Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste

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Abstract

A reference design and operational procedures for the disposal of high-level radioactive waste in deep boreholes have been developed and documented. The design and operations are feasible with currently available technology and meet existing safety and anticipated regulatory requirements. Objectives of the reference design include providing a baseline for more detailed technical analyses of system performance and serving as a basis for comparing design alternatives.

Numerous factors suggest that deep borehole disposal of high-level radioactive waste is inherently safe. Several lines of evidence indicate that groundwater at depths of several kilometers in continental crystalline basement rocks has long residence times and low velocity. High salinity fluids have limited potential for vertical flow because of density stratification and prevent colloidal transport of radionuclides. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the retardation of key radionuclides. A non-technical advantage that the deep borehole concept may offer over a repository concept is that of facilitating incremental construction and loading at multiple perhaps regional locations.

The disposal borehole would be drilled to a depth of 5,000 m using a telescoping design and would be logged and tested prior to waste emplacement. Waste canisters would be constructed of carbon steel, sealed by welds, and connected into canister strings with high-strength connections. Waste canister strings of about 200 m length would be emplaced in the lower 2,000 m of the fully cased borehole and be separated by bridge and cement plugs. Sealing of the upper part of the borehole would be done with a series of compacted bentonite seals, cement plugs, cement seals, cement plus crushed rock backfill, and bridge plugs. Elements of the reference design meet technical requirements defined in the study. Testing and operational safety assurance

requirements are also defined. Overall, the results of the reference design development and the cost analysis support the technical feasibility of the deep borehole disposal concept for high-level radioactive waste.

Acknowledgements

CONTENTS

FIGURES

TABLES

NOMENCLATURE

BHA	bottom hole assembly
BOPE	blow out prevention equipment
BWR	boiling water reactor
CSH	calcium-silicate-hydrate
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
HM	heavy metal
ID	inner diameter
OD	outside diameter
PC	port collar
psi	pounds per square inch
PWR	pressurized water reactor
ROP	rate of penetration
WOB	weight on bit

1.   INTRODUCTION

This report describes a reference design and general operational procedures for the disposal of high-level radioactive waste in deep boreholes. The reference design and operations are considered to be feasible with currently available materials, drilling, and engineering technology. In addition, the reference design was developed to be consistent with existing safety and anticipated regulatory requirements. Although numerous potentially viable design alternatives exist for a deep borehole disposal system, the reference design described in this report is intentionally simple. It is our belief that this simple design would maximize the probability of success of an initial implementation of the design and subsequent waste loading operations. This reference design can serve as the basis for cost and safety comparisons among alternative approaches.

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 (O'Brien et al., 1979; Woodward and Clyde Consultants, 1983; Juhlin and Sandstedt, 1989; Heiken et al., 1996; NIREX, 2004; Anderson, 2004; Gibb et al., 2008). 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.
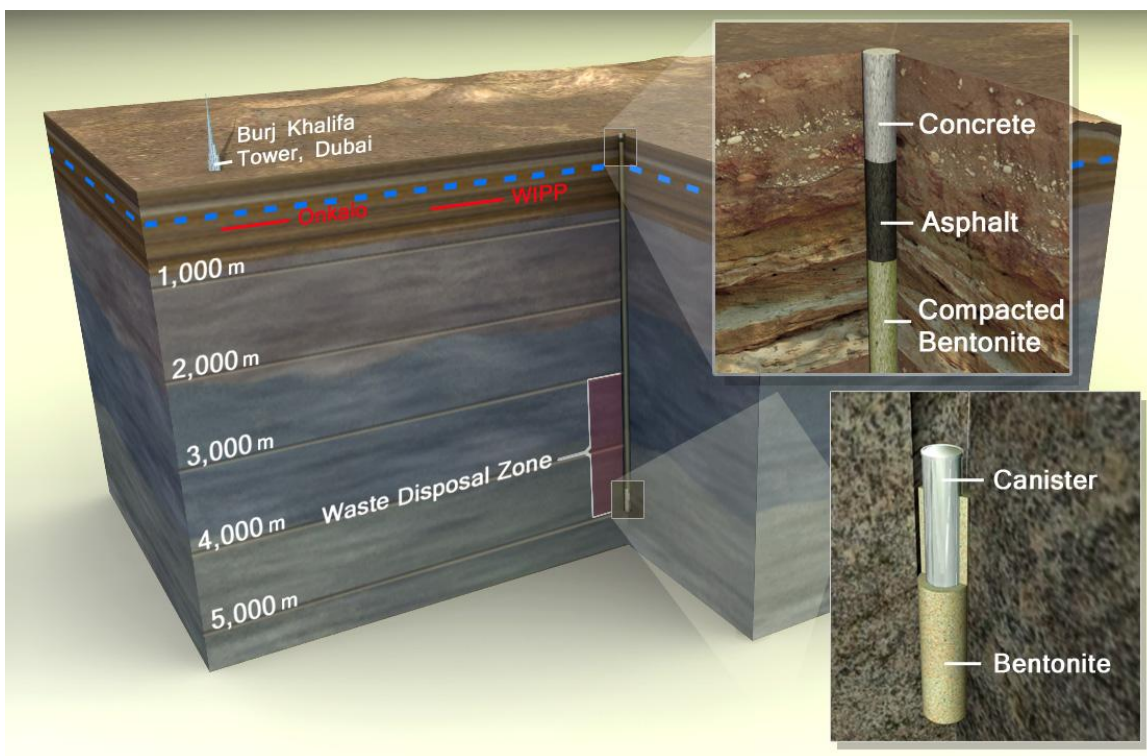
Figure 1. Generalized Concept for Deep Borehole Disposal of High-Level Radioactive Waste.

