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Deep Borehole Disposal of Nuclear Waste: Final Report

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Deep Borehole Disposal of Nuclear Waste Summary

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Abstract

Research and development activities carried out at Sandia National Laboratories from 2009-2012 have built the technical baseline for performance of a deep borehole for disposal of nuclear waste. Early work established the coupled thermo-hydrological-mechanical-chemical forces likely to control radionuclide movement from a deep borehole. This report emphasizes more recent borehole science and engineering activities including: 1. Establishing a reference borehole design; 2. Developing the design for borehole seals; and 3. Identifying the nature and extent of site characterization needed for deep borehole siting.

ACKNOWLEDGMENTS

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NOMENCLATURE

DBD	Deep borehole disposal
DOE	Department of Energy
LDRD	Laboratory directed research and development
SNL	Sandia National Laboratories

1. INTRODUCTION

A 3-year LDRD project advanced the technical baseline for deep borehole disposal (DBD) of nuclear waste by working out the thermal-hydrologic-mechanical-chemical controls over radionuclide transport from deep boreholes as documented in, e.g. Brady et al. (2009) and Arnold et al. (2010). This document describes follow on efforts to: 1. Establish a borehole reference design; 2. Design the borehole seals, and 2. Determine site characterization needs. Each of these topics has been addressed in separate reports and internal documents. This document draws from those sub-reports – in particular, the Reference Design Report (Arnold et al., 2011), the Borehole Seals Report (Herrick et al., 2011), and the draft Site Characterization Report (Vaughn et al., 2012).

1.1. Deep Borehole Disposal Concept and Background

Deep borehole disposal of high-level radioactive waste has been considered as an option for geological isolation for many years, including original evaluations by the U.S. National Academy of Sciences in 1957 (NAS, 1957). International efforts over the last half-century toward disposal of high-level waste and spent nuclear fuel have primarily focused on mined repositories. Nonetheless, evaluations of deep borehole disposal have periodically continued in several countries. An updated conceptual evaluation of deep borehole disposal and a preliminary performance assessment have also been completed (Brady et al., 2009). These studies have identified no fundamental flaws regarding safety or implementation of the deep borehole disposal concept.

The generalized deep borehole disposal 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 5,000 m, emplacing waste canisters containing used nuclear fuel or vitrified radioactive waste from reprocessing in the lower 2,000 m of the borehole, and sealing the upper 3,000 m of the borehole. As shown in Figure 1, waste in the deep borehole disposal system is several times deeper than for typical mined repositories, resulting in greater natural isolation from the surface and near-surface environment. The disposal zone in a single borehole could contain about 400 waste canisters of approximately 5 m length. The borehole seal system would consist of alternating layers of compacted bentonite clay and concrete. Asphalt may also be used in the shallow portion of the borehole seal system.

Several factors suggest that the deep borehole disposal concept is viable and safe. Crystalline basement rocks are relatively common at depths of 2,000 to 5,000 m in stable continental regions, suggesting that numerous appropriate sites exist (O'Brien et al., 1979; Heiken et al., 1996). Existing drilling technology permits the reliable construction of sufficiently large diameter boreholes to a depth of 5,000 m at a previously estimated cost of about $US 20 million each (Brady et al., 2009). The projected waste inventory from the current fleet of nuclear reactors in the U.S. could be disposed as spent fuel assemblies in about 950 boreholes, based on the preliminary design described in Brady et al. (2009). A non-technical advantage that the deep borehole concept offers over a repository concept is that of facilitating incremental construction and loading at multiple, perhaps regional, locations. Low permeability and high salinity in the deep continental crystalline basement at many locations suggest extremely limited interaction with shallow fresh groundwater resources (Park et al., 2009) (a typical lower boundary is shown by the dashed blue line in Figure 1), which is the most likely pathway for human exposure. The density stratification of groundwater would also oppose thermally induced groundwater convection from the waste to the shallow subsurface. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance sorption of many radionuclides in the waste, leading to limited mobility in groundwater.

