environmental Protection Agency (EPA 2001). Approximately 500 to 600 wells have been put into service, with depths from 3,000 to 12,000 feet. The injection intervals are typically separated from underground sources of groundwater by multiple low-permeability confining units. Injection wells have double casings, double-cemented, to isolate the waste path from overlying units. Final sealing and plugging of these wells follows established procedures for oil-and-gas wells.

The Characterization Borehole, discussed below, resembles boreholes drilled for scientific research. Whereas oil-and-gas wells are nearly always drilled in sedimentary rock and may penetrate to 6 km or deeper, deep boreholes in crystalline rock are far fewer and are drilled for scientific R&D. Several of these deep boreholes drilled for scientific research are listed in Table 1. They are instructive for the DBFT because of the drilling and completion methods used, the states of *in situ* stress encountered, the frequency of borehole breakouts, the rock permeability encountered, production of hydrogen gas, and many other aspects.

Site Activities

Site activities for the DBFT are scheduled to begin in early 2016 after selection of a site and a site management contractor (DOE 2015). Site specific activities will begin with a phase in which drilling engineers, geoscientists, and support personnel plan the details of the initial Characterization Borehole. This vertical borehole will be drilled to approximately 16,400 feet (5 km), at a relatively small diameter (8.5 inches) to characterize the crystalline basement (Figure 2). The drilling phase (approximately 7 months) will include initial testing such as stem tests, hydraulic fracturing stress measurements, wireline logs, etc. Core will be obtained for 5% of the borehole length, in selected intervals emphasizing the crystalline basement and the contact with overlying strata if one exists. The Characterization Borehole will be lined with steel casing from the surface to a depth of approximately 2 km, and open hole below that for testing.

The testing phase (approximately 7 months) will follow, involving wireline logs while pumping, specialized low-permeability packer tests, tracer tests, and formation fluid sampling (SNL 2015a) (Figure 3). The actual scope of testing will depend on borehole observations such as the distribution of permeability and the extent of borehole breakouts. Other tests may be performed later, such as a borehole heater test at depth to characterize the potential for thermally convective flow in the DRZ around the borehole.

When sufficient experience has been acquired with drilling and testing in the Characterization Borehole in the crystalline basement, a decision will be made whether to proceed with planning and drilling a larger-diameter Field Test Borehole, or whether the Characterization Borehole can be used for the remaining DBFT activities. The primary purpose of the larger borehole will be to demonstrate drilling and construction methods that could be used for future waste disposal (at a different site). The combination of 17-inch diameter and total depth of 16,400 feet in crystalline rock is at the margin of the envelope representing worldwide drilling accomplishments.

The Field Test Borehole will have a guidance casing at constant diameter (nominally 13-3/8 inches) from top to bottom to provide a secure path for emplacing test packages (SNL 2015b). The upper 3 km of guidance casing, and the liner between 2 km and 3 km depth, will be removable as they would in a disposal borehole for installation of seals directly against rock. Selected logs and tests in the Field Test Borehole will be used to test predictions based on Characterization Borehole data. The hole will then be available for demonstration of emplacement and retrieval of test packages.

Engineering Demonstration

In addition to large-diameter deep drilling, demonstration activities will include design and fabrication of test packages, then emplacement and retrieval of a small number of packages in the Field Test Borehole (SNL 2015b). The packages will be thick-walled, welded vessels capable of resisting the downhole pressure (9,650 psi, bounded by a fluid column with 1.3× the density of pure water), with an appropriate factor of safety. Packages will have threaded and/or tapered plugs, sealed by welding. Packages will be unshielded in order to maximize the volume available for waste (in a disposal application). They will have connections on the ends so they can be joined in strings if desired. The connectors can also be used to attach impact limiters below, and latches for grappling from above (Figure 4).

Handling of waste packages at a future disposal site will require a shielded cask that can be up-ended and set onto a receiving flange at the borehole collar (Figure 5). The cask must have doors at both ends so the waste package can be lowered into the borehole. Such a cask may be designed only for package transfers to the borehole from transportation casks of existing designs.

Two basic options are available for emplacing waste packages in the borehole: 1) lowering single packages on a modern electric wireline of the type used offshore and in deviated wells (Figure 4); or 2) lowering strings of packages that are threaded together, using threaded sections of drill pipe handled with a workover rig (Figure 6). The wireline method is conceptually simpler, whereas the drill-string method would require installation of more extensive equipment under the rig ("basement") to contain the equipment for threading packages together, in addition to blowout preventers and mud handling.