1.2. Previous Deep Borehole Disposal Design Studies

Although relatively simple in concept, actual implementation of deep borehole disposal requires assessment of many specific elements of the disposal system and has yet to be done or attempted. Several previous studies have evaluated various components of the system with regard to feasibility and made recommendations for technologies to be employed.

The evolving feasibility and cost of drilling deep boreholes have been evaluated by several studies, based primarily on experience from the petroleum industry, geothermal drilling, and scientific boreholes, such as the Gravberg-1, Kola, and KTB wells. Woodward-Clyde Consultants (1983) developed a reference deep borehole disposal system design that included a borehole with a diameter of 20 inches (0.51 m) to a depth of 20,000 ft (6100 m) based, in part, on projections of drilling technology thought to be available by the year 2000. Juhlin and Sandstedt (1989) concluded that deep boreholes with a diameter of up to 0.80 m suitable for disposal of used nuclear fuel could be drilled and constructed to a depth of 4 km, but at a total disposal cost greater than for the KBS-3 mined repository concept. Juhlin and Sandstedt also discuss the impacts of anisotropy in horizontal stress on borehole stability and the formation of borehole breakouts, which may result in conditions that interfere with drilling or waste emplacement at depths greater than 1 to 2 km. Ferguson (1994) concluded that boreholes of an unspecified diameter could be drilled to a depth of 4 km for the disposal of excess plutonium. Harrison (2000) proposed a borehole with a final depth of 4000 m and a diameter of 0.762 m as a feasible design for a deep borehole disposal system. A review of previous work on deep borehole disposal by Nirex (2004) generally supports the feasibility of constructing the necessary deep boreholes. A more systematic analysis of borehole diameter versus depth in completed boreholes by Beswick (2008) suggests that a borehole diameter of 0.30 m is readily achievable to a depth of 5000 m and a diameter of 0.50 m may be achievable, but that diameters of greater than 0.50 m are, in practice, not obtained with current drilling technology. Beswick also emphasizes the constraints of borehole stability at depths of several kilometers.

Multi-lateral boreholes are routinely used in the petroleum industry and a fanned array of inclined or horizontal boreholes from a central borehole has been suggested for a deep borehole disposal system by Chapman and Gibb (2003) and Gibbs (2010). A multi-lateral borehole system could potentially reduce drilling costs, limit the surface footprint of a borehole disposal program, and would result in a single seal system in the central access borehole. However, a multi-lateral system increases the complexity of the waste emplacement process and is not recommended by Beswick (2008).

Various designs for casing in the borehole have been proposed in previous studies. The reference borehole design in Woodward-Clyde Consultants (1983) proposed an uncased hole in the disposal zone from 10,000 ft (3050 m) to 20,000 ft (6100 m) depth and removable casing in the seal zone between 4,000 ft (1220 m) and 10,000 ft (3050 m) depth. The Juhlin and Sandstedt (1989) design uses a densely perforated "high void ratio" casing in the disposal zone to assure penetration of grouts or sealing material into the annulus between outer surface of the casing and the borehole wall. Intermediate depth casing in the Juhlin and Sandstedt design would be removed for setting the seals. Beswick (2008) suggests the possible use of expandable casing or well screen in the disposal zone, which is deformed outward to conform to the borehole wall by an oversized mandrel that is drawn upward through the casing.

The reference waste canister design in Woodward-Clyde Consultants (1983) is a carbon steel canister that is 10 ft (3.0 m) in length and 12.75 inches (0.32 m) outside diameter (OD). The Woodward-Clyde Consultants design assumes that the canisters will contain a fill material in addition to the used fuel assemblies to resist deformation of the canister from hydrostatic pressure. The Juhlin and Sandstedt (1989) study considers alternative canister designs

constructed with titanium or copper, 5 m in length with an inside diameter (ID) of 0.390 m and an OD of 0.500 m. The base canister design in Juhlin and Sandstedt (1989) includes a support matrix to fill voids within the canister. Hoag (2006) presented a waste canister for deep borehole disposal designed to contain a single pressurized water reactor (PWR) assembly or multiple boiling water reactor (BWR) assemblies. The Hoag design is 5 m in length with an OD of 0.340 m and an ID of 0.315 m; and would be constructed of T95 or C95 steel casing. The waste canister proposed in Hoag (2006) would be filled with a silicon carbide grit as packing material to resist external hydrostatic pressure on the waste canister. Canisters would be connected with external buttress threaded coupling tubing in the Hoag design.

Woodward-Clyde Consultants (1983) contains a relatively detailed design for the surface facilities that would be used for the transfer of waste canisters from transportation casks to insertion into the disposal borehole. The Woodward-Clyde design requires a separate waste canister emplacement rig that includes an elevated drill floor, a shielded room below the drill floor to position the transportation cask over the borehole, and a subsurface basement for insertion of the unshielded waste canister into the borehole. The general layout of the emplacement rig is shown in Figure 2.

The waste emplacement design in Woodward-Clyde Consultants (1983) calls for pumping cement grout to surround the waste canister string after it is positioned in the waste disposal zone. The Juhlin and Sandstedt (1989) waste emplacement procedure includes the introduction of higher density bentonite mud at the bottom of the borehole prior to lowering the waste canister string into the disposal zone. Beswick (2008) notes that the deployment of high-density mud at each stage of waste canister emplacement would not be difficult to engineer. Beswick (2008) suggests the use of bridge plugs and compacted bentonite blocks between the waste string stages to support the load of overlying canisters and serve as a barrier to flow.