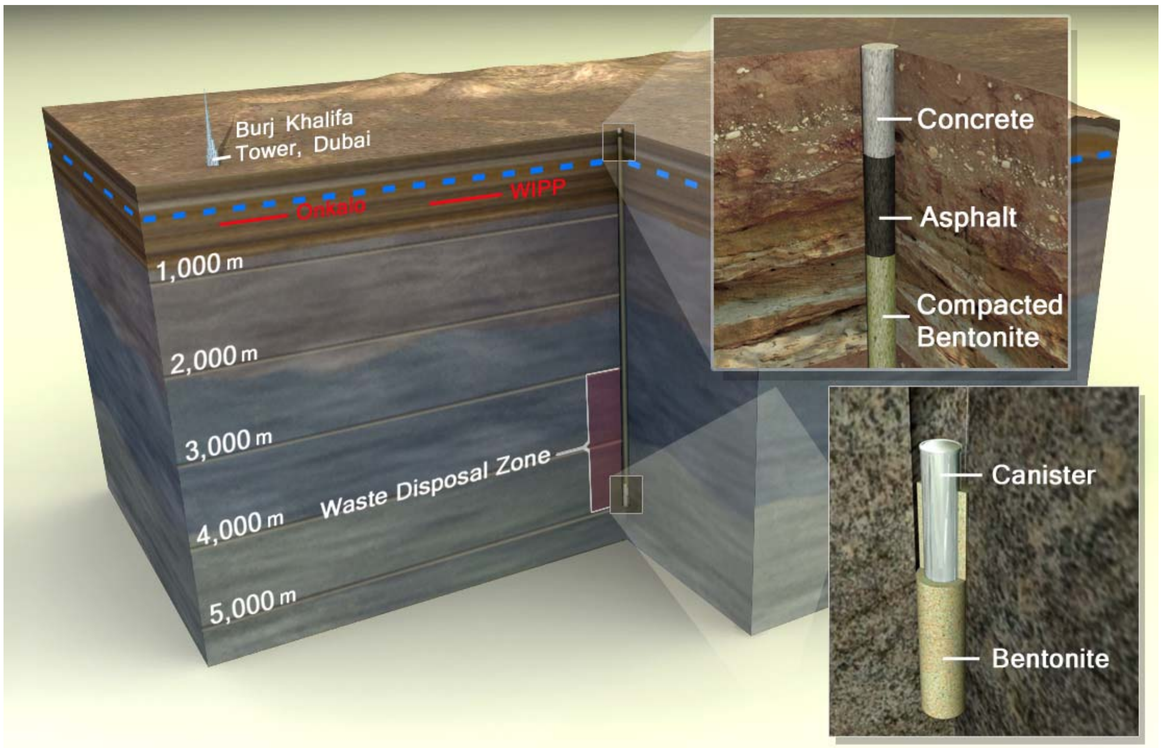

Figure 1. Generalized Concept for Deep Borehole Disposal of High-Level Radioactive Waste.

Actual implementation of borehole disposal requires a reference design, a plan for borehole sealing, and site characterization. Each of these is considered below.

2. REFERENCE DESIGN AND PROCEDURES

The subjective criteria used in selecting the borehole design, in order of priority are: (1) engineering and operational feasibility, (2) safety and engineering assurance, (3) simplicity, and (4) cost and efficiency. The primary elements of the reference design and operational basis are: (1) borehole construction, (2) waste canisters, (3) waste emplacement, and (4) borehole sealing and abandonment. Technical design requirements are defined for each of these elements based on the goals of safety, engineering assurance, and physical environmental conditions (e.g., pressure, temperature, mechanical stress) in the deep borehole system (Arnold et al., 2011).

The reference borehole is a telescoping design with a 36 inch (0.91 m) hole diameter to 457 m depth, 28 inch (0.71 m) hole to 1,500 m depth, 22 inch (0.56 m) hole to 3,000 m depth, and 17 inch (0.43 m) hole to 5,000 m depth. The corresponding casing diameters (OD) would be 30 inch (0.76 m), 24 inch (0.61 m), 18-5/8 inch (0.47 m), and 13-3/8 inch (0.34 m). The larger casing, extending to 1,500 m depth would be cemented in place. The 18-5/8 inch (0.47 m) casing would be left in place during waste emplacement, but would be cut and removed between depths of about 1,500 m to 2,900 m after waste emplacement and before emplacing the seals above the waste disposal zone. The 13-3/8 inch (0.34 m) casing would extend from the surface to the bottom of the borehole during waste emplacement to provide a high degree of confidence that the waste canisters would not become lodged in the borehole during emplacement. The slotted or perforated 13-3/8 inch (0.34 m) casing would remain in the waste disposal zone after emplacement of the waste canisters. The 13-3/8 inch (0.34 m) guidance liner casing above 3,000 m depth would be removed from the borehole before emplacement of the seals.

Logging and testing of the borehole would be conducted in stages as the borehole is advanced and before casing is set in various segments of the borehole. One significant finding of this reference design study is that a large fraction of the drilling costs for the initial borehole at a site would be associated with the rig time required for the logging, coring, and testing of the initial borehole. The option of drilling an initial exploratory borehole at a site should be given further consideration. Although the exploratory borehole could not be used for waste disposal, overall logging and testing costs would probably be less, and drilling experience gained would be useful in bit selection and drilling techniques for the construction of subsequent boreholes.

The reference waste canister design consists of carbon steel tubing, welded plugs for sealing the waste in the canister, and threaded connections for assembling a waste canister string in the borehole. The relatively simple design would withstand mechanical stresses associated with handling and emplacement of the canisters, under the hydrostatic pressures and temperatures expected during and after waste emplacement. Although not designed to withstand corrosion for long periods of time, the canisters would retain their integrity until after the borehole is loaded with waste, sealed, and abandoned.

