REGULATORY PERSPECTIVES ON DEEP BOREHOLE DISPOSAL CONCEPTS

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ABSTRACT

This report provides a brief history and general overview of the deep borehole disposal (DBD) concept for geologic disposal of high-level waste and spent nuclear fuel. Based on review of available literature, the aspects of potential DBD systems most important to performance are identified and critical uncertainties are highlighted from both preclosure operational safety and postclosure waste isolation perspectives. Available literature makes clear that the construction of boreholes in hard rock to the depths necessary for waste isolation is technologically possible and likely could be economically feasible. Significant technological uncertainties and potential safety challenges remain, however, in the areas of waste handling and procedures for lowering waste into the disposal boreholes. The ability to reliably evaluate postclosure performance of the DBD concept is limited by key uncertainties that include the effects of waste heat on the host rock and formation fluids and the resulting potential for increased fluid movement, and the long-term reliability of borehole sealing materials. Focused modeling and experimental studies would improve understanding and quantification of these uncertainties.

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1 INTRODUCTION

The national policy for disposal of high-level radioactive waste (HLW) is presently uncertain after the petition by the U.S. Department of Energy (DOE) to withdraw its license application for construction of a Yucca Mountain nuclear waste repository. The President of the United States chartered the Blue Ribbon Commission (BRC) on America's Nuclear Future to conduct a review of options for managing the back end of the nuclear fuel cycle, including alternatives for storage, processing, and disposal.

Deep borehole disposal (DBD), the topic of this report, is one of several options for permanent disposal of HLW and spent nuclear fuel (SNF) the BRC is considering. As conceptualized in recent studies (e.g., Brady, et al., 2009; Åhäll, 2006; Nirex, 2004), the DBD process consists of drilling a borehole into crystalline basement rock, typically granite, to depths up to 5,000 m [16,400 ft]. Waste canisters containing SNF or vitrified radioactive waste from reprocessing would be emplaced in the lower 2,000 m [6,500 ft] of the borehole. The upper 3,000 m [9,800 ft] would then be sealed as illustrated in Figure 1-1.

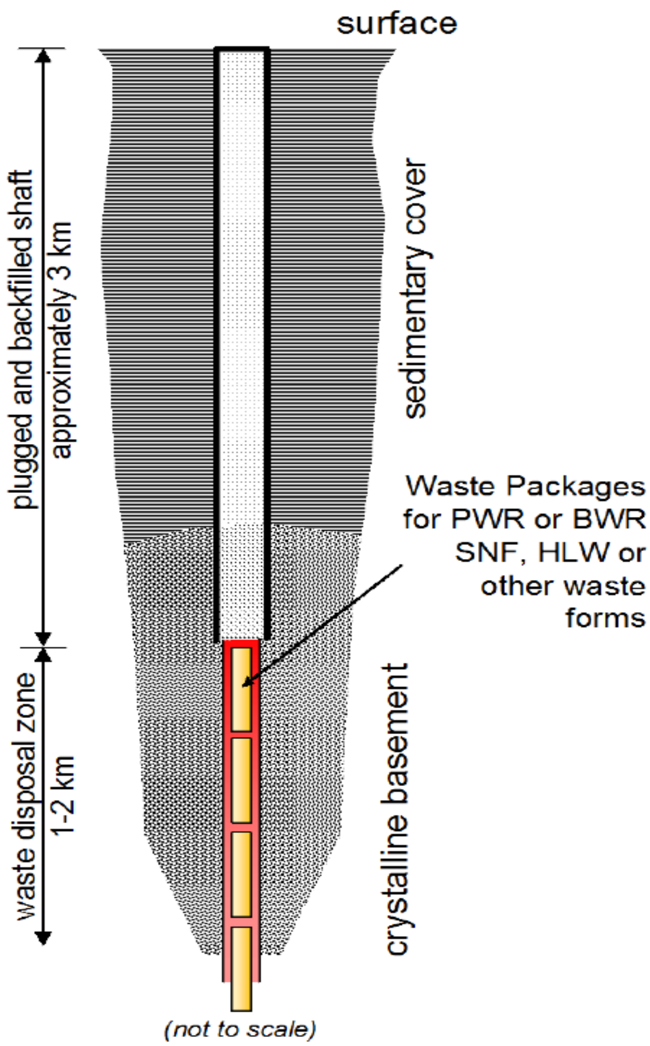

Figure 1-1. Conceptual Design of a Deep Borehole Disposal System (Brady, et al., 2009)

Most recent analyses of DBD make favorable conclusions regarding the potential for postclosure waste isolation, mainly based on assumed conditions at depth and assumptions that existing deep drilling technology can successfully be adapted for waste emplacement. Less research has been conducted regarding preclosure operational issues likely be associated with a functioning DBD facility. The purpose of this report is to evaluate the concept of DBD from the perspective of a regulator charged with ensuring protection of human health and the environment for both preclosure and postclosure periods. To this end, DBD is discussed in the context of which aspects of the system are most important to safety and waste isolation and the potential for deviations from assumed or expected performance that could pose safety or environmental risk. As appropriate, recommendations are made where detailed technical analyses are likely to be needed if developments in national policy result in pursuit of DBD as a disposal alternative for HLW.

The remainder of this section presents relevant history and background information.
In Section 2, preclosure and operational aspects of DBD are discussed. Section 3 discusses the natural system and engineered aspects of DBD that may affect postclosure waste isolation.