An alternative high-temperature waste emplacement strategy has been suggested by Gibb (1999) and Gibb et al. (2008b). In this strategy a greater mass of waste is emplaced in a larger diameter borehole and the heat output of the waste is sufficient to melt the surrounding granitic host rock. As heat output from the waste declines the melt would recrystallize, encapsulating the waste in a low-permeability rock mass and sealing the borehole. Another lower-temperature approach described in Gibb et al. (2008a) involves the introduction of metal alloy shot in the borehole around the waste canisters to serve as a high-density support matrix. The metal alloy would have a melting temperature of less than 200 ºC (392 ºC), would be melted by decay heat from the waste, and would support the waste canisters by buoyancy. As temperatures decline the high-density support matrix would serve as an additional barrier to the release of radionuclides.

The reference design for borehole seals in Woodward-Clyde Consultants (1983) includes the emplacement of alternating plugs of a gravel- and bentonite pellet- slurry; and cement grout. Juhlin and Sandstedt (1989) suggest emplacement of highly compacted cylindrical bentonite blocks in bentonite mud within the primary seal zone. The Juhlin and Sandstedt design includes separate asphalt and concrete seals in the upper 500 m of the disposal borehole.
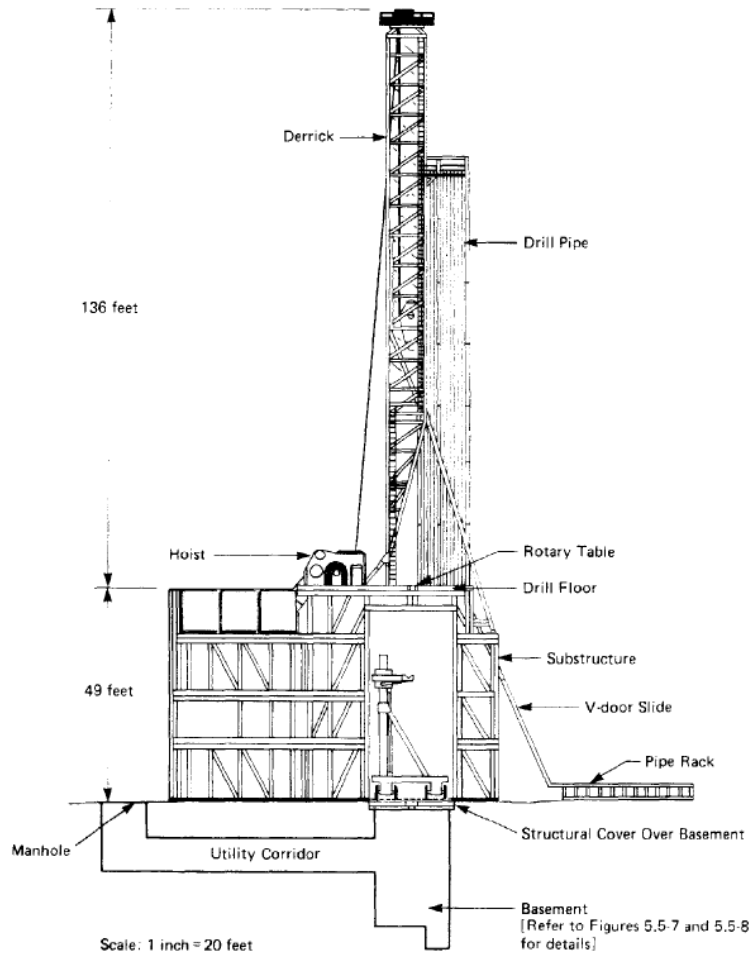
Figure 2. Generalized Schematic of the Waste Canister Emplacement Rig (from Woodward-Clyde Consultants, 1983).

Several design elements and operational procedures relevant to the deep borehole disposal concept were successfully developed and implemented in the Spent Fuel Test – Climax program at the Nevada Test Site (Patrick, 1986). Although this program was a test of disposal in a mined repository in granite, the canisters containing commercial PWR used fuel assemblies were lowered to and retrieved from the underground test facility via a borehole. The 11 stainless steel waste canisters had a diameter of 0.36 m and length of about 4.5 m and each contained a single PWR fuel assembly. The surface handling of loaded waste canisters was accomplished with a truck and transport cask system in which the cask was raised to a vertical position over the borehole for insertion of the canister. Canisters were lowered through a cased borehole with in inside diameter of 0.48 m using a wire-line hoist to a depth of about 420 m. After emplacement of the waste canisters in the floor of the underground test facility and a test duration of about 3.5 years, the canisters were retrieved and hoisted back to the surface through the same borehole. Test operations were conducted successfully, safely, and with minimal radiation exposure to workers.

1.3. Objectives of the Reference Design Activity

The reference design and general operational procedures for the disposal of high-level radioactive waste in deep boreholes described in this report constitute a synthesis of information developed by an interdisciplinary team. The members of this team bring together technical expertise in radioactive waste management, drilling engineering, geohydrology, geochemistry, and geomechanics for the selection of the reference design. The overarching objective of this task is to develop a simple and practically achievable, internally consistent system for waste disposal that meets regulatory requirements for operational safety and acceptable long-term risk to the public.