The baseline operational procedures in the reference design call for dismantling used nuclear fuel assemblies and packing the individual fuel rods into the waste canister. For the disposal of 400 canisters of used PWR fuel, a single borehole would contain about 253 metric tons of HM. Vitrified high-level radioactive waste from reprocessing could be poured directly into the canisters or poured into thinner-walled steel containers for insertion into the waste canister. Although the costs of dismantling used fuel assemblies are significant, consolidation of fuel rods in the waste canisters results in about a 37% increased waste capacity per canister, relative to direct disposal of unconsolidated used fuel assemblies. This increased waste capacity for consolidation of fuel rods translates into a directly proportional decrease in the total number of boreholes needed for disposal of the entire used fuel waste inventory. This consolidation also permits the use of smaller diameter boreholes, which reduces cost and increases confidence of success. Even using the conservatively high estimated costs of dismantling fuel assemblies at nuclear reactor sites from previous studies, consolidation of used fuel constitutes an overall cost savings for the entire deep borehole disposal system.

The waste emplacement design and procedures consist of surface handling activities, assembly of waste canister strings in the borehole, lowering canister strings to the disposal zone, and emplacement of plugs between canister strings. The design basis for surface handling of waste canisters is relatively simple and based on general descriptions from previous studies. Shipping casks would be unloaded from the tractor trailer adjacent to the drill rig and waste canisters would be extracted from the shipping cask directly into the borehole. This procedure avoids the need for surface facilities to unload and store loaded waste canisters in shielded structures, but requires close scheduling coordination between transportation of waste to the site and waste emplacement. As with any nuclear waste disposal system, waste transportation is a critical component with regard to the cost and feasibility of the system. It should be noted that transportation was not analyzed; however, the general issues and decisions are similar to those for a mined repository disposal system.

Waste canisters would be emplaced in strings of 40 canisters, separated by bridge plugs and cement plugs. This approach limits the mechanical stresses on the lower canisters from the weight of the overlying canisters and provides a degree of isolation for each canister string. An oil-based fluid with bentonite would be used in the waste disposal zone for emplacement of the canister strings.

The reference design assumes that the deep drill rig used to construct the borehole would also be used for waste emplacement and for setting seals and plugs. An alternative, probably less costly approach, would be to use a separate, lighter rig for waste emplacement and sealing operations. A heavier deep drilling rig would provide greater capacity for dealing with unplanned occurrences; in particular, it could apply greater forces to push, pull, and rotate the waste canister string if it became lodged in the borehole. Cutting and pulling long casing strings, as part of the sealing operations would also be facilitated by a heavier capacity rig.

The borehole would be sealed using a series of compacted bentonite seals, bridge plugs, cement plugs, and backfill (see below). The seals and plugs would be seated against the borehole wall from a depth of about 1,500 m to 2,900 m depth. Casing that has been cemented into the borehole would be left in the upper 1,500 m of the borehole and the casing would be sealed with bridge plugs, cement plugs, and sand/crushed rock backfill.

2.1. Costs and Schedule

The estimated system costs per borehole are summarized in Table 1. As expected, the costs are dominated by drilling and construction of the borehole. The second largest costs are for the waste canisters and loading them with used nuclear fuel. The costs for emplacing the waste and sealing the borehole are of lesser and roughly equal amounts. Given the waste loading design for used PWR fuel rods and the disposal of 400 waste canisters in a borehole, the total mass of HM disposed in a single borehole would be about 253 metric tons. This results in an estimated disposal cost of about $158/kg HM. For comparison, the nuclear waste fee collected on electricity from commercial nuclear power plants is $0.001/kW-hour, which equates to roughly $400/kg HM waste (Gibbs, 2010). Although the deep borehole disposal costs shown in Table 1 do not include transportation or any storage associated with management of the used nuclear fuel inventory, the estimated disposal costs are well within the amount provided by the nuclear waste fund.

Table 1. Estimated System Costs

	Cost per Borehole
Drilling, Casing, and Borehole Completion	$27,296,587
Waste Canisters and Loading	$7,629,600
Waste Canister Emplacement	$2,775,000
Borehole Sealing	$2,450,146
Total	**$40,151,333**

Note: All costs are in 2011 $US and approximately for 2011 expenses.

This cost estimate is for a full-sized disposal borehole, but without the logging and testing of the initial borehole at a site. As such, this estimate and the associated total cost correspond to the incremental costs of an additional borehole at an existing, approved site for deep borehole disposal. The costs of dismantling the fuel assemblies and loading used fuel rods into the waste canisters are a large fraction of the total costs for producing the loaded waste canisters in the reference design. These costs would probably be substantially less for dismantlement of used fuel assemblies in a dedicated facility, perhaps at a centralized storage site.

The total time for onsite drilling, borehole completion, waste emplacement, and borehole sealing operations is estimated to be about 186 days. This estimate is based on the assumption of continuous, uninterrupted operations through all phases of the disposal process. In particular, this schedule assumes that the loaded waste canisters would be available to be unloaded from the shipping casks on trucks in a more-or-less continual basis during the approximately 33 days of waste canister emplacement. For comparison, about four drill rigs operating on this schedule could dispose of the commercial used nuclear fuel from the current fleet of nuclear power plants producing waste at the rate of about 2,000 metric tons per year.