1.1 History of Deep Borehole Disposal Concepts

In 1957, the U.S. National Academy of Sciences (NAS) Committee on Waste Disposal considered the deep disposal of liquid radioactive waste brines in permeable formations at depths of 1,500 m [5,000 ft] or greater. At that time, it concluded that available technology was not yet sufficient to prevent clogging of pore space as the solutions are pumped into the rock nor to reliably predict or control the rate and direction of movement. NAS also examined the mined storage of radioactive waste in salt deposits and favored this approach with a caveat that disposal could be greatly simplified if the liquid waste of concern at that time could be converted to a relatively insoluble solid form. Since publication of the NAS report in 1957, this type of technology has been successfully developed and no longer remains a barrier. Deep disposal of liquid wastes was revisited from time to time (e.g., Drescher, 1965), but research that focused on deep disposal of solid waste forms in boreholes did not receive serious attention until the late 1970s, following advancements in deep drilling technology by the petroleum industry.

A feasibility study by O'Brien, et al. (1979) provided a thorough analysis of the DBD concept, highlighting several key uncertainties and technological hurdles, many of which are relevant today and highlighted in the following sections of this report. The DBD concept was eventually set aside in the United States, however, in favor of pursuing disposal at a conventionally mined geologic repository.

Other countries that have conducted research on the DBD concept include, Denmark, Sweden, Switzerland and the United Kingdom. Nirex (2004) thoroughly summarizes previous international studies and concepts for DBD. Issues related to hydrogeology, hydrochemistry, geomechanics, canister construction, canister retrievability, and drilling technology, among others, have been identified and, to varying degrees, examined.

The evaluation of DBD as a disposal option for HLW in the United States has gained renewed interest in the past decade. Massachusetts Institute of Technology (MIT, 2003) concluded that DBD for SNF has the potential to significantly reduce risk of long-term radiation exposure and that the concept merited a significant research and development program. Brady, et al. (2009) recently published an in-depth analysis of DBD by Sandia National Laboratories, including a formal scenario screening analysis and performance assessment. Their performance assessment for a single disposal borehole indicated that radiological dose to a human receptor via the groundwater pathway would be limited to a single radionuclide (I-129) and would be negligibly small, approximately 10 orders of magnitude below the current regulatory criteria for Yucca Mountain. In that analysis, the mechanism considered for upward movement of fluid was thermal expansion of formation fluids; scenarios such as errors in emplacement or borehole seal failure were not considered.

1.2 Potential Advantages of Deep Borehole Disposal

Most research in the United States and other countries pertaining to the geologic disposal of HLW and SNF has focused on mined repositories, which would include the 25-year site investigation of Yucca Mountain and screening of several other potential U.S. repository locations. Recent evaluations, however, have found that there may be technical, safety, and cost advantages associated with the DBD approach (Brady, et al., 2009). With disposal depths of 3–5 km [1.8–3.1 mi], DBD systems would be much deeper than typical mined repositories, which generally are limited to depths of several hundred meters [1 m = 3.281 ft]. Under ideal conditions, the transport of radionuclides away from HLW and SNF at such 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 (i.e., more dense with depth) saline fluids (Brady, et al., 2009). Åhäll (2006) and Brady, et al. (2009), suggest that DBD can also allow easier control of the "thermal footprint" by simply adjusting borehole spacing at the surface, whereas in a mined geologic repository, increased spacing of waste emplacement drifts would require significantly greater lengths of access tunnels. According to Gibb, et al. (2008a), in comparison to the excavated geologic repository concept, potential benefits of DBD include higher security (against terrorist or accidental intervention), wider availability of geologically suitable sites, and less environmental disruption. Additionally, there is potential for increased cost effectiveness. Because the DBD concept is modular, construction and operational costs are likely to scale approximately linearly with waste inventory (Orrell, 2011).

Determining appropriate site locations for DBD depends on a number of factors. Several scenarios have been proposed. Placement at an existing nuclear power plant may be advantageous because there would be no transportation-related concerns and reduced waste canister manipulation issues. However, the geology at many plants may not be suitable for DBD and additional infrastructure would be needed for transferring waste from existing storage into a container format suitable for insertion into boreholes. Development of state or regional DBD sites would reduce total transportation distance, thus reducing but not eliminating the potential for transportation-related safety issues. A regional DBD scenario would require separate licensing of each facility. Finally, the concept of a single national DBD site is potentially attractive in that only one facility would require licensing. However, there would be no advantage of reducing or eliminating the need for transportation.

1.3 Uncertainties Associated with Deep Borehole Disposal

Because a fully operational DBD facility has never been constructed, there are a number of uncertainties associated with the DBD concept. It is not entirely clear that existing drilling technologies are applicable to DBD because most experience drilling deep boreholes has been in the oil and gas and mining industries and has involved smaller diameter boreholes. A better understanding is needed of several technical issues, including borehole stability under increased pressure as well as potential heat and radiation loadings that would exist in deep boreholes. The movement of groundwater at very great depths is an area requiring additional research, as is the potential impact that boreholes themselves can have on groundwater movement at disposal depths. At this point it is also unclear how much of a borehole would require lining and at what depths. For unlined boreholes, systems will be needed for recovering casings and sealing the upper portions of boreholes when waste emplacement is completed. Technology for handling packages at depth will need to be developed, and the effect of mechanical load on a column of waste canisters during and following their emplacement will need to be assessed. The impact of borehole fluids on waste emplacement procedures will also require examination. Finally, technology for monitoring boreholes over a very prolonged time frame may be desirable (von Hippel and Hayes, 2010; Nirex, 2004).