Individual objectives of the reference design task include

- Develop an update to the conceptual design for deep borehole disposal described in Brady et al. (2009). The updated reference design includes more detail on the design components, incorporates technical insights on total system behavior, and more fully evaluates the engineering aspects of the system.

- More completely evaluate the feasibility of all elements in the deep borehole disposal system, including associated operational plans. Consideration has been given to available materials, interaction of the design components with the high-pressure, high-temperature, and high-salinity deep borehole environment, and operational assurance in deployment of the disposal system.

- Consider preliminary design alternatives. Developing the reference design has provided an opportunity to evaluate potential design alternatives and to consider tradeoffs among operational assurance, long-term safety, and cost.

- Provide a reference design for performance assessment and risk analysis. The reference design can serve as a design basis for more detailed analysis of disposal system performance.

- Provide a reference design for more accurate cost estimates. The reference design and associated operational plan will allow a more complete cost estimate for implementing a deep borehole disposal system.

1.4. Criteria Used for Selecting the Reference Design and Operations

Selection of the reference design outlined in this report is based on the following prioritized list of subjective criteria: (1) engineering and operational feasibility, (2) safety and engineering assurance, and (3) simplicity, and (4) cost and efficiency.

The feasibility assessment assumes currently available drilling and borehole construction technology. The reference design also favors the use of readily available materials, such as standard borehole casing and canister connections. Although specially built engineering systems will be required for some components of the deep borehole disposal system (e.g., for transport and insertion of waste canisters at the top of the borehole), the engineering challenges are similar to those associated with emplacement of waste in mined repositories and can be overcome.

Safety and engineering assurance are considered with regard to preclosure and postclosure risks in the development of the reference design. Preclosure risks include exposure of workers, accidents, and the potential for operational failures (e.g., waste canisters lodged in the borehole above the disposal zone). Postclosure risks are associated with potential releases of radionuclides to the biosphere, generally at very long times in the future. The most likely postclosure risks are related to thermally driven fluid flow and the effectiveness of the seals system, as evaluated in a preliminary manner by Brady et al. (2009). Some decisions made in the development of the reference design involve tradeoffs between assurance of preclosure and postclosure safety (e.g., fully cased borehole in the waste disposal zone versus the ability to set seals against the borehole walls within the disposal zone). Given the high degree of geological isolation inherent in the deep borehole disposal concept, operational assurance of being able to emplace the waste canisters at the desired depth is generally favored in these decisions.

Keeping the design and operations simple is important for a first demonstration. Because the deep borehole concept has never been implemented, there are likely to be a number of lessons learned from a working demonstration. One key concern is waste emplacement. The need for retrieval of waste during operations must be avoided. A stuck waste container or string during the emplacement operation would greatly tax current engineering capabilities. By keeping the design simple and accounting for this key concern, and by appropriate characterization of the target formation, the probability of a lodged canister condition can be kept near zero.

Costs and efficiency are subjectively considered in selection of the reference design; however, no formal, quantitative effort is made to optimize the system design. Costs are related to feasibility and are analyzed accordingly. Many design alternatives are available, but attempts to optimize the design and operations are premature, given the current technical maturity of the deep borehole disposal concept.

2. BOREHOLE CONSTRUCTION

2.1. Borehole Requirements

Technical requirements of the reference design include

- Borehole is drilled and completed to a depth of about 5,000 m with the waste disposal zone located between 3,000 and 5,000 m depth.

- Borehole and casing system must have sufficient stability and durability to provide a high level of assurance that waste canisters can be emplaced at the desired depth, with minimal probability of canisters becoming stuck during emplacement.

- Borehole and casing must have sufficiently large diameter to accommodate emplacement of waste canisters.

- Deviation of the borehole from its designed trajectory must be controlled such that the distance between any two boreholes is greater than 50 m at a bottom depth of 5,000 m. Modeling has shown the thermal interference between disposal boreholes is relatively small for spacing of greater than 50 m. Drilling of multiple boreholes in an array must preclude the possibility of intercepting another borehole in which waste has already been emplaced. The spacing of waste disposal intervals at sites with multiple boreholes must meet thermal management requirements for disposal.

- Borehole and casing system must be designed such that casing can be removed from intervals where borehole seals are to be set. Optimal performance of borehole seals requires direct contact between seals and borehole wall.

- Casing and grout in the waste disposal zone must allow thermal expansion of fluid and flow into surrounding host rock to avoid overpressuring of fluid surrounding waste canisters.

- Drilling and borehole construction must be conducted to allow characterization of host rock in the waste disposal zone prior to waste emplacement.

- Borehole and casing system must have sufficient stability and durability to allow retrieval of waste canisters during the operational period, if necessary. The operational period is defined as the time until all borehole seals are emplaced and surface abandonment of the borehole is completed.

2.2. Drilling

Again, well design is based, in part, on the criterion that drilling should be done with currently available technology. The depth of the hole is not exceptional, as projects in Australia (Beardsmore, 2007), France (Bamgartner et al., 2007), and the United States (Duchane and Brown, 2002) have reached 4.5 – 5 km depths in granite, although the diameters of those holes were less than required here. Boreholes to the same depths with the 17" (0.43 m) bottom hole diameter of the reference design in this report should be feasible; there are no known technical issues that present unreasonable barriers to drilling to this diameter at depth. Current geothermal practice is relevant because geothermal resources are usually found in hard, igneous rock and because the flow rates in geothermal production require large-diameter holes. Given that comparison, the drilling will most likely be done with a large, but conventional, drill rig using either rotary pipe and hard-formation, tungsten-carbide insert, journal bearing, roller-cone bits or possibly a downhole turbine with diamond-impregnated bits. The choice between these two methods, and the selection of specific bits and operating parameters (rotary speed, hydraulics, and bit weight), will be driven by the rock properties in a given location. It will be important from a sealing perspective, as well as drilling engineering, to know these properties in some detail, so it is likely that a considerable amount of coring for formation samples and logging for various geophysical measurements will be required. A preliminary list of logging and testing requirements is given in Table 1.