The cost and schedule analysis in this report is more detailed and has a broader scope than the analysis presented in Brady et al. (2009). The greater cost estimate of about $27M in this study for drilling and construction of the borehole is greater than the estimate of $20M in the Brady et al. study because of consideration given to logging and testing of the borehole, a more detailed analysis, and contingency costs of 15%. Waste canister, waste loading, waste emplacement, and sealing and plugging costs were not analyzed in the Brady et al. (2009) report.

Borehole seals deserve closer examination because their performance will largely control long-term borehole performance.

3. BOREHOLE SEALS

The most likely path for radionuclide transport will be up the sealed borehole and adjacent disturbed rock zone, where permeabilities in the host rock may be further altered by thermally induced mechanical stresses and fluid pressures. A series of borehole seals and engineered backfill will extend from just above the waste emplacement zone to the surface. Sealing materials must provide physical stability to the hole while preventing the movement of water, and dissolved radionuclides, upwards from the waste disposal zone. The seal system design consists of multiple types of barriers emplaced in a redundant manner. Effective seals slow fluid movement because they possess intrinsically low hydraulic conductivity and because the seal material adheres to the wall rock and fills connected void spaces. The materials will be specifically selected for their favorable strength, stability, and hydraulic properties.

Bentonite, which is central to the seals design proposed below, is a particularly effective sealing material because of its low permeability and because its high swelling pressure under confined conditions allows it to form tight seals. Also, because of high surface areas and high cation exchange capacity, bentonites sorb many cationic radionuclides, yet they can also be chemically engineered to sorb anionic radionuclides such as ^{129}I, an important dose driver. The high anionic surface charge of bentonite causes bentonite mixtures to electrostatically inhibit the diffusive transport of anionic radionuclides through anion exclusion.

In addition to limiting fluid flow, seals must isolate those sections of the borehole that intersect fracture zones, which might otherwise permit rapid vertical transport of radionuclides. Effective site characterization should eliminate sites where fracture flow of fluids is pervasive. Seals also divide the borehole into multiple sections to provide a redundant barrier system, so that if an individual seal is breached, fluid transport can be localized. Figure 2 identifies the primary components of the seal system, the spatial relationship between the waste emplacement zone, seals, borehole casing, disturbed rock zone, bridge plugs, and keyed structural seals and backfill components. The seals will be designed typically in sets of barriers with the placement of a structural cement/concrete component keyed at the bottom to constrain the swelling pressure of clays above. This sequence is topped by another cement/concrete seal to limit clay swelling. Between these components, there would typically be longer segments of mixed backfill whose emplacement would require less design and construction controls. While this backfill would serve to support the next seal system sequence above, its performance would generally not be considered when estimating the seal system overall hydrologic performance. Such backfill could include sand or sand-bentonite mixtures.

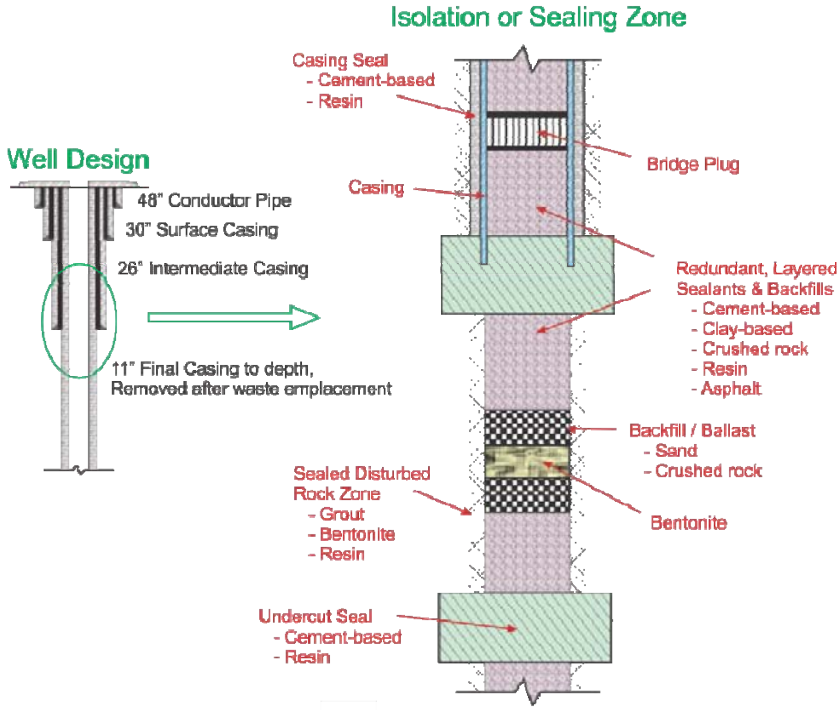

Figure 2. Schematic of borehole seal components.

