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SITE CHARACTERIZATION FOR A DEEP BOREHOLE FIELD TEST

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Deep Borehole Disposal (DBD) of radioactive waste has some clear advantages over mined repositories, including incremental construction and loading, enhanced natural barriers provided by deep continental crystalline basement, and reduced site characterization. Unfavorable features for a DBD site include upward vertical fluid potential gradients, presence of economically exploitable natural resources, presence of high permeability connection from the waste disposal zone to the shallow subsurface, and significant probability of future volcanic activity. Site characterization activities would encompass geomechanical (i.e., rock stress state, fluid pressure, and faulting), geological (i.e., both overburden and bedrock lithology), hydrological (i.e., quantity of fluid, fluid convection properties, and solute transport mechanisms), chemical (i.e., rock and fluid interaction), and socio-economic (i.e., likelihood for human intrusion) aspects. For a planned Deep Borehole Field Test (DBFT), site features and/or physical processes would be evaluated using both direct (i.e., sampling and in-hole testing) and indirect (i.e., surface and borehole geophysical) methods for efficient and effective characterization.

Surface-based characterization would be used to guide the exploratory drilling program, once a candidate DBFT site has been selected. Borehole based characterization will be used to determine the variability of system state (i.e., stress, pressure, temperature, petrology, and water chemistry) with depth, and to develop material and system parameters relevant for numerical simulation. While the site design of DBD could involve an array of disposal boreholes, it may not be necessary to characterize each borehole in detail. Characterization strategies will be developed in the DBFT that establish disposal system safety sufficient for licensing a disposal array.

I. INTRODUCTION

DBD of Spent Nuclear Fuel (SNF) and High-Level Waste (HLW) has been considered as an option for geological isolation for many years[1,2,3], beginning with evaluations by the US National Academy of Sciences in 1957[4]. The generalized DBD concept is illustrated in Figure 1. The concept consists of drilling a borehole (or array of boreholes) into crystalline basement rock to a depth of about 5 km, emplacing waste canisters in the lower 2 km of the borehole, and sealing the upper 3 km of the borehole. The disposal zone in a single borehole could contain 400 5-m waste canisters. As shown in Figure 1, waste in the DBD system is several times deeper than typical mined repositories, resulting in greater natural isolation from the surface and near-surface environment. The borehole seal system would consist of alternating layers of compacted bentonite clay and concrete.

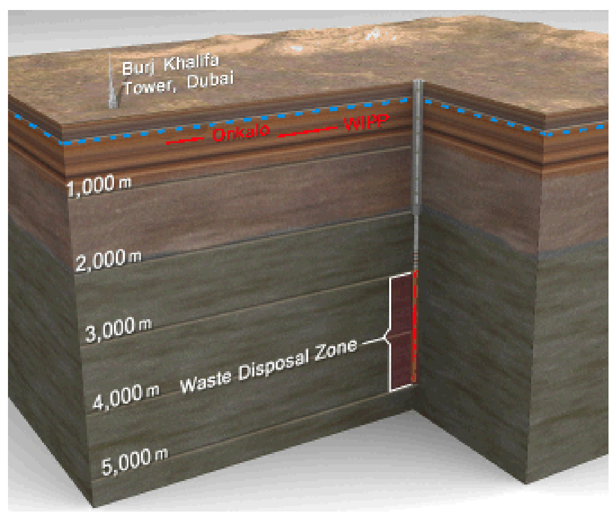

Fig. 1. Generalized concept for Deep Borehole Disposal of radioactive waste[5,6]; dashed blue line indicates lower limit of typical fresh water

Factors suggesting DBD of SNF and HLW is inherently safe include several lines of evidence indicating crystalline-basement-rock groundwater at depths of several kilometers has long residence times, high salinity, and minimal convection. Stratified high-salinity fluids have limited potential for vertical flow. Salinity prevent colloidal transport of radionuclides. Geochemically reducing conditions in the deep subsurface stabilize low solubility phases and enhance the retardation of key radionuclides. Other advantages of DBD over mined repositories are incremental construction and disposal at multiple regional locations. As directed by the US Department of Energy Used Fuel Dispostion Campaign, a DBFT is being planned to confirm the safety and feasibility of the concept[7,8].