The requirement that the minimum distance between storage intervals of separate holes should be 50 m implies an average deviation in the hole trajectory of less than 0.6º, so this will necessitate directional drilling to control or correct deviation. There are several ways to accomplish this with standard technology.

Drilling in the crystalline rock will be slow, with penetration rates possibly as low as 1 m/hr, and bit life will be limited, which implies frequent trips for bit replacement. These conditions, coupled with the large diameters and site-specific drilling factors, mean that well costs will be not only high, but unpredictable, especially for the first hole in a particular location. These factors are discussed in more detail in Section 6.1.

As in any drilling project, the casing design is the crux of wellbore definition and determines most aspects of how the hole will be drilled. It is also important in eliminating the risk of a stuck waste package during emplacement. This is described in more detail in Section 2.4

2.2.1 Possible Exploratory Alternative

A large fraction of the drilling cost will be driven by the large borehole diameters, so it may be cost effective to drill the first hole in a given location as an exploratory borehole, with no intention of waste disposal in it. Having the bottom hole diameter at the smallest dimension that will allow the necessary logging and testing (on the order of 8.5 inches, 0.22 m) would yield a substantial reduction in cost for that well. Smaller drill rig size, less material for casing and cementing, and lower rig rates for logging and testing for an exploratory borehole would result in lower costs than a larger-diameter disposal borehole. Experience in the pilot hole would also be extremely useful in predicting possible trouble spots in the large boreholes, and in refining bit

selection and drilling techniques. An exploratory borehole would be plugged and sealed in a manner similar to disposal boreholes.

An exploratory hole would greatly simplify logging and coring. Commercially available logging tools for several of the measurements listed in Table 1 are limited to a maximum hole size of approximately 20 inches (0.51 m), so logging in a full-scale hole would require drilling a pilot hole capable of being logged with available tools and then reaming that hole to final diameter.

Very large (>17 inches, 0.43 m) core bits would be extremely expensive (> $250,000 each), even if they were available, which is unlikely because of the very low demand for this size.

2.3. Borehole Testing

Borehole testing and subsurface characterization at a specific site would proceed from an initial determination of the general suitability of that location for deep borehole disposal to specific characterization of the host rock in the disposal zone of individual boreholes. Given the general lack of geological information at depths of 3 to 5 km in crystalline basement rock, the first borehole at a potential disposal site would be used to characterize the geology, hydrogeology, and geological history of crystalline rocks and fluids at depth. Detailed testing of the initial and subsequent boreholes would also obtain data for use in waste disposal operations, as summarized in Table 1. The list of proposed logging and testing in Table 1 is preliminary in nature and has been compiled primarily for the purpose of making cost estimates.

Because of the greater geological isolation inherent in the deep borehole disposal concept relative to shallower mined geological repositories, site characterization requirements would be more limited, both in terms of breadth and detail. For example, the detailed characteristics of shallow hydrogeological system such as infiltration, recharge, groundwater flow in the upper few hundred meters, and discharge are largely decoupled from the hydrogeological system at depths of greater than 3 km in stable continental regions and thus of limited relevance to safety of the deep borehole disposal system. A few key characteristics of the system at depth, such as high-salinity groundwater, geochemically reducing conditions, and lack of overpressured fluids, are highly important to waste isolation. However, detailed characterization of some aspects of the host rock, such as complexities of the fracture network, which would be necessary for a shallow mined geological repository would not be required in the deep borehole. Major hydrostructural features such as faults and fracture zones might be of significance to site safety, but minor features of the fracture network would be expected to behave as a continuum at the scale of transport to the surface (at least 3,000 m). Furthermore, in the absence of significant driving gradients in fluid potential (e.g., overpressured conditions at depth), flow of groundwater toward the surface would be negligible, regardless of fracture network interconnectivity.

Table 1. Borehole Logging and Testing.

Borehole Logging or Testing Procedure	Interval or Frequency	Initial Borehole	Subsequent Boreholes	Logging Size Limited	Purpose of Logging or Testing
Borehole caliper log	Entire borehole	yes	yes	no	Locate borehole breakouts, assess borehole stability and clearance for setting casing
Gamma ray log	Entire borehole	yes	yes	no	Identify lithology
Resistivity log	Entire borehole	yes	yes	20"	Identify lithology
Spontaneous potential log	Entire borehole	yes	yes		Identify lithology
Temperature log	Entire borehole	yes	yes	no	Determine geothermal gradient, locate groundwater inflow and outflow
Neutron porosity log	Entire borehole	yes	yes	no	Determine porosity
Formation micro imager log	Entire borehole in initial borehole, waste disposal zone in subsequent boreholes	yes	yes	21"	Determine location, orientation, spacing, and aperture of fractures, determine orientation of bedding and foliation
Anisotropic shear wave velocity log	Entire borehole	yes	no		Estimate anisotropy in horizontal stress
Coring	20 m core every 500 m depth or major change in lithology	yes	no	Very expensive above 12.25"	Obtain rock core for mineralogical, petrophysical, geochemical, mechanical, thermal, and hydrological testing
Drill cuttings log – lithology and sampling	Entire borehole	yes	yes	no	Identify lithology while drilling, obtain continuous samples for petrologic and geochemical testing
Drill stem test – shut-in pressure and fluid sampling	One every 1,000 m depth	yes	no	no	Determine vertical hydraulic gradient, obtain groundwater samples for salinity and geochemical testing
Drill stem test – pump test	One every 500 m depth in waste disposal zone	yes	no	no	Determine bulk permeability and storage coefficient of host rock