A multi-attribute utility study was performed to compare the risks and costs associated with the two emplacement options identified, for disposal of 400 waste packages in a single, prototypical borehole. For each option, an event tree was constructed to represent possible outcomes including waste package drops, drill string drops, and packages becoming stuck above or within the designated disposal zone (Figure 7). A hazard analysis identified four types of initiating events involving package or drill-string drops, and getting packages stuck. These top-level initiating events were decomposed and probabilities developed using fault trees. A panel of subject matter experts developed the probability estimates needed for fault tree calculations, as well as estimates of the probability of breaching one or more waste packages during drops or fishing operations. Costs were estimated for the normal and off-normal outcomes including costs for fishing stuck packages, remediating contamination, and opportunity costs from termination of disposal operations.

The multi-attribute study produced a recommendation to use the wireline emplacement method, because the total probability of a breached package is estimated to be lower by a factor of about 55 for wireline emplacement versus drill-string emplacement, and the cost of wireline emplacement is estimated to be substantially less. The lower probability of a waste package breach with wireline emplacement results because lowering single packages involves much less weight and facilitates the use of impact limiters on every package. The formidable weight of a package string or a drill string is likely to breach waste packages in the event of an accidental drop. Costs for off-normal event recovery are dominated by delay and decontamination that would ensue from breaching a package. Although more trips are needed in and out with the wireline method, increasing the risk of becoming stuck, the trips are faster and the resulting minimal risk of breaching a package by an accidental drop leads to the preference for wireline over drill-string emplacement.

Planning for the engineering demonstration is proceeding with engineering contractors performing design studies, fabricating test packages, and developing a protoype handling/emplacement system. The objective is to demonstrate the entire process including test packages, handling and transfers, and emplacement/retrieval in the Field Test Borehole. The demonstration will emphasize developmental aspects unique to potential future waste disposal in deep boreholes. Package instrumentation will be used for monitoring of downhole conditions such as package temperature and acceleration. The demonstration will also focus on the working interface between nuclear materials handling specialists and borehole contractors (e.g., drilling, wireline logging) that would be required for future disposal operations.

Sealing Technology R&D

As discussed above, there is thought to be a need for borehole seals during the thermal period. Many sealing materials are available, and R&D is underway to understand the evolution of representative materials over hundreds to thousands of years. The current approach is to investigate the properties and stability of cementitious and clay-based materials (e.g., bentonite), starting with cements that are used in oil and gas wells because they are used successfully in deep boreholes. Properties and longevity can be effectively studied in the laboratory without the expense of *in situ* testing. Tests of emplacement methods could be implemented in shallower test wells. Eventually, a field test of seal emplacement could be performed at full depth of up to 10,000 ft (3 km).

Technology Challenges for the DBFT

An expert panel recently indicated that the Field Test Borehole is technically feasible (https://www.webcaster4.com/Webcast/Page/909/10895), but field experience is limited. The Field Test Borehole will advance international experience with drilling of large-diameter, deep boreholes in crystalline rock. Another challenge is sampling of deep formation water (free water and pore water) in sufficient quantities and with sufficient preservation of ambient quality for a range of chemical and isotopic analyses. This will be accomplished using an integrated approach that combines available borehole methods with the use of tracers in all fluids introduced to the Characterization Borehole.

Test packages will have a function that is unique to geologic disposal applications: containment with external pressure and corrosion, at downhole conditions (pressure, temperature, salinity). Staging of shielded casks over a borehole is a new requirement, especially if heavy shielding is used. Lowering of waste packages presents challenges in controlling pressure surge in the borehole, and in predicting package behavior in the event of a drop.

3. Postclosure Performance of DBD

The basis for waste isolation performance in deep boreholes was summarized by Brady et al. (2009): "...physical transport of radionuclides away from HLW and SNF at multi-kilometer depths would be limited by: low water content, low porosity and low permeability of crystalline basement rock, high overburden pressures that contribute to the sealing of transport pathways; and the presence of convectively stable saline fluids." Crystalline rock has low intact porosity and low matrix permeability, because previous metamorphic or igneous processes have determined the rock fabric. Hydraulic permeability is dominated by fractures that form due to injection or tectonics, but which are at least partially closed by *in situ* stresses acting at depth. The presence of ancient saline groundwater is evidence for static hydrology over geologic time, and it resists convective circulation that might be caused by changes in the hydraulic head gradient (vertical or lateral), surface loading, or localized heating. Such stable conditions have been represented in idealized, generic (non-site specific) projections of waste isolation performance (Arnold et al. 2013, Freeze et al. 2015). More advanced mechanistic studies of potential perturbations are underway, supported by systematic development and screening of features, events and processes (FEPs) specific to borehole disposal (Brady et al. 2009). Some of these processes are discussed further below.

Thermally driven convective circulation is included in thermal-hydrology simulations (Hadgu et al. 2015) which show that the magnitude and duration are likely to be insignificant. Thermal convection is sensitive to changes in permeability, but only if assigned much greater values of permeability than are expected to be present along potential transport pathways. Permeability is an important parameter to be investigated by the DBFT Characterization Borehole.