The sealing effect of bentonite can be inhibited by chemical conversion of the bentonite to non-swelling clays (e.g. illites and chlorites) by calcium from groundwater and/or cements. Cements are used predominantly by the petroleum industry for permanent plugging and abandoning of wells; when the appropriate cement is selected and properly placed, the durability of the cement and the cement job is assumed to be indefinite. However, because hydrated cement phases are not uniformly stable under in situ borehole conditions, cement might be expected to alter to more thermodynamically stable and crystalline assemblages – whose performance might be less. This may be especially true at elevated temperatures and/or over the much longer time periods required for nuclear waste disposal. Our focus below is on seals of bentonite and cement because of their effective sealing properties, the long industrial experience with their use, and the existence of natural analogues.

Technical requirements of the reference design include

- Borehole seals must have low permeability and form a low-permeability bond with the borehole walls to prevent fluid flow around the seals. Some seals material, such as compacted bentonite, should decrease the permeability of the host rock near the borehole by penetrating fractures. (Sites with high fracture densities will be eliminated in the site characterization phase)

- Borehole seals must be durable, particularly during the peak thermal period (< 2,000 years), when the potential for fluid flow is highest.

- Borehole seals must have the strength to resist mechanical loads from overlying materials, swelling pressures from bentonite sealing materials, and potential overpressuring from below.

- Borehole sealing materials must be chemically stable at 100 – 200 ºC for at least 2,000 years, the time it takes for the thermal pulse, and driving force for vertical fluid movement, to pass.

- Some materials used for borehole seals should have the ability to be amended with compounds that would serve as "getters" to retard the transport of non-sorbing radionuclides, such as ^{129}I.

- Multiple seals and seal materials will be used to provide redundant defense in depth thus maintaining performance even after failure of an individual seal.

- Redundancy is also used because the aging degradation of potential seal materials is poorly constrained over the longer regulatory time periods.

3.1. Cement

Cements have low permeability, can penetrate small fractures, can be very durable, and the methods to emplace the materials downhole are quite mature. Fluid transport that would bypass the cement seal only occurs through the interface between the cement and the adjacent rock or through the damaged rock zone adjacent to the borehole. Cement admixtures are used to: modify the setting time of the mixture; change the viscosity (workability) of the fresh cement product, and/or to alter the properties of the hardened cement product, especially shrinkage potential. The typical value for the permeability of a Portland cement, having a water/cement ratio of 0.4 and a curing period of two weeks, is 10^{-20} m^2 (e.g., Smith, 1989). Shrinkage, fracturing, or chemical alteration may increase this value. Field values can be two or three orders of magnitude higher (SKB 1987).

Thompson et al. (1996) showed that more than 100 pore volumes of leachants (they considered both fresh water and brine) must pass through the concrete before failure. For reasonable physical characteristic values (including a permeability of 10^{-16} m^2) of a 100 m plug in a sealed borehole, the plug life according to their analysis is on the order of about two hundred thousand years (this number is dependent on the pressure difference across the plug). Because cement phases will react after setting the assumption of performance over the regulatory period must be supported by modeling (e.g. Berner, 1990; Thompson et al., 1996).

Cementitious materials are the primary means for sealing boreholes in the oil industry. API Class A, B, and C cements are used from the surface to 1.8 km (6000 ft), Classes G and H are used down to 2.4 km (8000 ft), Class D from 1.8 to 3.1 km (6000 to 10,000 ft), and Classes E, F, and J are intended for use at depths greater than 3.1 km (10,000 ft). Classes A, C, G, and H cements are typically used in plugging operations; the actual selection of a cement composition will depend on well depth, formation temperatures, formation properties, and borehole fluid properties. Numerous placement techniques have been developed that can reliably deliver cement of the appropriate properties to great depth (Smith 1989).

3.2. Testing and Verification of Seals

High priority seals testing and verification activities will include:

- Ex situ strength and permeability testing of cement, bentonite, and bentonite-sand mixtures.
- In situ strength tests can be accomplished by applying vertical loads via the drill rig itself, or via application of pressure below a packer system if the overall formation permeability is low.
- In situ permeability testing using a packer system to apply pressure above a seal system component and monitor pressure decay to determine system permeability.
- Accelerated component aging tests of seals materials. These can be accomplished by applying heat and concentrated fluids to samples of seal materials to detect/anticipate material aging.
- Geochemistry testing to optimize designed equilibration of materials with the borehole environment, and/or to identify additives that would potentially sorb radionuclides.