The initial borehole at a disposal site would be used to collect data using periodic coring, drill stem tests, geophysical logging, and pump testing. Periodic or side-wall coring in the borehole would be used to obtain intact samples of the crystalline host rock for petrologic, mineralogic, geochemical, and petrophysical characterization. Age dating, stress indicators (e.g., borehole breakouts and fracture orientations), geochemical, and isotopic data would be used to infer the geological, tectonic, and hydrogeological history of the host rock. Mineralogical and petrophysical data, such as mineral composition, porosity, and bulk density, would be used to calculate radionuclide retardation and migration. Petrophysical data on thermal conductivity and coefficient of thermal expansion would be used to assess the impacts of waste emplacement on the thermal and mechanical response of the system. The presence of economically recoverable mineralization, or elevated geothermal heat fluxes, would disqualify the site from waste disposal. Go/no-go criteria would be established prior to initial drilling that would identify the specific exceedances (in e.g., heat flux, borehole stability, upward fluid velocity, etc.) necessary to disqualify a particular site or borehole. Shut-in pressures from drill stem tests would measure vertical gradients in fluid potential under ambient conditions. Groundwater samples from drill stem tests would be used to determine the geochemical characteristics of fluids in the crystalline host rock, including salinity, major ion, trace element, and isotopic composition. Groundwater geochemical data would be used to infer the history and residence time of fluids in the deep borehole disposal zone. Geophysical logging could potentially include a large suite of measurements, including borehole caliper, temperature, gamma, resistivity, spontaneous potential, formation micro imager, shear-wave velocity, and neutron logs. Data from geophysical logging would provide continuous lithologic information, borehole stability, fracture spacing and estimated apertures, zones of groundwater inflow and outflow, anisotropy in horizontal stress, and porosity. Pump testing would be used to estimate host rock permeability in packed intervals.

Subsequent boreholes at the same site would be characterized with a subset of the geophysical logging used in the initial borehole. Borehole caliper, temperature, and formation micro imager logs would be sufficient to identify zones of borehole wall instability, dense fracturing, or fluid inflow or outflow. Information on these host rock or borehole conditions would be used in the positioning of borehole seals and bridge plugs, and potentially to identify segments of the borehole unsuitable for emplacement of waste canisters.

2.4. Casing and Completion

In general, the well is designed from the bottom up to the surface casing (whose maximum depth is limited by the depth that can be safely drilled without a blowout preventer); that is, the expected depth and diameter of the waste emplacement zone will determine the wellbore geometry and casing program and most of the drilling equipment requirements will follow from those criteria.

Given that the wellbore must accommodate waste canisters with 10.75 inches (0.27 m) outside diameter and couplings between them with 11.75 inches (0.30 m) OD (see Section 3.4) over a depth interval from approximately 3000 to 5000 m, then the principal criteria for casing design

(in addition to those in Section 2.1) are well control and casing strength. Well control considerations are generally addressed by using standard blow-out prevention equipment (BOPE) on the surface casing and all subsequent casing strings, while casing strength issues are controlled primarily by collapse pressure requirements. Based on the wellbore schematic shown in Section 2.5, the design considerations for each interval are discussed in more detail below. A summary table of casing properties is shown in Table 2. A schematic view of the borehole completion is shown in Figure 3.

Conductor (40", 1.0 m casing in 48", 1.2 m hole; not shown in schematic): The conductor is usually line pipe set to a depth of 50 to 100 feet (15 to 30 m) and cemented in place. It provides a flow conduit and prevents surface rubble from falling in the hole while drilling for the surface casing. This pipe is often set by a separate contractor as part of the site preparation and is not part of the drilling operation carried out by the principal drilling contractor.

Surface casing (30", 0.76 m casing in 36", 0.91 m hole): Maximum depth of the surface casing is controlled by requirements on BOPE (that is, how deep will regulatory agencies allow drilling without well control).   This casing material is standard, minimum-property pipe weighing approximately 235 lb/ft (350 kg/m) and with a tensile yield strength of 56,000 psi (390 MPa). These properties give ample strength for the casing to support its own weight hanging in the hole, and to support an external pressure of 772 psi (5.32 MPa). Using a pore pressure gradient of 0.433 psi/ft (0.0098 MPa/m), the external pressure differential on an empty pipe would be 649 psi (4.47 MPa), so collapse is not a problem. This casing is cemented to surface and will have BOPE installed after cementing.

Intermediate 1 (24", 0.61 m casing in 28", 0.71 m hole): This casing will be made of higher strength (125,000 psi, 862 MPa) material because of collapse requirements. It runs from the surface to approximately 1500 m, and is cemented full-length. Its collapse capability is 1170 psi (8.07 MPa) but external pressure at 1500 m would be 2131 psi (14.7 MPa), so the pipe cannot be allowed to be empty (this would be unlikely in any event). Fluid level must be maintained at or above 690 m below surface.