Corrosion of metals, cement, and other engineered materials is potentially significant during disposal operations (e.g., the first few years) when it is important that packages provide containment, and that disposal zone geometry is preserved. However, after permanent closure (i.e., after sealing and plugging of a disposal borehole) such containment may not be as important, and it is not included in current predictive models of waste isolation performance. The disposal zone will eventually be filled with corrosion products (e.g., magnetite) and residues from degradation of cements and waste forms. Consolidation of this mixture may occur to the extent that any significant voids remain. Long-term degradation behavior of engineered materials in the disposal zone, and other sealing and plugging materials, is being addressed by laboratory studies associated with the DBFT.

Corrosion of metals in water at reducing conditions in the disposal zone will produce hydrogen (Grundfelt and Crawford 2014). Some H_2 will dissolve in water at *in situ* pressure, but mass balance arguments show that the total H_2 production will exceed solubility in the borehole, and that the rate of production might exceed the rate that H_2 can diffuse away from the borehole (see Neretnieks 2010). Expulsion of contaminated fluid into the overburden has been proposed as the endpoint for a H_2-generation scenario (Grundfelt and Crawford 2014). However, this may essentially be a material selection problem, and there are slowly corroding materials available (e.g., stainless steel casing). Also, experience with oil and gas wells suggests that well-cemented casing corrodes slowly even in aggressive chemical environments (with appropriate choice of cement). In addition, buildup of H_2 pressure will eventually dissipate and H_2 gas generation would likely never lead to unworkable requirements on disposal zone completion. This issue will be examined further during the course of the DBFT.

4. Closing Discussion

Technical criteria for selection of the DBFT location include attributes such as maximum depth of 2 km to the top of the crystalline basement and evidence for ancient groundwater at depth (DOE 2015). The DBFT Characterization Borehole and associated scientific investigations are planned to determine whether these technical attributes exist, and to demonstrate the use of state-of-the-art methods for obtaining supporting measurements and samples. These activities are scheduled to get underway in early 2016, with borehole completion by mid-2017 and downhole scientific testing in the following months. A program of sampling and testing activities has been prepared for planning purposes (SNL 2015a), but will be reviewed in 2016 with site management and the drilling contractor support team.

Planning for engineering demonstration activities is underway, and conceptual design will be completed in mid-2016. Final design activities will follow, then prototype fabrication and testing, system integration testing, and finally field demonstration in 2018 or 2019. The demonstration will evaluate prototype test package performance, and evaluate the selected system for package handling, transfer, emplacement and retrieval. The demonstration will generate new information on technical performance, operational efficiency and safety, and cost that will support a feasibility evaluation for future DBD projects.

At the conclusion of drilling, construction, downhole testing and field demonstration activities, the DBFT boreholes and field site will be available for additional R&D. This might include transfer of ownership to an entity such as an institute or university, to be used for downhole testing or as an observatory.

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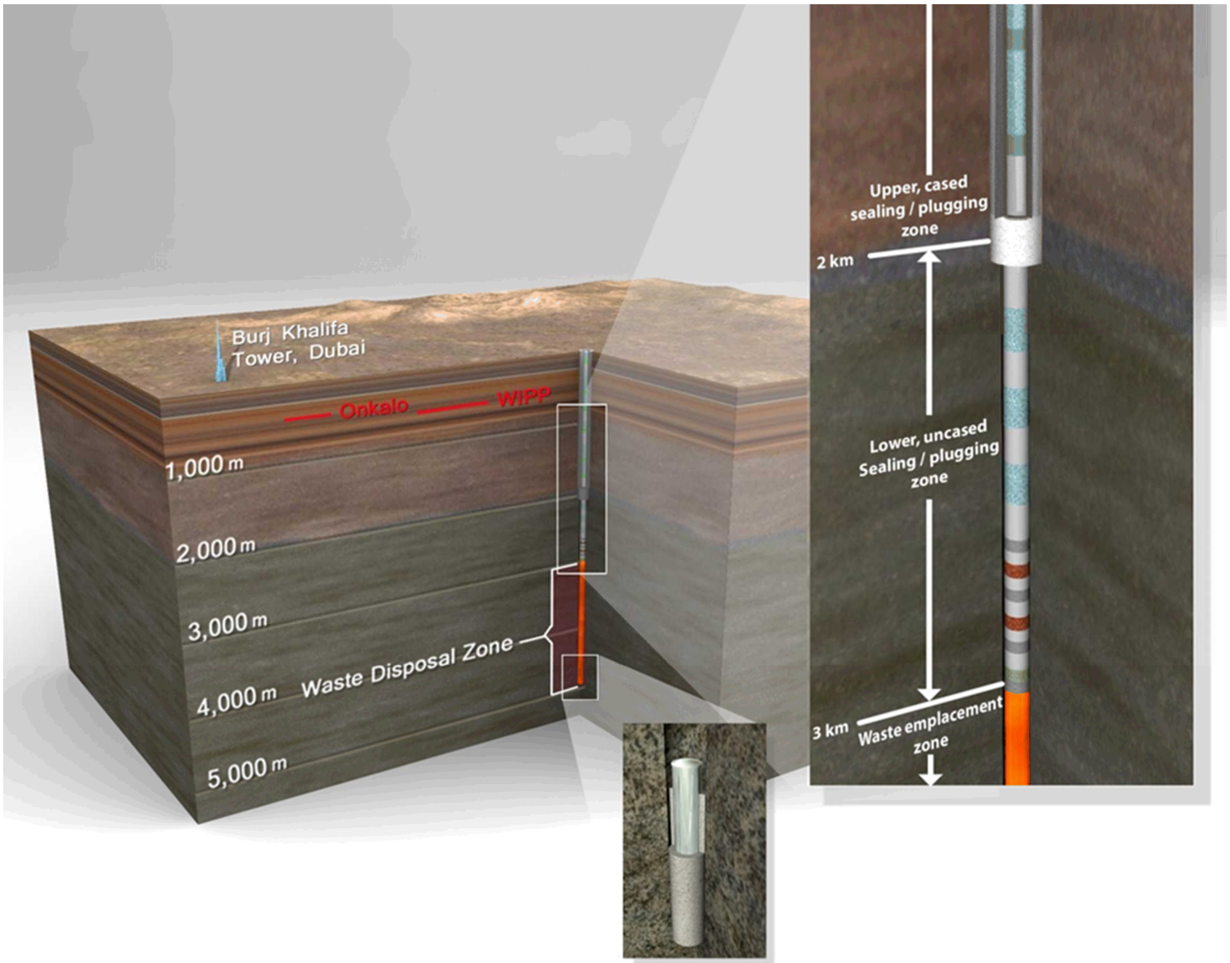