The DBFT site characterization will include both surface and downhole methods, covering geomechanical, geological, hydrological, and geochemical aspects of the borehole-disturbed bedrock zone.

II. GEOLOGICAL CHARACTERIZATION

Geological characterization includes lithology, mineralogy, physical properties, fracture characterization, and delineation of faults and structures in the subsurface. Characterization information can be obtained from surface-based methods prior to drilling. Besides standard surface-based remote sensing methods, standard downhole geophysical and logging methods from the petroleum and mineral exploration industries would be used to characterize the geology at depth.

Understanding large-scale faults or fractured zones is critical to identifying interconnected zones of high permeability from the waste disposal zone to the surface or shallow subsurface. A high-permeability pathway from the waste disposal zone to the shallow subsurface could facilitate radionuclide transport, particularly by thermally driven flow during the period of high heat output by the waste. A focus of site characterization will be to identify any of these preferential pathways intersecting the borehole at depth.

II.A. Surface-Based Characterization

Surface-based characterization includes ground-based and airborne surveys, which measure either naturally occurring anomalies (gravitational or magnetic) or variations in the electrical resistivity or seismic wave velocity of the subsurface. In general, surface-based characterization is the first step to confirming that a site is potentially suitable. For example, detailed mapping of the basement rock from existing geologic data and new geophysical profiles will help determine if the basement rock is deep or shallow enough to be suitable for a DBFT. It can also be used to evaluate the existence of transmissive pathways from the waste disposal zone to the surface or shallow subsurface.

Surface-based characterization methods may include: 3D seismic surveys, microgravity surveys, aeromagnetic surveys, electrical resistivity surveys, self-potential surveys, and surface geological mapping. All of these would be used to evaluate suitability of the specific site. If results are suitable, surface-based characterization can also guide the drilling program to locate the hole and plan drilling (e.g., estimate depth to crystalline basement).

II.B. Borehole Characterization

During and after borehole drilling, down-hole based characterization can be used for more detailed site characterization. In addition, some features (e.g., mineralogy, porosity, and other petrophysical characteristics) cannot be evaluated without borehole-based characterization.

Borehole characterization methods can infer characteristics of the drilled borehole itself, the formations intersected by the borehole, and pore fluids collected at various depths. Some methods only interrogate the borehole disturbed zones. Others can penetrate deep into the surrounding formations. Data from these methods provide insight into thermal, hydrologic, and geologic properties such as thermal conductivity, porosity, permeability, fracture spacing and aperture, lithology, mineralogy, water quality and composition. Examples of borehole characterization methods include geophysical logging, logging of drill cuttings, coring of boreholes, hydrologic testing, thermal testing, and water sampling and analyses. Borehole logging methods include some of the standard methods listed below. These logging methods provide information on lithology, porosity, fractures, and structure for general characterization of the rocks penetrated by the borehole.

During drilling, rock cores will be collected at intervals to provide samples for geologic characterization, laboratory thermal/mechanical/hydrologic/chemical testing, and extraction of *in situ* pore water samples. In other intervals of the borehole, samples from drill cuttings and rock flour can be characterized using X-ray fluorescence and X-ray diffraction[9]. The drilling fluid will be regularly sampled and analyzed for dissolved species and gas content. During drilling deviation surveys will be used help ensure a straight borehole.

Borehole-based geophysical logging methods will likely include: nuclear magnetic resonance, induction and laterolog resistivity, spontaneous potential, neutron porosity, formation micro-imager, borehole televiewer, natural gamma, and gravity. After cementing casing across any portions of the borehole, cement bond logs would be run to assess the quality of the cement emplacement (i.e., find voids behind the casing).