1.4 Legal and Regulatory Framework

The Nuclear Waste Policy Act, as amended, limits consideration of HLW disposal to a mined geologic repository at Yucca Mountain. Therefore, implementation of a DBD system for disposal of HLW would require amendment or revision of the Nuclear Waste Policy Act. Regulations at 10 CFR Part 63, which are specific to geologic disposal at Yucca Mountain, also cannot be applied to DBD because they require a repository design that permits the option of retrieval for up to 50 years after waste emplacement is initiated. Because retrieval or reversibility generally is not a viable option with DBD, a regulation that recognizes the permanent disposal nature of a DBD system would be needed. If permanent, irreversible disposal is not intended, then a DBD system may not be the best choice (Brady, et al., 2009). Even so, the inherent inaccessibility of canisters in DBD systems may be advantageous for some waste classes, such as those that may contain weapons grade nuclear materials.

Changes to the specific regulations associated with U.S. Environmental Protection Agency (40 CFR Part 191) and NRC (10 CFR Part 60) would be required for the adoption of any HLW DBD system. However, much of the existing performance assessment regulatory framework for geologic repositories (40 CFR Part 197 and 10 CFR Part 63) could be applied as part of a new DBD regulatory scheme. There are a number of specific preclosure and operational issues that are likely to merit attention as part of any rulemaking exercise related to DBD. Performance-based regulations would need to be developed regarding canister construction specifications, surface transport to the disposal site, handling of HLW onsite, filling and sealing of waste canisters, lowering of waste packages, and backfilling and sealing of boreholes. Specific performance criteria for waste packages, shafts, and boreholes would need to be established.

2 PRECLOSURE OPERATIONS

Preclosure operations for a DBD facility would include the design and construction of the boreholes, transfer of waste into disposal canisters, placement of canisters into the waste disposal zone, and final plugging.

2.1 Deep Borehole Design and Construction

With an estimated current U.S. waste inventory of 109,300 metric tons (120,480 tons) heavy metal (Brady, et al., 2009, Appendix A), up to 950 deep boreholes would be required for disposal, assuming no reprocessing or other mechanical consolidation of SNF. Brady, et al. (2009) estimated that with boreholes placed approximately 200 m [650 ft] apart, the total projected U.S. inventory could be disposed in 1 or more areas totaling approximately 30 km^2 [3,000 ha].

General design criteria for boreholes would need to take into account local geologic features, waste package design, and emplacement technology. There are numerous engineering challenges associated with drilling large-diameter holes to depths of 3–5 km [1.8–3.1 mi] where they would be subject to conditions of increased heat and pressure (Ferguson, 1994). Boreholes must minimally be wide enough to accommodate waste packages that may contain items as large as SNF assemblies. According to Beswick (2008), the technology required to drill boreholes of adequate width is either already known or could likely be developed in the near future. Sandia National Laboratories believes that the technology required for DBD is mature enough that it warrants a pilot demonstration that could test its feasibility and viability (Orrell, 2011).

Several studies evaluated the feasibility of drilling large-diameter boreholes to great depths, given that deep drilling technology used in the oil and gas industry generally does not require large-diameter holes. One such study Sweden's SKB commissioned (Harrison, 2000) concluded that, although challenging, it was possible to drill a borehole with a 0.83-m [2.7-ft] diameter to a depth of 4,000 m [13,100 ft] with the then-existing technology. Harrison (2000) estimated it would take about 137 days to drill such a hole at a cost of approximately $7 million, not including any logging and testing activities. In a 2009 presentation, however, Beswick (2009) estimates the cost of drilling 5-km–[3.1-mi] deep, 0.5-m [1.6-ft]-diameter boreholes at $57 million to $65 million with subsequent boreholes costing somewhat less at $41 million to $49 million each. Other estimates include $11 million to $29 million per borehole for holes of diameters of 0.6–0.8 m [1.92–6 ft] (Åhäll, 2006) and $20 million per borehole for a 5-km [3.1-mi]–deep borehole with a 0.44-m [1.5-ft] diameter (Brady, et al., 2009). Because the amount of rock to be removed increases in proportion to the square of the diameter, the economic feasibility of DBD can be expected to diminish quickly with the size of the hole. Gibb (2010) cites a study of drilling technology by Beswick (2008) for the United Kingdom's Nuclear Decommissioning Authority, which concluded a borehole with a useable diameter of 0.5 m [1.6 ft], drilled and cased to a depth of 4,000 m [13,100 ft], is practicable with existing technology. That study estimated that it would take around 9 months to drill and case such a borehole and between 6 months and 2 years to emplace the waste packages, depending on size, number, and method used. The same study also concluded that larger holes up to 0.75 m [2.5 ft] in diameter would be difficult to implement beyond 3 km [1.8 mi], and that 1.0 m [3.3 ft] holes are presently impractical at such depths. However, Beswick (2009) commented that improvements in the drilling process could be made with additional research and development in a number of areas including large diameter drilling tools and drill strings; casing design and installation procedures for large diameters; cementation methods for upper large diameter casing; waste deployment procedure and handling tools; annulus sealing in the disposal zone; and upper borehole seals and near-surface abutment.

Most recent analyses of the DBD concept (e.g., Brady, et al., 2009; Åhäll, 2006; Nirex, 2004) conclude that disposal depths of 3–5 km [1.8–3.1 mi] would be sufficient in low-permeability crystalline rock. In determining how deep a disposal borehole should be, however, local geologic and hydrogeologic characteristics must be considered on a site-specific basis (O'Brien, et al., 1979). If DBD becomes national policy, a regulatory framework for DBD that utilizes generic criteria may be preferable to developing site-specific standards (Brady, et al., 2009).

Borehole diameters must accommodate the diameter of the waste canister with sufficient clearance to enable emplacement (see Section 2.2 for waste canister discussion). Brady, et al. (2009) considered a borehole design with a surface diameter of 1.22 m [4 ft] that would decrease to 0.44 m [1.5 ft] in the disposal zone, as illustrated in Figure 2-1.