Figure 1. Schematic of deep disposal borehole depicting sealing and plugging.

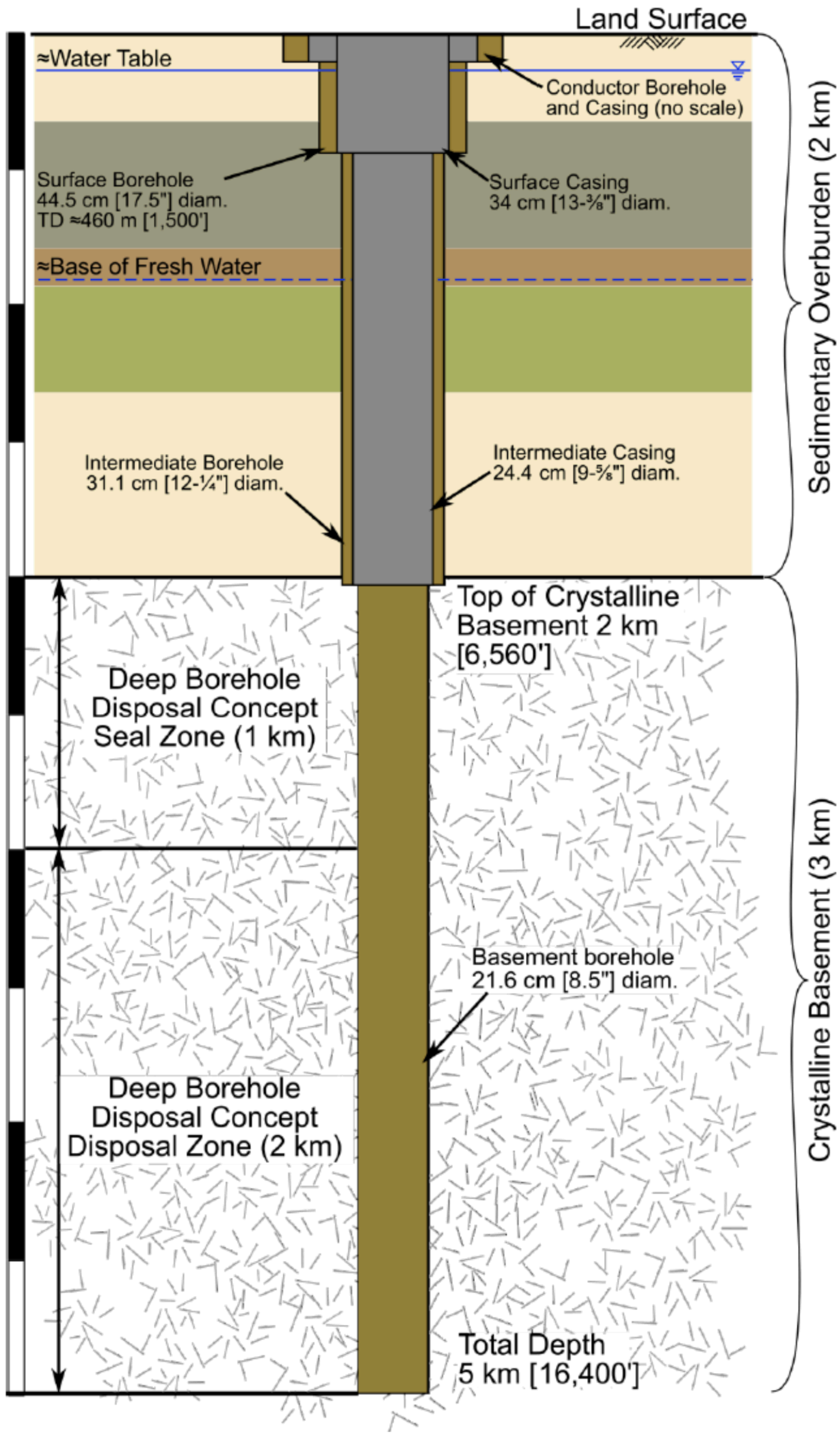

Figure 2. DBFT Characterization Borehole diameter and casing plan.