III. HYDROGEOLOGY

Hydrogeological characteristics of the disposal and sealing horizons should be determined to populate performance assessment (PA) numerical models. These characteristics include permeability, flow porosity, fluid pressures, vertical hydraulic gradient, solute transport properties, and characteristics of the disturbed rock zone. In particular, deep overpressured conditions or vertically conductive fracture zones connecting to shallower aquifers, would be detrimental to safe performance of the disposal system. Evidence that deep waters are briney, reducing, and very old (i.e., isolated from shallow water over geologic time) would support the safety case for DBD and provide bases for PA modeling. Some of the downhole methods are standard testing techniques, but some would require adaptation to provide the information needed within a DBFT. Particular care will be used to obtain representative samples of deep fluids that have not been either (a) contaminated by drilling mud or fluids (water or gases) from other, stratigraphically higher, formations, or (b) re-equilibrated (e.g., degassed, solutes precipitated) extensively upon removal to the surface.

III.A. Drill Stem Tests of Shut-In Pressure

Drill stem tests (DST) are common in the drilling industry, providing three basic pieces of information on the host formation: formation pressure, formation permeability, and water chemistry. DST equipment consists of a down-hole pressure measurement, surface-controlled flow control valves, and a down-hole sampling device placed in the drill pipe.

Ambient fluid pressure in the rock formation surrounding the borehole is the shut-in pressure. After the packer system is inflated to isolate the test interval a valve is opened allowing equilibration of fluid pressure within the drill stem and the formation. Fluid pressure is monitored until it stabilizes. Drilling will alter fluid pressures within the formation and the equilibration process allows such anomalous pressures to dissipate. Assuming the volume and compressibility of permeable rock hydraulically connected to the borehole is sufficient to bring the water in the borehole and its disturbed zone back up to static formation pressure, measurements would represent the undisturbed conditions.

Accurate measurements of ambient formation pressure are used to determine vertical hydraulic gradients in the system and to develop an overall conceptual model of groundwater flow in the hydrogeological system. Fluid pressure measurements in combination with fluid density and viscosity (determined by water temperature and salinity) as a function of depth are used to calculate the fluid potential profile along the vertical extent of the borehole. Vertical gradients in fluid potential are the driving force for vertical fluid movement. Maintenance of overpressured or underpressured conditions across geologic time indicates very low vertical permeability. Overpressured conditions would indicate the long-term potential for upward migration of groundwater, which is undesirable for a disposal system. Hydrostatically stable or underpressured conditions between the disposal zone and the shallow groundwater system are favorable natural conditions for the safety case of a DBD system.

III.B. Drill-Stem Slug and Pumping Tests

Drill-stem slug and pumping tests are both conducted for shorter periods of time than packer pumping tests and are executed with the drill string still in the borehole. These tests are used to determine the hydrologic properties of formations and performance characteristics of boreholes. The hydrologic properties determined include horizontal and vertical permeability, formation compressibility.

Drill-stem-slug and pumping tests consist of rapid pressure drawdown in a packed-off borehole interval, followed by a pressure recovery period, during which pressure and flow rate are measured. Analogous fluid injection and pulse tests can also be performed. Formation properties are estimated from the pumping test by evaluating pressure and flowrate data for an interval using analytical and numerical flow solutions to constrain the best-fit hydrologic parameters. Results from drill-stem-slug and pumping tests may have significant uncertainties due to short test durations, small test volumes, test interval skin from drilling mud invasion, and leaks from packers.

III.C. Packer Pumping Tests

Packer pumping tests commonly include surrounding guard zones and are generally longer-duration and better controlled hydraulic tests than drill-stem pumping tests. Packer pumping tests are performed after the borehole is completed and use inflatable packers to seal the annular space between the packer pipe and the borehole wall, isolating an open interval to be evaluated. Additional equipment includes a pump to inflate and/or deflate the packers, a sampling pump, flow meters, and pressure gauges. Because packers can be deflated, moved to other locations in the borehole, and re-inflated they can be used to conveniently determine the vertical distribution of hydraulic system parameters.

There are a number of considerations associated with packer inflation that require special attention when applied to the depths associated with a deep borehole. These relate to the method used to inflate the packer and the proper sizing of lines and pumps. The packer inflation pressure must be sufficient to expand the packer gland against the borehole wall and it must overcome hydrostatic pressure at depth. Therefore, the inflation pressure required will vary significantly over the 3 km of bedrock in the borehole.