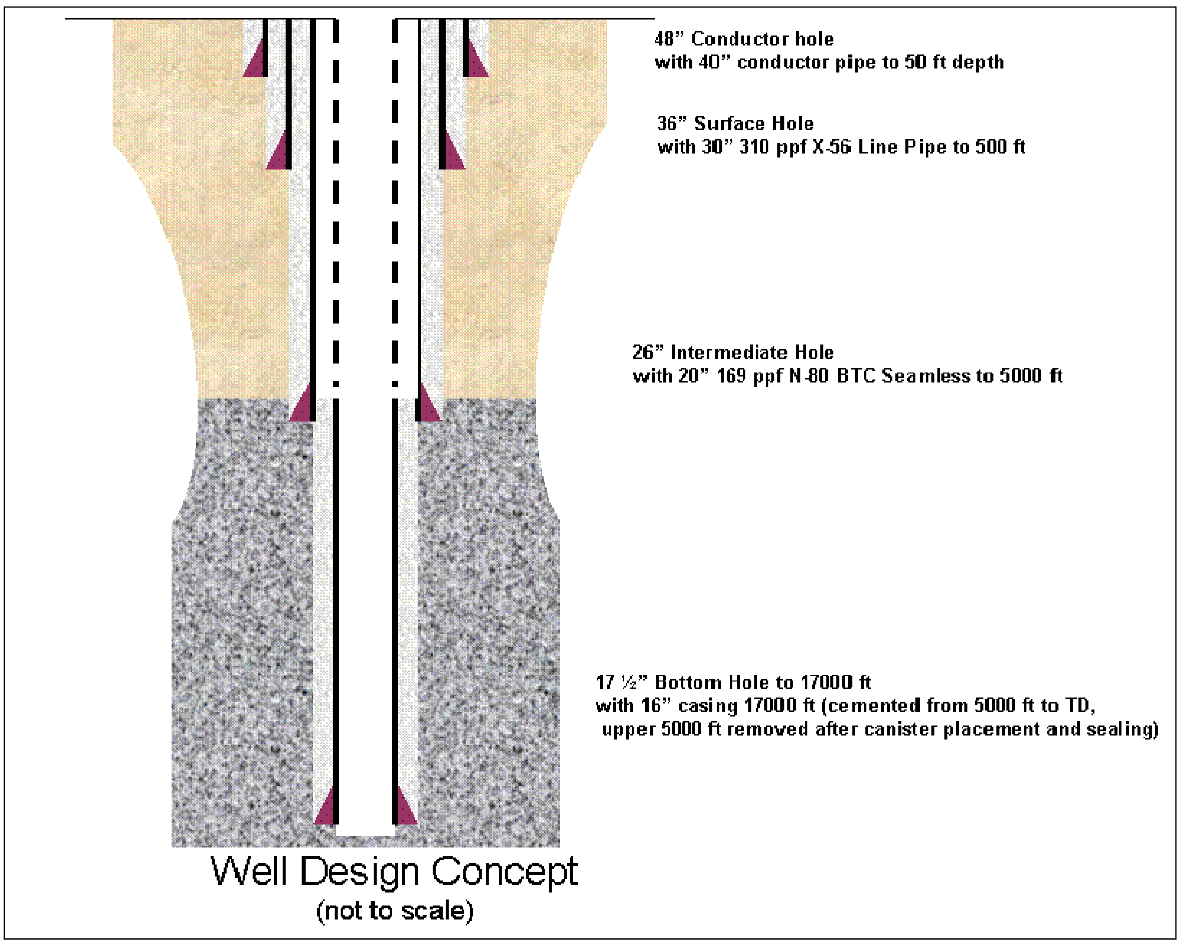

Figure 2-1. Deep Borehole Disposal Drilling Design Concept (Brady, et al., 2009)

With the insertion of casing, the diameter available for waste emplacement packages would be limited to 0.4 m [16 in]. DBD facilities are likely to feature arrays of multiple boreholes. The optimal distance between disposal boreholes would depend on several site characteristics and design considerations, such as rock properties, heat load, and whether there is a need to control temperatures near the waste canisters or within the rock mass. Brady, et al. (2009) assumed a spacing of 200 m [660 ft] would be sufficient in their design scenario, based on analyses showing the thermal perturbation in the rock mass around a borehole is minimal beyond about 100 m [330 ft] for the specified heat load scenario. Should DBD become national policy, further analysis could help to evaluate the question of optimum spacing based on factors such as heat load, rock mechanics, and potential effects on convective water flow.

Utilization of multiple angled, deviated, or fanned boreholes from the same surface location is an attractive option from an economic and land use perspective and one that may warrant regulatory guidance. This approach allows placement of more waste from a single location, minimizing the surface footprint of the DBD facility infrastructure. Even small deviations in drilling angle would result in access to large volumes of rock at depth. However, drilling deviated boreholes through crystalline rock at recommended waste disposal zone depths may pose challenges to current drilling technology. For example, it may be difficult to precisely control deviation at these depths (Nirex, 2004). Furthermore, there may be elevated risk of canister jams during emplacement operations.

Nirex (2004) considered the benefits and disadvantages of lined versus unlined boreholes. A lined borehole may be the only feasible option in terms of providing adequate confidence in borehole stability. A liner could potentially serve as an additional engineered barrier for waste isolation. However, a corroded or degraded liner may provide a pathway for vertical movement of fluid within the disposal zone via the annulus between the rock and the liner that could permit fluid to travel at least up to the point of overlying sealed sections. Under such circumstances an unlined disposal zone might be preferable because dense grout could be used to provide a seal against the borehole wall rock. Management of borehole fluids, whether representative of the local geology or introduced as drilling mud, is another issue that may merit regulatory attention (Nirex, 2004).