Figure 3 shows the borehole seals reference design. The lower, uncased section will begin above the port collar of Intermediate 2 liner. Between the last waste container and the port collar will be a 100 m section of cement to provide both sealing and some thermal insulation to the borehole above, topped by a bridge plug. The borehole seal system involves a series of seals (cement sections with bentonite or bentonite-sand seals in between) immediately above the waste disposal zone and below cement plugs higher up in the bore hole. The cement sections serve to constrain expansion of the bentonite and support the weight of the seal/backfill system. A silica sand or finely crushed rock ballast will separate the cement and clay to minimize possible chemical interaction. Other parts of the borehole will be filled with a continuous cement plug. The length of the plug is a principal factor in its longevity and at least a 100 m long plug is recommended. Both the cement and bentonite are expected to penetrate to some degree into the fractures of a possible disturbed rock zone surrounding the borehole. This lower section will also have sand or finely crushed rock that is chemically compatible with the wall rock and seals added for backfill, to retard shrinkage of the cement, and to save on the overall cost of plugging the borehole.

In the upper cased section, the borehole will be plugged predominantly with cement or cement mixed with sand and rock. The bottom of the 24 inch (0.61 m) Intermediate 1 casing will be cemented with a solid segment that extends 50 m above and below the casing shoe. Above the bottom of the casing will be one or more bridge plugs. API recommends plugs in which a bridge plug is positioned and covered with a column of cement. This is topped with a second bridge plug and another column of cement. Again sand and/or finely crushed rock will fill the remaining spaces.

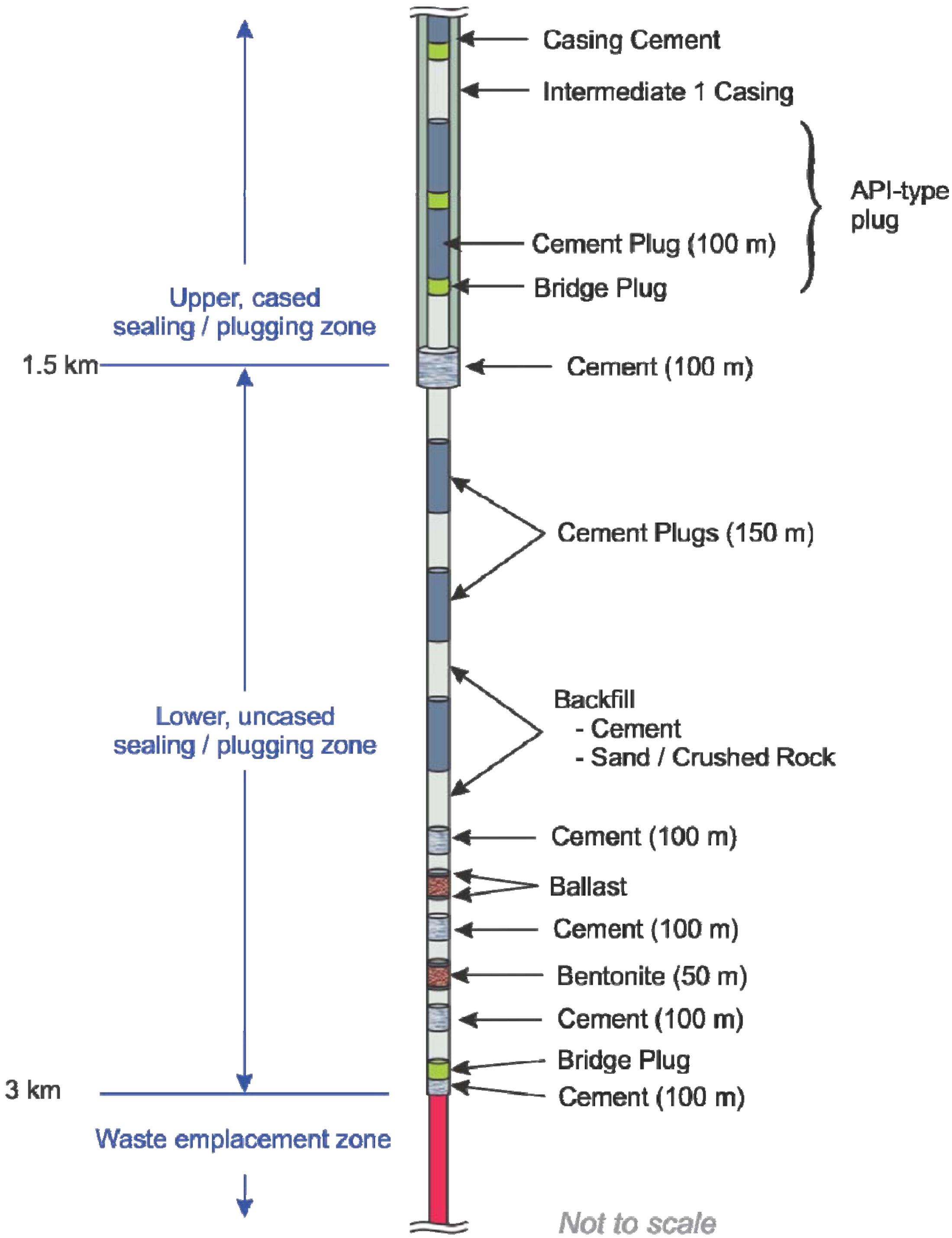

Figure 3. Borehole Sealing, Plugging, and Backfilling Reference Design Schematic.