Packers are commonly made of rubber which should be kept below ~120°C; they can be damaged by scraping against sharp portions of the borehole wall. Any leakage around packers will compromise the measurements. Leakage may occur at the packer-wall interface or in the supply lines. The potential for leakage increases with depth because of the increased sealing pressures to inflate the packer and lower formation permeability leading to longer equilibration times. If packers are overinflated they can burst or damage the borehole. The packer's thermal limits should pose no restriction on testing unless they might be used in combination with electrical heater tests. The other operational issues can be minimized by careful testing procedures.

Three common packer testing methods are:

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

2) Discharge Tests: The isolated zone is pumped and water discharged from the borehole with the decay in formation pressure recorded after an equilibration period.

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

III.D. Vertical Dipole Tracer Testing

Vertical dipole tracer testing consists of injecting a dissolved tracer into a packed-off borehole interval followed by pumping and measuring tracer concentration from another interval in the same borehole[10,11]. Solute transport that would occur vertically through the rock mass between the injection interval and the pumping interval and around the intervening packer interval in the borehole, as shown in Figure 2. *In situ* transport properties of the rock mass are determined from the observed breakthrough curve of the tracer in the extraction interval.

This tracer testing method has the advantage of using a single borehole, versus at least two wells required in traditional cross-hole testing. The vertical dipole tracer testing method also interrogates the solute transport characteristics of the borehole disturbed zone immediately adjacent to the packed borehole, which may be a primary pathway for vertical migration of radionuclides from a disposal system.

Radionuclide solute transport properties in fractured crystalline host rock that can be derived from a vertical dipole tracer test include flow porosity, dispersivity, sorption coefficient, and matrix diffusion rate. Multiple tracers with contrasting values of molecular diffusion coefficient and sorption coefficient can provide stronger evidence of matrix diffusion and better constrained values of transport parameters in the modeling analysis of the tracer test results[10,12].

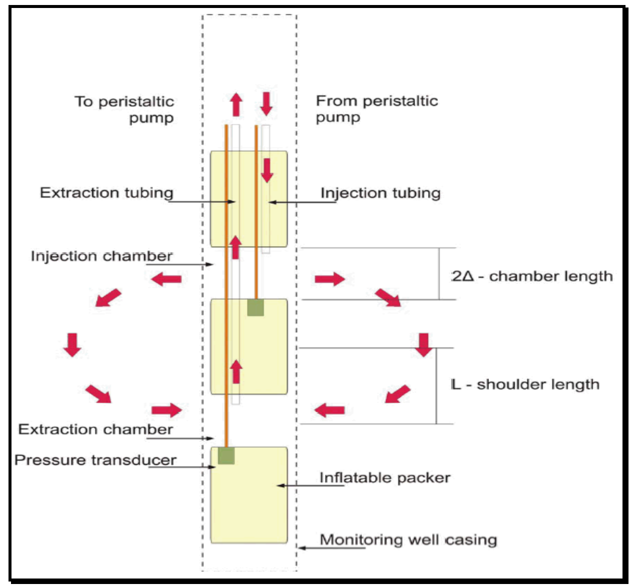

Fig. 2. Schematic Diagram of the Vertical Dipole Tracer Test Configuration[13].

III.E. Push-Pull Tracer Testing

Push-pull tracer testing (also referred to as single-well injection-withdrawal tests) consists of injecting tracer solution into the host rock and then extracting groundwater from the same borehole interval. A rest period between injection and extraction may be included in the test to allow more time for the tracer to diffuse into the rock matrix and allow transport via advection under ambient flow conditions[14].

Analysis of the tracer extraction breakthrough curves provides information on dispersivity, matrix diffusion, reaction rates for reactive tracers, and ambient groundwater flow rates. For push-pull tracer tests in porous media without any rest period, the tracer follows approximately the same pathway back during the withdrawal phase that it followed into the rock formation during the injection phase. In this case, the shape of the withdrawal breakthrough curve is governed by small-scale, local dispersivity[15].