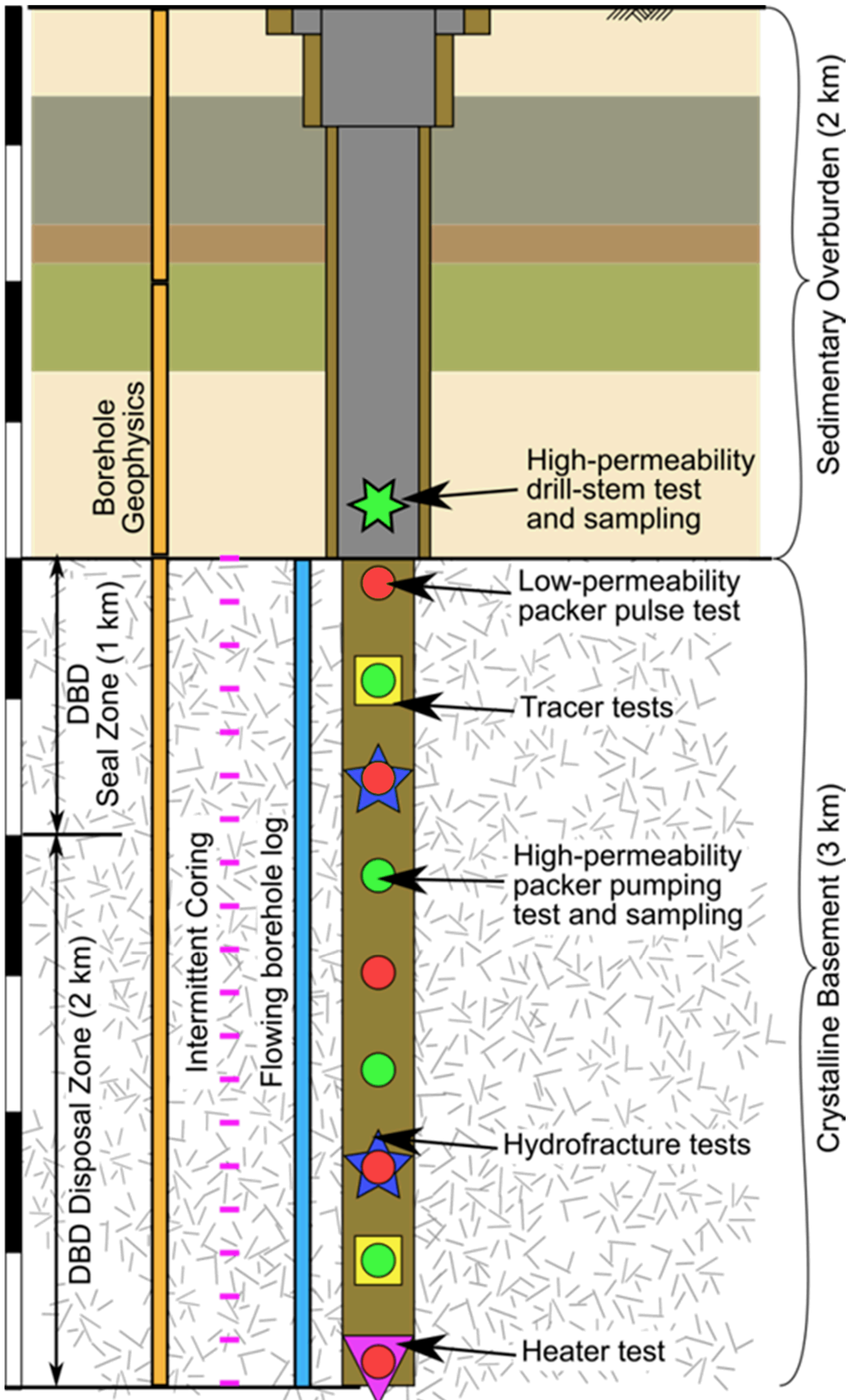

Figure 3. Schematic of sampling and measurement locations planned for the Characterization Borehole.