4. SITE CHARACTERIZATION

The early steps for site characterization would be placed on ruling out a few conditions or environments that are considered to be less desirable or undesirable:

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

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

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

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

3) Interconnected zone of high permeability from the waste disposal zone to the surface or shallow subsurface (e.g., fault zone): A high-permeability pathway from the waste disposal zone to the shallow subsurface could conduct significant groundwater flow and associated radionuclide transport, particularly by thermally driven flow during the period of high heat output by the waste.

4) Occurrence of Quaternary-age volcanic rocks or igneous intrusions: Direct release of radionuclides to the biosphere could occur if the magmatic conduit for a volcanic eruption intersected the waste disposal zone. The presence of igneous rocks of Quaternary age at the surface or intersected by the borehole would indicate a potentially

significant probability of future volcanic activity and associated impacts on repository performance.

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

A FEPs analysis then provides guidance, focus and direction for the deep borehole site characterization program (Vaughn et al., 2012). For example, determining the location of the basement rock using geophysical profiles will help determine the basement rock is deep enough to make the site suitable for DBD. Surface-based methods can also be used to locate transmissive pathways from the waste disposal zone to the surface or shallow subsurface. If it is decided that a site is potentially suitable, surface-based characterization can help guide the drilling program (e.g., estimate how deep to drill the well). During and after well drilling, bore-hole based characterization can be used for more detailed site characterization. In addition, some features cannot be evaluated without borehole-based characterization.

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

Characterization should focus particularly on:

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

4.1. Faults and Fractures

It is important to understand the interconnected zone of high permeability from the waste disposal zone to the surface or shallow subsurface (e.g., faults or highly fractured zones). A high-permeability pathway from the waste disposal zone to the shallow subsurface could conduct significant groundwater flow and associated radionuclide transport, particularly by thermally driven flow during the period of high heat output by the waste. In addition, the possibility of these preferential pathways intersecting boreholes at depth needs to be evaluated. The location, displacement, and orientation of faults exposed at the surface should be identified. Faults that are exposed at the surface often extend into the deep subsurface. Finally, it is important to exclude the possibility of igneous rock in the waste disposal zone overthrusting above sedimentary rocks.

The methods that could assist with characterization of fault and fractures zones are listed in Table 2.

Table 2. Methods for characterizing faults and fractures.

Method	How
Surface Geological Mapping	Correlate surface structures to inferred subsurface faults identified with surface-based geophysical methods
3D Seismic	Determine whether the boreholes intersect any high permeability pathways
Borehole caliper logging	Possibly identify larger fractures
Spontaneous Potential Log	Identify high permeability features
High-resolution temperature logging in conjunction with fracture imaging methods such as FMI logs	Identification transmissive fractures and fracture zones
Neutron Porosity Log (in combination with other logging methods)	Asses the fracturing in the host rock
Borehole gravity logging	Identify fault zones

4.2 Stratigraphy

Understanding the stratigraphy of a potential DBD site (Table 3) is important to 1) locate the crystalline basement rock, 2) identify features such as folds, igneous intrusions, and salt domes, and 3) locate Quaternary-age volcanic rocks or igneous intrusions. Direct release of radionuclides to the biosphere could occur if the magmatic conduit for a volcanic eruption intersected the waste disposal zone. The presence of igneous rocks of Quaternary age at the surface or intersected by the borehole would indicate a potentially significant probability of future volcanic activity and associated impacts on repository performance.

Table 3. Stratigraphic characterization methods.

Method	How
Surface Geological Mapping	Determine surface lithology, Potential correlation of surface lithology with rock types in the boreholes
3D Seismic	Image stratigraphy
Gravity and Magnetic Surveys	Find the contact between igneous and sedimentary formations
Electrical Resistivity Profile	Locating the contact of the crystalline basement rock
Gamma Ray log	Differentiate shale and other fine-grained sediments from other sedimentary units and other rock types.

Resistivity log	Provide information about lithostratigraphy,
Spontaneous potential log	Provide information on lithology
Neutron porosity log	Contributes to the lithological and structural interpretation of the borehole, in combination with other logging methods
Drill Cuttings	Provide a semi-continuous vertical profile of bedrock lithology
Intermittent Coring	Provide a semi-continuous vertical profile of bedrock lithology.

4.3 Physical, Chemical and Transport Properties and Lithologic Information

Physical, chemical, and transport properties are needed to develop both conceptual model for groundwater flow and radionuclide transport and provide parameters for flow and transport numerical models. Certain properties must be defined in order to develop conceptual models to determine whether or not a site is suitable and what the important processes are at a site. In addition, conceptual models are needed in order to develop numerical models. In turn, numerical models must be populated with parameters determined or estimated from site characterization activities. Transport parameter characterization methods are listed in Table 4.

Table 4. Transport parameter characterization methods.