For these tests in fractured porous media, tracer mass exchange between groundwater in the advectiondominated (fracture) and diffusion-dominated (matrix) portions of the rock plays an important role in tracer recovery[16]. A multi-rate model of matrix diffusion, related to the heterogeneous size of matrix blocks, is required to explain the tracer breakthrough curve in many systems[17,18]. Interpretation of push-pull tracer test results may be complicated by the overlapping effects of dispersive and diffusive processes in highly heterogeneous fractured rocks[19].

IV. GEOMECHANICS

Stress conditions, primarily the difference between minimum and maximum horizontal stresses, are important at the depths of DBD and will be evaluated in the DBFT. Mechanical behavior of the host rock and the borehole stability directly affect ease of drilling and casing the borehole. The local stress state at depth reflects the regional tectonic regime and can influence the extent of the disturbed rock zone, the ability to demonstrate canister placement/retrieval in a DBFT, and ultimately the long-term isolation of radionuclides in a DBD system.

IV.A. Borehole Caliper and Imaging Logs

Borehole caliper logging and borehole televiewer or formation microimager logging provide measures of the condition of a borehole – indicating breakouts, tensile fractures, cave-ins or swelling. The measuring tools determine the size and shape of the borehole through mechanical, sonic, or electrical observations.

Borehole caliper logging would be used in DBFT to determine the integrity of the well, where casing or cementation is needed, and identifying larger fractures. The orientations and extent of borehole breakouts and tension fractures provide information on the direction of the maximum and minimum principal horizontal stress and some indication of the difference in the magnitudes of these stresses[20].

IV.B. Dipole Shear-Wave Velocity Log

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

V. GEOCHEMISTRY

The chemical and isotopic compositions of deep groundwater help establish groundwater age, degree of long-term isolation, redox conditions, degree of equilibration with host rock, and solution speciation. These in turn are used to evaluate the expected degree of deep fluid interaction with shallower aquifers, the potential for canister corrosion, waste form mobilization, and chemical transport from a disposal zone.

V.A. Fluid Samples from Packer Testing

In situ fluid samples can be obtained through packer pumping tests, drill stem pumping tests, and key first-strike water sampling performed while drilling. Special care will be taken to obtain representative groundwater samples that are not contaminated by drilling fluids or other formation water and surface gases.

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

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

Environmental and isotopic tracers will be analyzed to build models of groundwater provenance, groundwater residence times, flow rates through the system, and the interaction of deep groundwater flow with the shallow hydrosphere. Fracture fluids will be sampled for stable isotopes of water (δD, $\delta^{18}O$), dissolved noble gas isotopic compositions, ^{36}Cl and ^{129}I concentrations. Core samples will be taken to determine pore fluid helium isotopic concentrations and the helium, neon, and argon isotopic compositions of minerals and fluid inclusions. Special sampling techniques, such as maintaining pressurization, are required to obtain representative fluid samples for dissolved gas tracers. Depressurization and cooling of sampled fluids is accompanied by degassing and mineral precipitation that may alter solution composition at the surface. Reconstruction of fluid composition at conditions at depth (at pressure and temperature) could be accomplished from quantitative analysis of exsolved gases and precipitated solids, facilitating analysis of fluid-rock equilibria at depth in the DBFT.

VI. HEAT TRANSFER

Temperature and thermal gradient data are important for determining the physical conditions at depth and the potential for future exploitation of geothermal resources at the site. In addition, high-resolution temperature logging in combination with fracture locations can be used to identify and quantify zones of groundwater inflow and outflow in the borehole. Data collected during DBFT heater testing provides information on the thermal/mechanical properties of the host rock used to evaluate maximum projected temperatures of waste canisters in DBD.

VI.A. Borehole Temperature Log

Temperature logging data are acquired generally after drilling, however continuous downhole temperature measurements during drilling are also possible. Temperature logs can also be recorded as a function of time after drilling and casing to correct prior temperature data that were perturbed by the drilling process. The DBFT may use distributed temperature sensing systems to measure simultaneously temperatures over the length of the permanently deployed fiber optic cable[21,22].