Intermediate 2 (18.63", 0.47 m casing in 22", 0.56 m hole): This liner (also 125,000 psi, 862 MPa tensile yield) is hung from the bottom of the Intermediate 1 liner and runs to approximately 3000 m. Approximately 160 m above the bottom of the liner will be a "port collar" (PC), which is a device that can be opened to create a passage from the inside of the casing to the annulus. Because the upper section of this casing must be removed to emplace seals, the upper section cannot be cemented, so after displacing cement up the annulus to a point above the port collar, it will be opened and the cement above circulated out with drilling fluid. The position of the PC in the liner will be determined by the depth of the granite formation. For an effective seal, the PC must be at least 100 m below the top of the granite. This liner also has collapse capability less than pore pressure at depth, so it cannot be allowed to be empty – fluid level must be maintained at or above 1530 m below surface.
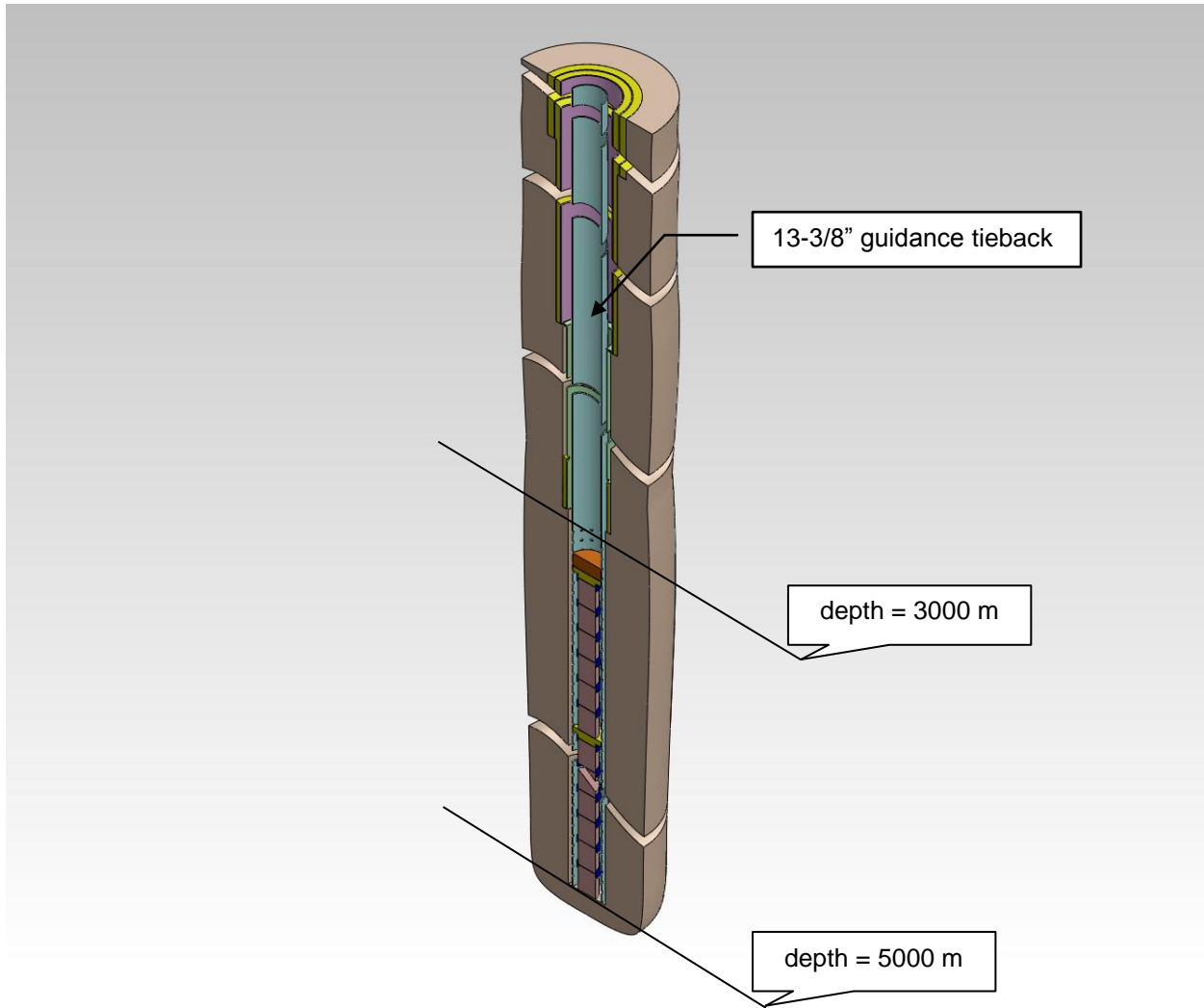
Figure 3. Schematic of Borehole Completion. Note that vertical dimensions are not to scale and borehole seals are not shown. The configuration shown is after waste emplacement and setting the overlying cement plug, but before cutting and removing the 18-5/8 " casing.

Guidance liner (13.38", 0.34 m casing in 17", 0.43 m hole): This liner hangs from the bottom of the Intermediate 2 liner and runs to the bottom of the disposal zone at approximately 5000 m. It will be slotted or perforated to allow pressure build-up caused by canister heat to bleed off into the formation. This also means that the liner will not see any differential collapse pressure, so its only strength requirement is to support its own weight while hanging in the hole.

Guidance tieback (13.38", 0.34 m casing in 18.63", 0.47 m casing): This casing runs from surface to the liner hanger in the bottom of Intermediate 2, so that there will be a smooth, constant-diameter path for the canisters as they are emplaced in the disposal zone. This casing will be completely removed after all canisters are emplaced, so it is neither cemented nor sealed at the bottom, and will not see any collapse pressure. The bottom of this casing will fit into a

receptacle in the liner hanger that will assure a smooth transition into the liner but will allow the casing to expand and contract in length as temperature changes.