2.2 Canister Design

In the DBD concept, waste canister dimensions are constrained by the waste dimensions and the borehole diameter. SNF assemblies come in two types: those used in pressurized water reactors (PWRs) and those used in boiling water reactors (BWRs). Nearly all (98 percent) of U.S. BWR assemblies are uniform in size. Most (80 percent) PWR assemblies are also of uniform size but are slightly shorter and wider than BWR assemblies. BWR assemblies are less than half the weight of PWR assemblies (see Table 2-1).

In perhaps the simplest approach, Hoag (2006) suggested that a standard oilfield casing 5 m [16.4 ft] long with an inner diameter of 31.8 cm [12.5 in] and an outside diameter of 34 cm [13.38 in] could serve as a canister that would hold one PWR assembly or, with considerable extra space, one BWR assembly. Such a canister would offer minimal shielding, thus necessitating design of a process that does not require worker proximity in the canister hoisting and lowering operations. After insertion of the assemblies, end caps would be welded on. In this example, the canister would not possess any significant long-term, waste-isolating characteristics beyond those necessary for emplacement (Brady, et al., 2009), and the waste

Table 2-1. Reference Pressurized Water Reactor and Boiling Water Reactor Fuel Assembly Dimensions and Masses*			
	Length–cm [feet/inches]	**Width–cm [inches]**	**Mass–kg [lbs]**
PWR	405.9 [13' 3"]	21.4 [8.5"]	666 [1468]
BWR	447.6 [14' 7"]	13.9 [5.5"]	297 [655]
*Brady, P.V., 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. Albuquerque, New Mexico: Sandia National Laboratories. 2009.			

isolation capability would be provided by the depth within the rock formation and the plug used to isolate the disposal zone.

Unalloyed or alloyed metals have traditionally been utilized for canister designs due to their strength and durability. Anderson (2004) suggested that DBD canisters could be constructed of copper, which is corrosion resistant in nonoxidizing aqueous environments. Use of titanium canisters has also been recommended (Nirex, 2004). However, utilization of copper or titanium could possibly be cost prohibitive and unnecessary. Additionally, these metals may be in high demand as economic resources, posing the risk that future societies might attempt to mine them. To counter such undesirable outcomes, construction of lead canisters has been proposed because lead is a relatively common material and is less likely to be exploited by deep mining activities (Vicente, 2007). Lead would also offer some degree of radiation shielding during handling.

Canisters could also be constructed of steel alloys, which may not be designed to be corrosion resistant or to last for extended periods of time. Steel may be chosen if it is demonstrated that the host rock and plugging materials can effectively serve as the primary barrier preventing waste from returning to biosphere (Hoag, 2006).

In addition to SNF assemblies, additional HLW forms may include vitrified or ceramic HLW (Anderson, 2004). For HLW in any form, the disposal canister must be sturdy enough to prevent releases and exposure during waste emplacement. The dimensional constraints on DBD canisters provide minimal shielding from radiation. Additionally, existing oilfield technologies require close proximity of workers to the borehole opening, so appropriate waste emplacement technology and methodology would need to be developed to remotely lower canisters into the hole.

From a regulatory perspective, performance-based standards may be needed to ensure adequate canister shielding; ability to withstand drops; and the ability to withstand high pressures, temperatures, chemical environments, and wall friction during emplacement operations. For a given design concept, it would be necessary to specify whether the canister is expected to serve as an engineered barrier for an extended period of time or whether it would be permissible for the canister to degrade relatively quickly.

Presently, there does not appear to be a preferred conceptual model on whether the transfer of waste into DBD canisters would be conducted at or near the borehole operation facility or elsewhere and transported to the borehole site. Hoag (2006) describes a system in which DBD canisters are loaded immediately prior to emplacement. Most other recent analyses of DBD do not address this question. Assuming the relatively thin DBD canisters would not be suitable for transportation, the movement of waste from present storage to the DBD canisters could require at least two transfer operations: for example, one transfer from storage casks to transportation packaging and a second transfer from transportation packaging to DBD canisters. The potential for additional risk incurred by multiple transfer operations should be assessed when considering DBD feasibility.

2.3 Canister Emplacement

Once onsite at the operations facility, canisters would need to be reoriented to the vertical position prior to insertion into a borehole. Depending on the type and form of HLW waste, radiation shielding systems or facilities may be needed to ensure worker safety as canisters are received, inspected, stored temporarily onsite, reoriented, and finally lowered into boreholes. The extent of external shielding required may depend on the inherent shielding capabilities of the canisters as well as the type and amount of waste contained in them. Remote handling equipment would be essential for limiting onsite worker radiation exposure during emplacement if sufficient shielding is not afforded by the canister.

Approximately 200 to 400 canisters could be inserted per borehole, assuming 5 m [16.4 ft] spacing throughout the 1–to 2–km [0.6–1.2-mi] disposal zone of the borehole. Hence, numerous trips into and out of the borehole will be required, while ensuring safety and providing for a reasonably efficient rate of emplacement. Hoag (2006) presents a concept for emplacement that involves remotely lowering canister strings through an open hole via cable or drill pipe from outside a shielded area. Harrison (2000) described a potential emplacement method in which drilling mud is replaced by bentonite-based mud that is as thick as possible while still allowing the canister to be pressed downward without damage. The purpose of pressing the canisters downward through the mud, as opposed to lowering through an open hole, would be to provide a safety advantage by reducing the risk of dropped canisters. To improve efficiency, strings of two or more canisters would be fitted together in a column with bentonite blocks between them before being pushed down. Brady, et al. (2009) suggest that emplacement of strings with groupings of as many as 10 to 20 canisters could be considered; however, they did not discuss the equipment or methodology needed to work with such long canister strings.