Temperature data will be used to calculate fluid viscosity and density, apply thermal corrections to other geophysical logs, assess geological basin hydrodynamics, identify zones of fluid inflow, and detect zones of potential overpressure in DBFT. In groundwater studies temperature logs are used in conjunction with fracture imaging tools to identify zones of active inflow and outflow from the wellbore, particularly in fractured media, to determine intra-well flow, and to delineate patterns of vertical flow in regional groundwater flow systems. Temperature logs are used in geothermal exploration and production to delineate high-temperature resources, calculate energy content of the system, estimate in situ thermal conductivity of the rock, and identify productive fracture zones. Borehole temperature logging is also used to estimate geothermal heat flux, to infer paleoclimatological conditions, and to study tectonic and volcanic systems.

VI.B. Mockup Canister Electrically Heated Test

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

VII. SUMMARY

We present a suite of surface and borehole investigative methods to be used in a Deep Borehole Field Test characterization program. One of the proposed advantages of the DBD concept is the high level of containment provided by the geologic system, which allows more localized characterization programs for DBD than mined waste repositories.

Deep borehole characterization differs from mined repository characterization in similar lithology as follows:

1. Detailed mapping of small-scale fracture patterns and distributions as in a mined repository is not needed in DBD.
2. Because the deep borehole is filled with water or drilling mud, it avoids the steep pressure gradients (atmospheric pressure) and multiphase (air + water) flow complications of a mined repository.

Deep borehole characterization/siting differs from hydrocarbon or mineral exploration borehole characterization as follows:

1. Hydrocarbon and mineral exploration are rarely conducted in basement granite plutons, the ideal lithology for deep boreholes. A lack of exploitable resources is a desirable DBD quality.
2. Most resource exploitation is seeking hydraulically conductive units or is typically associated with hydrothermal alteration (often connected to permeable pathways for regional water circulation). Low host-rock permeability is a desirable DBD site attribute.

Deep borehole characterization/siting differs from geothermal exploration efforts as follows:

1. Traditional geothermal reservoirs are associated with elevated geothermal gradients and permeable rock, which are to be avoided for a DBD site.
2. Enhanced geothermal reservoirs may be viable in less steep geothermal gradient areas, but would not be profitable in low geothermal gradient, low permeability rocks, such as those sought for DBD.

Overpressure fluid conditions at depth are also typically advantageous for resource exploitation (hydrocarbon or geothermal development), but would be undesirable for DBD sites.

The nature of the DBD concept allows some high-level simplifications to the siting and characterization process for disposal of radioactive waste. In DBD, the characterization process primarily seeks to confirm (a) the absence of high-permeability pathways to shallow aquifers, (b) the age, salinity, and reduced condition of pore water at depth, and (c) the existence of a low geothermal gradient. These points can be confirmed readily in a borehole through existing characterization technologies as will be demonstrated in a DBFT. This flexibility allows a DBD project to thoroughly characterize a site for a safety case and to move efficiently to the disposal phase is successful, or to efficiently reject a site if not. This can be contrasted with the extended (sometimes multiple decades) characterization period in mined repositories (e.g., the site-specific underground research laboratory).