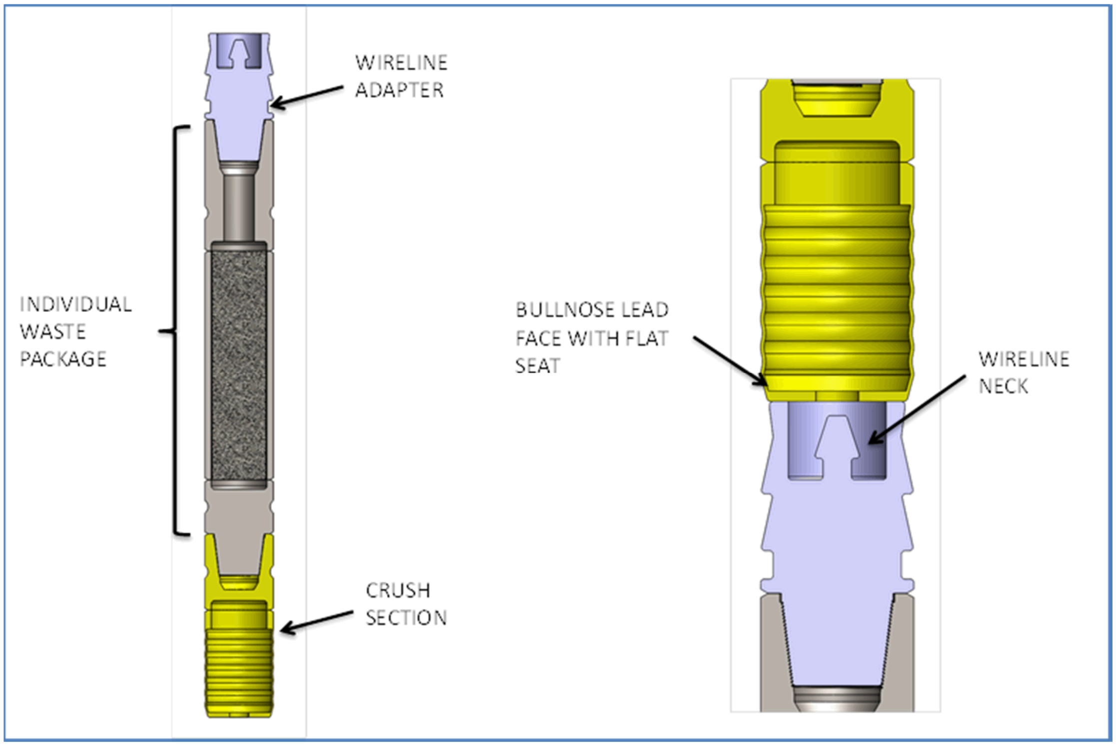

Figure 4. Conceptual design for waste packaging with threaded ends for connecting packages in strings, or for attachment of adapters and impact limiters to single packages (package length not to scale).