Specially designed hoisting and lowering equipment would be required to reorient, insert, and lower canisters. Redundant safety systems would be required to counter any equipment failures. Detailed protocols and specially engineered equipment would need to be developed to insert canisters, interlock multiple canisters as part of strings, and release the waste packages after they have been lowered into the desired position.

Canister breaches prior to final plugging could pose a risk during the waste emplacement phase, especially if radioactive wastes escape containment and contaminate the hoisting equipment that returns to the surface. Hence, the structural integrity of canisters during the emplacement phase would need to be assessed. The compressive stress from the weight of many canisters is one potential mode for canister failure prior to final plugging. These stresses could be alleviated by using bentonite mud or similar material to provide support to the canisters, or inserting bridge plugs at intervals throughout the waste disposal zone to transfer some of the load to the borehole walls before further canisters are emplaced (Nirex, 2004). Filling the canisters with packing material that has high compressive strength could also be considered to protect individual canisters from crushing under high hydrostatic or lithostatic pressures. Retrieval of breached canisters, even if technically feasible, may have consequences for worker health and safety.

Emergency preparedness plans should be in place to handle above- and belowground incidents of canister breaching, leakage, or spillage during emplacement.

During the emplacement phase, canisters may not suffer breach failures but could still become "stuck" or "jammed" during the descent. During conventional oilfield operations, it is not uncommon for drilling bits to be dropped or become stuck. Statistics pertaining to such episodes could be evaluated to aid in understanding how human reliability and equipment reliability may affect borehole disposal operations. Tools and techniques are available to remedy these problems in conventional drilling operations. However, retrieving jammed or dropped canisters in a DBD system could pose additional engineering challenges because of the much greater weight of a waste package compared to a drilling bit and the need to ensure radiological protection. If efforts to retrieve canisters or to break canister impasses are unsuccessful, one possible option would be to leave the jam in place and backfill and seal the borehole, provided that the jam does not occur above the approved waste disposal zone.

3 POSTCLOSURE WASTE ISOLATION

In this section, the concept of DBD is discussed in terms of its natural system and engineered system characteristics likely to be important to waste isolation after final plugging of the deep disposal borehole.

3.1 Natural System

A suitable site for DBD requires access to a tectonically stable, laterally extensive, sparsely fractured, low-permeability rock formation that is accessible within approximately 1–2 km [0.6 –1.2 mi] or less below ground surface. The most common DBD concept discussed in recent literature involves disposal in crystalline rock (e.g., granite), which is more likely to meet these characteristics compared to sedimentary or volcanic rock formations. The main barrier capability is provided by the low permeability and porosity of the rock combined with the long travel distance of 3 km [1.8 mi] or more to the accessible environment. Sites with accessible deep crystalline bedrock are relatively common within the United States, affording the potential, from a geotechnical perspective, to identify several disposal sites that could limit the amount of waste disposed at any one site and potentially shorten transport routes.

Within the disposal zone, at depths of approximately 3–5 km [1.8–3.1 mi], the low permeability of the crystalline rock would be the key natural system barrier to contaminant migration. The permeability of unfractured granite is very low, on the order of 10^{-19}–10^{-18} m^2 [~10^{-7}–10^{-6} darcy] (e.g., Freeze and Cherry, 1979). To put this permeability number into perspective, under a hydraulic gradient of 1.0, which is much higher than typically encountered in such formations, it would take on the order of 3,000–30,000 years for a nonsorbing radionuclide to travel 1 m [3.2 ft] by advective flow. Diffusive transport is also significantly limited by the low porosity of crystalline rocks, which typically is on the order of one percent or less at such depths. Thus, with the uppermost waste containers placed 3 km [1.8 mi] or more below the surface, a properly sealed disposal borehole could potentially isolate waste for several million years or longer.

The barrier capability afforded by the low permeability and porosity could be compromised, however, by any interconnected fractures that provided a relatively fast transport pathway to the accessible environment. Although massive crystalline rock formations are typically sparsely fractured at depth, permeable fracture networks in granite formations have been documented. For example, Younger and Manning (2010) report discovering fractured granite at more than a 400-m [1,300-ft] depth with permeability greater than 200 darcy, which is comparable to a high-permeability coarse gravel aquifer. Accordingly, the hydraulic isolation of disposal boreholes would need to be verified prior to waste emplacement.

A performance assessment analysis for DBD by Brady, et al. (2009) recognized the potential for enhanced permeability along the borehole due to the excavation damage of rock during borehole construction. Other factors affecting the adjacent rock permeability may also be important and would merit further evaluation if DBD is pursued. For example, additional fracturing around the borehole could be caused by the stresses imposed by the temperature gradient resulting from the heat load. Such fracturing could enhance permeability along the heated zone of the borehole. Additionally, as mentioned in Section 2.1, potential pathways along the borehole caused by improper or degraded sealing material or corroded liner material could also lead to a high-permeability vertical flow pathway. Although high lithostatic pressures at such great depths could result in resealing of any induced fractures or other flow paths, this potential sealing process is not fully understood in the context of waste isolation. Hence, should

DBD be pursued as a potential alternative, additional modeling or experimental studies of rock mechanics and sealing of fractures under high overburden pressure should be pursued. Thermal effects on rock are further discussed in Section 3.2.