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REFERENCES

1. M. T. O'BRIEN, L. H. COHEN, T. N. NARASIMHAN, T. L. SIMKIN, H. A. WOLLENBERG, W. F. BRACE, S. GREEN, and H. P. PRATT, *The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste Disposal*. LBL-7089, Lawrence Berkeley Laboratory: Berkeley, CA (1979).
2. WOODWARD-CLYDE CONSULTANTS, *Very Deep Hole Systems Engineering Studies*. ONWI-226, Office of Nuclear Waste Isolation: Columbus, OH (1983).
3. C. JUHLIN and M. SANDSTEDT, *Storage of Nuclear Waste in Very Deep Boreholes: Feasibility Study and Assessment of Economic Potential*. SKB 89-39, Svensk Kärnbränslehantering AB: Stockholm Sweeden (1989).
4. H. H. HESS, J. N. ADKINS, W. B. HEROY, W. E. BENSON, M. K. HUBBERT, J. C. FRYE, R. J. RUSSELL, and C. V. THEIS, *The Disposal of Radioactive Waste on Land, Report of the Committee on Waste Disposal of the Division of Earth Sciences*. Publication 519, National Academy of Sciences - National Research Council: Washington, D.C. (1957).
5. P. V. BRADY, B. W. ARNOLD, G. A. FREEZE, P. N. SWIFT, S. J. BAUER, J. L. KANNEY, R. P. RECHARD, and J. S. STEIN, *Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2009–4401, Sandia National Laboratories: Albuquerque, NM (2009).
6. B. W. ARNOLD, P. V. BRADY, S. J. BAUER, C. HERRICK, S. PYE, and J. FINGER, *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011–6749, Sandia National Laboratories: Albuquerque, NM (2011).
7. DOE, *Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel*, US Department of Energy: Washington, D.C. (2014).
8. SNL, *Project Plan: Deep Borehole Field Test*, FCRD-UFD-2014-000592, Rev 0, US Department of Energy Used Fuel Disposition Campaign: Albuquerque, NM (2014).
9. R. EMMERMANN and J. LAUTERJUNG, "Double X-Ray analysis of cuttings and rock flour: a powerful tool for rapid and reliable determination of borehole lithostratigraphy", *Scientific Drilling* 1(6):269–282 (1990).
10. W. E. SANFORD, P. G. COOK, and J. C. DIGHTON, "Analysis of a vertical dipole tracer test in highly fractured rock", *Ground Water* 40(5):535–542 (2002).
11. J. -S. CHEN, C. -W. LIU, T. -C. CHAN, C. -F. NI, and K. -K. KAO, "Effect of transverse dispersion on solute transport in a vertical dipole flow test with a tracer", *Journal of Hydrology* 402(3-4):206–216 (2011).
12. P. W. REIMUS and T. J. CALLAHAN, "Matrix diffusion rates in fractured volcanic rocks at the Nevada Test Site: Evidence for a dominant influence of effective fracture apertures", *Water Resources Research* 43(7) (2007).
13. G. N. ROOS, *Development of the Dipole Flow and Reactive Tracer Test (DFRTT) for Aquifer Parameter Estimation*. MS Thesis. University of Waterloo: Waterloo, Canada (2009).
14. D. I. LEAP and P. G. KAPLAN, "A single-well tracing method for estimating regional advective velocity in a confined aquifer: Theory and preliminary laboratory verification", *Water Resources Research* 24(7):993–998 (1988).
15. O. GUVEN, R. W. FALTA, F J. MOLTZ, and J. G. MELVILLEI, "Analysis and interpretation of single-well tracer tests in stratified aquifers", *Water Resources Research* 21(5):676–684 (1985).

16. L. C. MEIGS and R. L. BEAUHIEM, "Tracer tests in a fractured dolomite: 1 Experimental design and observed tracer recoveries", *Water Resources Research* 37(5):1113–1128 (2001).
17. R. HAGGERTY, S. W. FLEMING, L. C. MEIGS, and S. A. MCKENNA, "Tracer tests in a fractured dolomite: 2 Analysis of mass transfer in single-well injection-withdrawal tests", *Water Resources Research* 37(5):1129–1142 (2001).
18. B. MALAMA, K. L. KUHLMAN, and S. C. JAMES, "Core-scale solute transport model selection using Monte Carlo analysis", Water Resources Research 49(6):3133–3147 (2013).
19. I. NERETNIEKS, *Single Well Injection Withdrawal Tests (SWIW) in Fractured Rock – Some Aspects on Interpretation*. SKB R-07–54, Svensk Kärnbränslehantering AB: Stockholm Sweeden (2007).
20. M. D. ZOBACK, *Reservoir Geomechanics*, Cambridge University Press (2010).
21. J. S. SELKER, L. THÉVENAZ, H. HUWALD, A. MALLET, W. LUXEMBURG, N. VAN DE GIESEN, M. STEJSKAL, J. ZEMAN, M. WESTHOFF, and H. B. PARLANGE, "Distributed fiber-optic temperature sensing for hydrologic systems", *Water Resources Research* 42(12) (2006).
22. B. FREIFELD and S. FINSTERLE, *Imaging Fluid Flow in Geothermal Wells Using Distributed Thermal Perturbation Sensing*. LBNL-4588E, Lawrence Berkeley National Laboratory: Berkeley, CA (2010).