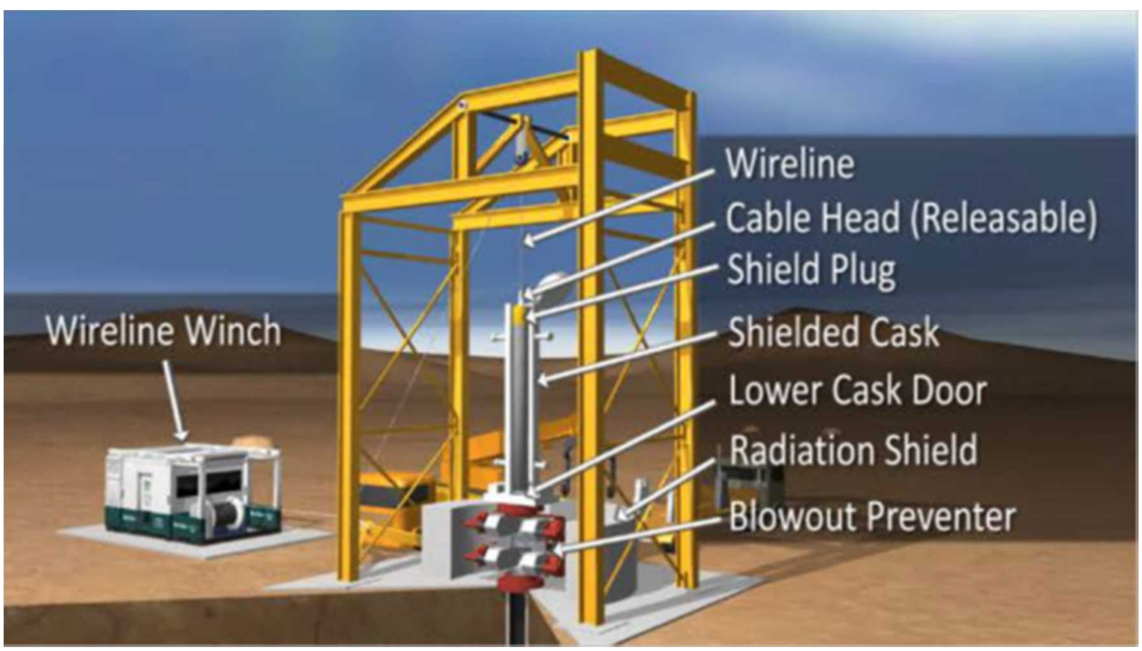

Figure 5. Visualization of wireline method for waste package emplacement

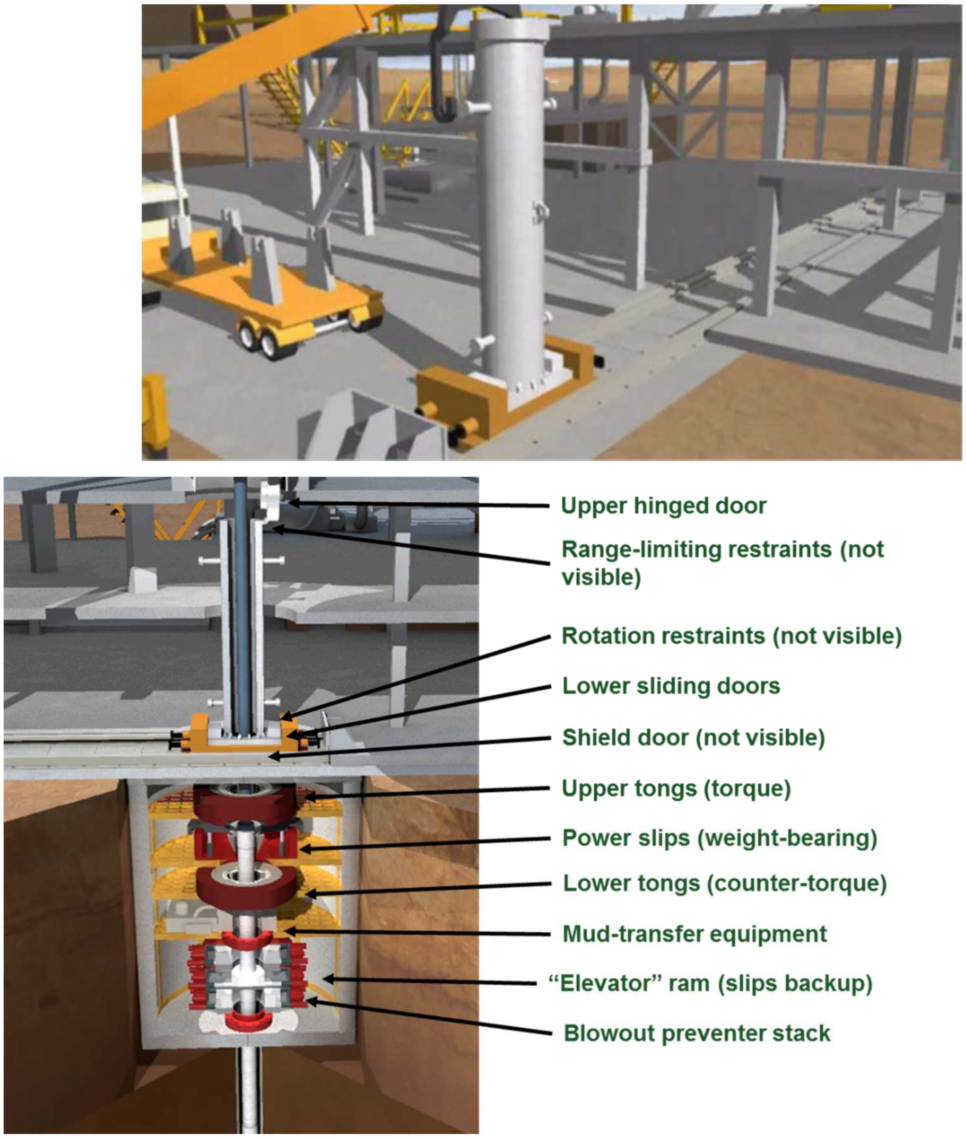

Figure 6. Visualization of drill-string method for waste package emplacement: (upper) waste package in shielded transfer cask, installed on carrier car to be translated under the drill rig; and (lower) rig basement showing specialized equipment for assembling strings of waste packages, threaded together, for lowering in the borehole on drill pipe.