Geochemical conditions favorable to DBD include the presence of saline, reducing pore waters of high ionic strength typically found at such great depths. Reducing chemical environments in granite generally result in much lower radionuclide solubilities and much greater sorption partitioning coefficients (e.g., Crawford, et al., 2006). Additionally, depending on the type of waste canister selected, reducing environments can potentially provide for much slower corrosion rates. High-ionic-strength, saline brines also limit or eliminate the potential for degraded waste forms or corrosion products to form colloids that might facilitate transport of strongly sorbing nuclides, such as plutonium or americium (Brady, et al., 2009). Another benefit of saline pore water at depth is that it has a higher density than the typically less saline waters at shallower depths. The increasing water density with depth provides a convectively stable configuration in which the denser fluids will tend to remain in place. These favorable geochemical conditions conceptualized for a DBD system would significantly support the waste isolation capability. Hence, geochemical conditions within the disposal zone would need to be characterized and evaluated in any DBD system.

3.2 Engineered System

In the context of this report, the engineered system refers to the waste canisters, any sealing material inserted into the deep borehole, and any resulting interactions or effects on the surrounding near field. Based on reviews of available literature, three aspects of the engineered system are likely to be of high importance to waste isolation capability of a DBD system, but are presently uncertain in the context of DBD. These are

- Differential thermal expansion of host rock that may lead to fracturing
- Borehole sealing processes and materials
- Gas generation and thermal expansion of formation fluids, which could drive fluids upward from the disposal zone

<u>Differential Thermal Expansion in the Host Rock</u>

Differential thermal expansion could occur in the host rock around the disposal zone because of unequal temperature gradients normal and parallel to the borehole axis and nonhomogenous temperature distributions within and around the disposal zone (e.g., Gibb, et al., 2008b). If rock stress due to differential thermal expansion is sufficient to cause fracturing, the resulting fractured zones in the host rock could connect to form relatively permeable flow paths for radionuclide-bearing fluids. Whether rock stress due to differential thermal expansion is sufficient to cause fracturing depends on the magnitude and history of thermal load and the thermal and mechanical properties of the host rock. For example, an analysis of a conceptual design (Nirex, 2004, Figure 9) indicates that the rock immediately above the disposal zone could be subjected to tensile stress of approximately 69 MPa [10 ksi], which could be large enough to cause tensile fracturing of granitic rock. The disposal design thermal load is expected to play a key role in the potential for fracturing because of its effect on temperature.

The calculated maximum temperature at the borehole wall in the disposal zone could vary from a few tens to hundreds of degrees Celsius depending on the content and associated heat load of deployed canisters (Nirex, 2004; Gibb, et al., 2008b, Section 3.2; Brady, et al., 2009). Most recent analyses of DBD have focused on so-called low-temperature systems, in which disposal canisters contain a single SNF assembly or similar heat load. High-temperature storage concepts also have been proposed (e.g., Attrill and Gibb, 2003; Gibb, et al., 2008a). In the high-temperature concept, which is also known as "deep rock melting," the composition and amount of HLW in the containers would be designed to deliver the energy necessary to achieve maximum temperatures of 800–900 °C [1,772–1,652 °F] at the container/rock interface. After the boreholes have been filled and sealed, the heat generated by continued decay may be expected to partially melt the immediately adjacent granite rock. Recrystallization of the rock would then occur as the waste cools, encasing it in a zone of dry, newly crystallized rock, which would function as a barrier impeding any exchange with the rock outside the melt zone (Gibb, 1999). It is not clear, however, whether such melted and recrystallized rock would perform any better as a barrier than the original unaltered host rock surrounding the borehole. In other high-temperature conceptual scenarios, the melting of rock would result in waste packages that continue to sink deeper into the rock until the heat load is sufficiently depleted in what is referred to as "deep self-burial" (Nirex, 2004).

Because of the importance of identifying potential flow paths for transport of radionuclides to the biosphere, it would be necessary to develop a better understanding of the mechanical response of the host rock to thermal loads, and the potential development of preferred flow paths. Because differential thermal expansion is an inherent feature of the DBD concept, the minimum information needed for assessment may include the technical basis for the potential for rock fracturing due to differential thermal expansion. In their analysis of features, events, and processes for a DBD performance assessment, Brady, et al. (2009) categorized thermally induced stress changes in the near field as a "high priority" process that should be included; they also recognized that consideration of this process could pose modeling challenges due to the complexity of representing coupled thermal, hydrological, mechanical, and chemical processes.

Borehole Sealing

Conceptual DBD designs include sealing the borehole within and above the disposal zone to restore the disposal system permeability to a value not greater than the initial host rock permeability. Several sealing approaches and materials have been discussed. For the borehole above the disposal zone, Brady, et al. (2009) indicated possible sealing with bentonite, asphalt, or concrete, and Gibb, et al. (2008a) indicated possible backfilling with crushed host rock that could be sealed at intervals using one or more methods, such as partial melting and subsequent recrystallization of the backfill and wall rock. The sealing concept discussed for the disposal zone varies with disposal design features, such as low temperature versus high temperature or specific gravity of canisters. Brady, et al. (2009) suggested that a bentonite-water slurry placed around the canisters would later harden to form a buffer and seal. Gibb, et al. (2008c) suggested a similar approach using cement grout for low density (i.e., those with a specific gravity smaller than about four) canisters. For high density canisters (i.e., specific gravity from 8–11) and relatively low-temperature design, Gibb, et al. (2008c) suggested using a metallic backfill (e.g., lead-based alloy) that would melt and later recrystallize to encase the canisters in the borehole. For a relatively high-temperature design, Gibb, et al. (2008c) discussed surrounding the high heat-generating canisters with an aqueous slurry of crushed granite. The canisters would produce enough heat to partially melt the crushed granite and part of the host rock, and the melt would later recrystallize, potentially entombing the canisters as the waste cools.