Method	How
Borehole Gravity Log	Estimate host-rock bulk density and host-rock porosity
Formation Micro Imager Log (FMI)	Provide information to estimate bulk permeability, fracture aperture, and therefore host-rock porosity. Identify vertical gradient direction in conjunction with temperature logging.
Intermittent Coring	Provide samples for laboratory testing for parameters such as sorption coefficients, bulk density, porosity, permeability, geo-mechanical properties, thermal properties. Provide information about mineralogy, which is relevant to radionuclide adsorption.
Neutron Porosity Log	Provide an estimate of the porosity, in conjunction with measurements on core samples and other logging methods that image fractures in the borehole wall such as FMI logs
Borehole gravity logging	Estimate host-rock density and porosity. Potential identification of mineral alteration.
Pump Testing	Estimate hydraulic conductivity (horizontal and vertical), specific storage or storativity, and transmissivity of strata of interest, formation pressure and formation permeability. Fluid samples from pump tests can be used to estimate the salinity and/or salinity profile.
Tracer Testing	Estimate flow porosity, dispersivity, sorption coefficient, and matrix diffusion rate dispersivity and matrix diffusion

	rate. Estimate the ambient groundwater specific discharge in the host rock.
Drill Stem Testing	Provides information on formation permeability and pressure.
Bore-hole based Resistivity Log	Provide information about lithostratigraphy, formation permeability, fluid saturations, and water quality.
Temperature Log	Assess geological basin hydrodynamics. Estimate fluid viscosity and density. In conjunction with fracture imaging methods such as FMI, infer the vertical hydraulic gradient by identifying zones of groundwater inflow and outflow from the borehole
Resistivity logging	Can provide information on formation permeability and fluid saturations.
Waste Canister Mockup Electrical Heater Test	Estimate the bulk thermal conductivity of the host rock.
Drill Cuttings	Provide samples for laboratory testing for parameters such as sorption coefficients, bulk density, porosity, permeability, thermal properties
Borehole caliper log	Infer orientation of anisotropy in horizontal stress

4.4 Fluid Chemistry

The types of measurements that can be made to assist in site characterization for DBD include (Table 5):

1. Major ion concentrations of the host-rock groundwater,
2. Salinity and vertical salinity profile,
3. Environmental tracers, and
4. Isotopic composition of the host-rock groundwater.

Table 5. Geochemistry characterization tests.

Method	How
Drill Stem Pump Tests	Provide water samples for groundwater chemistry testing
Fluid Samples from Packer Testing	Provide water samples for groundwater chemistry testing
Packer Pump Tests	Provide water samples for groundwater chemistry testing
Resistivity Log (Borehole Based)	Can provide information about water quality
Spontaneous Potential Log	Determine pore-water quality (e.g. salinity and ionic concentration)

4.5 Borehole and Seal Integrity

The integrity of the borehole and borehole seals are clearly important for the containment of waste. If needed, site characterization tools can be used to identify and/or characterize important properties and features to address borehole integrity (Table 6): host-rock mechanical properties, stress fields (specifically anisotropy in horizontal stress fields), and faults intersecting boreholes. Mechanical properties of the host rock are relevant to borehole stability and the effectiveness of seals. The identification of these features does not necessarily eliminate a site for DBD. Borehole seals can be used to fill in borehole breakouts and isolate faults that intersect boreholes.

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

Table 6. Borehole stability and seals performance.

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

4.6 Likelihood of Human Intrusion

Potential of human intrusion is an exclusion criterion for the development of a deep borehole field. In general, any potential subsurface resources, would make human intrusion a possibility. Underground resources include, petroleum reserves, ore deposits an geothermal sources. The methods listed in Table 7 could all be used to identify such resources.

Table 7. Human intrusion potential characterization methods.

Method	How
3D Seismic	Identify potential underground resources
Electrical Resistivity Profile	Identify potential underground resources
Gamma Ray Log	Identify underground uranium resources
Gravity and Magnetic Surveys	Identify potential underground resources
Temperature Log	Determination of the geothermal gradient and the potential for geothermal resource development

4.7 Structural Stability

A site with the potential for earthquakes (or a history of earthquakes) would not be suitable for DBH disposal. There are several site-characterization methods that can be used to determine the earthquake potential (Table 8). Differential horizontal stress may give geological evidence regarding the tectonic history and structural stability of the site. Geochemical (e.g., bulk composition of major, minor, and trace elements) and fluid inclusion studies will provide information on the geologic history of the system, which is relevant to the long-term stability of the site and isolation of the waste.

Table 8. Structural stability characterization methods.

Method	How
Formation Micro Imager Log (FMI)	Determine the location of borehole breakouts and drilling induced-fractures
Drill Stem Testing	Provides information on formation pressure
Dipole Shear-Wave Velocity log	Measure horizontal stress fields.
Intermittent Coring	Provide geochemical characteristics of the various lithologies encountered

5. CONCLUSIONS

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

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

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