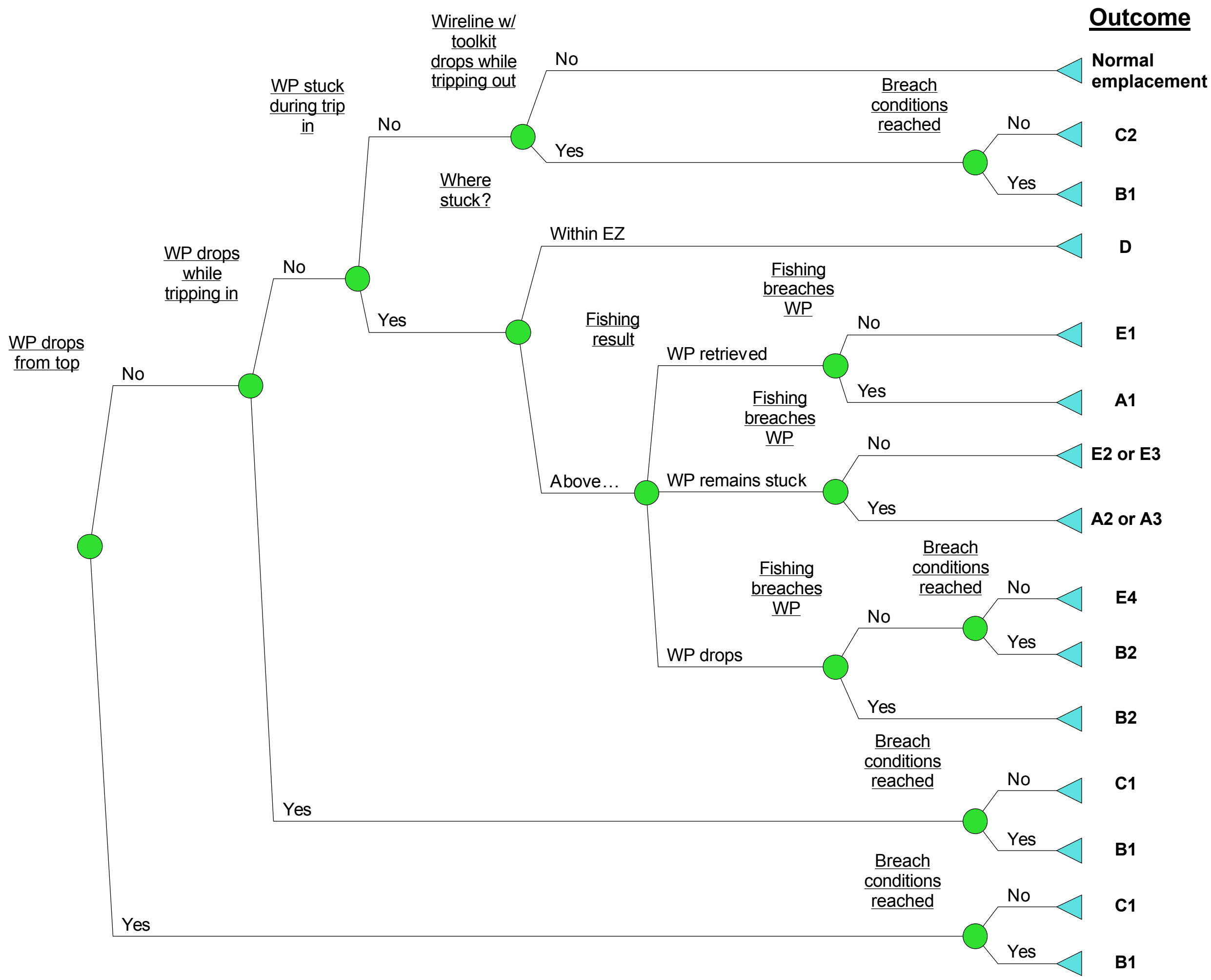

Figure 7. Event tree for preclosure operations, wireline emplacement.

Table 1. Summary of selected deep scientific drilling projects conducted internationally.

Site	Location	Years	Depth [km]	Diam * [in]	Purpose
Kola SG-3	NW USSR	1970-1992	12.2	8½	Geologic Exploration + Tech. Development
Fenton Hill	New Mexico	1975-1987	4.6	9⅞	Enhanced Geothermal
Urach-3	SW Germany	1978-1992	4.4	5½	Enhanced Geothermal
Gravberg	Sweden	1986-1987	6.6	6½	Gas Wildcat
Cajon Pass	S California	1987-1988	3.5	6¼	Geologic Exploration
KTB	SE Germany	1987-1994	9.1	6½	Geologic Exploration + Tech. Development
Soultz-sous-Forêts GPK	NE France	1995-2003	5.3	9⅝	Enhanced Geothermal
SAFOD	Central California	2002-2007	4 (3)#	8¾	Geology Exploration
Basel-1	Switzerland	2006	5	8½	Enhanced Geothermal

* borehole diameter at total depth
# true vertical depth