The borehole seals are designed to ensure the borehole or annulus does not form a preferential flow path for any radionuclide-bearing fluids. If the borehole seal could fracture because of differential thermal expansion, the resulting fracture zones could connect with fracture zones in the surrounding rock to form preferential flow paths. Clearly, each DBD disposal option would present its own challenges in terms of needs for experimental verification and performance confirmation to ensure the sealing process can work as conceptualized with high confidence. Because of the critical importance of the borehole seal to maintain waste isolation over extended time periods, it may be necessary to develop (i) confirmable technical criteria, specifications, or standards or (ii) performance confirmation criteria to develop confidence in the effectiveness of the seal design and placement.

Gas Generation and Thermal Expansion of Formation Fluids

Gas generation at the disposal horizon may result from corrosion of waste canisters or waste forms or from gas release from the host rock as the rock heats up (Ferguson, 1994; Xu, et al., 2008; Schwartz, 2009; Brady, et al., 2009). Xu, et al. (2008) estimated that gas pressure due to hydrogen generation as a result of corrosion under anaerobic conditions is unlikely to increase enough to affect mechanical response of the host rock. Additional analysis of pressure buildup due to gas release may be needed to determine whether two or more gas generation processes could combine to produce a significant effect on rock stress when considered along with the effects of differential thermal expansion.

Thermal expansion of liquids and gases within the heated zone of the host rock could occur and may cause pressure buildup. For example, Brady, et al. (2009, Section 4.3.3) calculated fluid pressure histories in the host rock for a hypothetical case and concluded that the effects of buildup of fluid pressure on potential rock fracturing could be excluded from further analysis because the maximum fluid pressure should be smaller than the horizontal rock stress. However, additional study of fluid pressure buildup may be needed to understand how the pressure may interact with stress changes due to differential thermal expansion in the host rock. Although Brady, et al. (2009) ruled out the effects of thermal expansion of liquids on host rock integrity, they did consider this process as a driving force for advective flow of water up the borehole where permeabilities are likely to be higher than those of the undisturbed bedrock.

4 CONCLUSIONS

This report provides a brief history and general overview of the DBD concept for geologic disposal of HLW and SNF. Available literature was reviewed to identify the aspects of potential DBD systems most important to performance and to highlight critical uncertainties from preclosure operational safety and postclosure waste isolation perspectives.

According to the available literature, the construction of boreholes in hard rock to the depths necessary for waste isolation is technologically possible with some modification to existing oilfield technology and can be economically feasible. Significant technological uncertainties and potential safety challenges for preclosure operations remain in the areas of waste handling and procedures for lowering waste into arrays of disposal boreholes. Should the nation decide to pursue DBD as a potential option for geologic disposal, focused regulatory analyses would need to be undertaken to evaluate whether existing regulations are sufficient to ensure operational safety or whether new performance-based standards are needed. Because the DBD concept imposes several constraints on waste canister design, performance-based standards or guidance may be needed to ensure canister shielding; ability to withstand drops; and the ability to withstand high pressures, temperatures, chemical environments, and wall friction during emplacement operations. For any given design concept, it would be necessary to specify whether the canister is expected to serve as an engineered barrier for an extended period of time or whether the canister is expected to degrade relatively quickly. Performance-based standards also would need to address the safety and reliability of transporting, hoisting, lowering, interlocking, and potentially retrieving a canister from a deep borehole. Small-scale pilot studies would be essential to demonstrate the implementability of the DBD concept and could be used to inform the development of a regulatory framework.

Regulatory analyses to define or evaluate the need for postclosure performance standards will also be needed if the DBD concept becomes national policy. Standards for individual protection developed for the Yucca Mountain project (40 CFR Part 197 and 10 CFR Part 63) could be adapted for application to DBD, but other aspects of the Yucca Mountain regulatory framework cannot be applied. For example, retrievability of waste is unlikely to be a viable option for DBD. Hence, a policy decision must be made regarding the desirability or feasibility of postclosure canister retrievability to permit retrieval for up to 50 years after waste emplacement. The concept of multiple barriers, consisting of both engineered and natural system components, may not be applicable to DBD, because the natural system would be the only significant barrier to radionuclide migration.

Other potential regulatory considerations include the possibility that phased licensing may not be applicable to DBD facilities because emplacement is likely to take only months or years per borehole, as opposed to decades for a conventional mined geologic repository. Therefore, a single license application may need to contain all the information required for licensing. Assuming that multiple locations would be utilized as part of a national DBD policy, it may be preferable to adopt a reactorlike licensing process. Under this scenario, a standardized methodology for DBD would be approved and individual DBD facilities would be required to secure site permits.

Compared to the more conventional mined geologic repository concept, a DBD system would place the waste much deeper and has the potential to provide effective waste isolation for a comparable timeframe. Under most concepts discussed in the literature, DBD is essentially a single barrier system that relies on the low permeability and porosity, and the geologic stability of deep, massive crystalline rock formations. Accordingly, strong emphasis should be placed on better understanding of the uncertainty and potential risk significance related to the long-term performance of sealing materials and thermal effects on rock stress and fluid pressure that could lead to fracturing and upward hydraulic gradients. Focused modeling or experimental studies would improve understanding and quantification of these uncertainties for DBD disposal of HLW and SNF.

Consideration should also be given to whether certain waste forms are better suited to DBD disposal than others. For example, glass or ceramic waste forms from reprocessing could be designed specifically for deep borehole storage such that heat loads are compatible with host rock characteristics. Glass or ceramic waste forms also could be shaped to fit the geometric constraints within a DBD system. Additionally, the lack of retrievability may be less of a concern for glass and ceramic waste forms because it is generally not suitable as a potential future fuel source.

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