Table 2. Casing Specifications.

Interval	OD (inches)	Wall Thickness (inches)	Drift Diameter (inches)	Weight, (lb/ft)	Tensile Strength (psi)
Surface	30	0.75	28.0	235	56,000
Intermediate 1	24	0.688	22.437	174	125,000
Intermediate 2	18.63	0.693	17.052	136	125,000
Guidance liner	13.38	0.380	12.459	54.5	56,000
Guidance, tieback	13.38	0.380	12.459	54.5	56,000

2.5. Reference Design and Operational Sequence
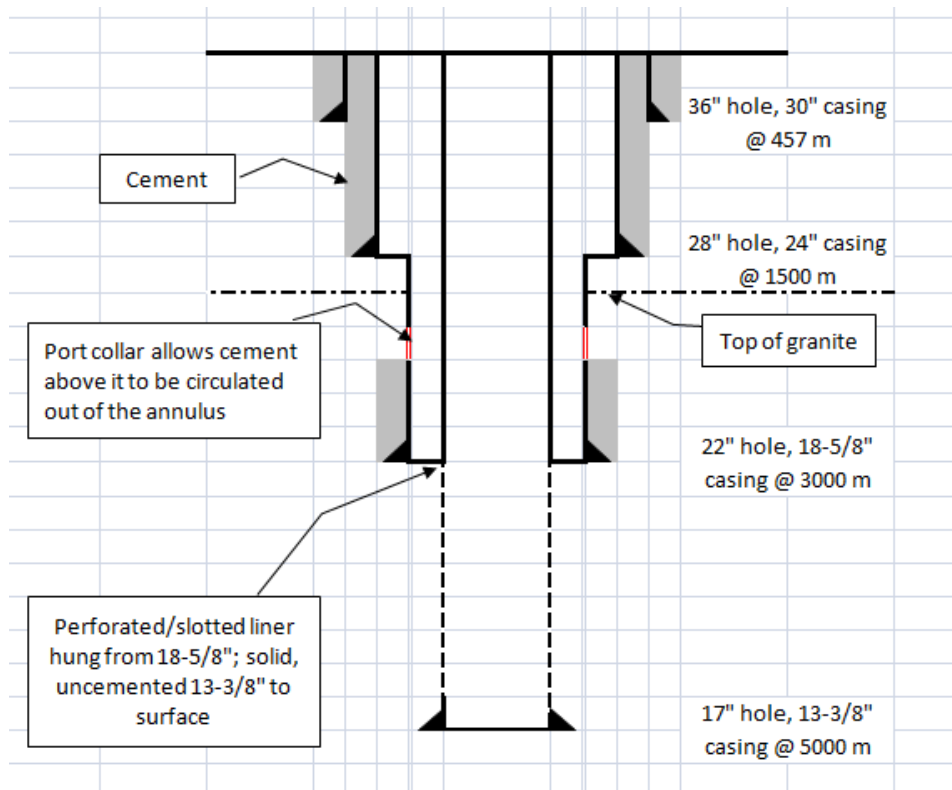
Figure 4. Borehole Design.

The operational sequence for drilling the hole profile shown above is outlined below. This procedure is only for preparation of the Figure 4 hole; all activities related to canister

emplacement are described in later sections. Also note that the coring and drill-stem tests defined in Table 1 are done only in the first hole for a given disposal location; the sequence below is for the typical hole drilled for disposal and does not include those activities. The question of logs that are limited by maximum hole size is not addressed here.

1. Contract for site preparation and installation of 40" (1.0 m) conductor to approximately 30 m depth.
2. Move in, rig up, and drill 36" (0.91 m) hole to approximately 497 m. (Alternatively, drill 26", 0.66 m hole and open to 36", 0.91 m)
3. Log open-hole section from bottom of conductor to 497 m.
4. Run 497 m of 30" (0.76 m) casing.
5. Cement 30" (0.76 m) casing to surface.
6. Weld on 30" (0.76 m) flange, install and test BOPE.
7. Drill out casing shoe and perform leak-off test.
8. Drill 28" (0.71 m) hole to approximately 1500 m.
9. Log open-hole section from 497 m to 1500 m.
10. Run approximately 1500 m of 24" (0.61 m) casing.
11. Cement 24" (0.61 m) casing to surface.
12. Cut off 30" (0.76 m) flange and weld 24" (0.61 m) flange to casing. Install master valve on 24" (0.61 m) flange.
13. Install BOPE on top of master valve and test.
14. Drill out casing shoe and perform leak-off test.
15. Drill 22" (0.56 m) hole to approximately 3000 m.
16. Log open-hole section from 1500 m to 3000 m.
17. Run approximately 1500 m of 18-5/8" (0.47 m) liner and hang at bottom of 24" (0.61 m) casing. Liner will have port collar at a position in the string such that it will be the required distance below the top of the granite formation.
18. Cement the lower part of the liner, displacing cement until it is higher than the port collar. Once the top of cement has passed the port collar, open the collar and circulate the cement above it out of the annulus.
19. Close port collar, drill out casing shoe and perform leak-off test.
20. Drill 17" (0.43 m) hole to approximately 5000 m.
21. Log open-hole section from 3000 m to 5000 m.
22. Run 2000 m of slotted or perforated 13-3/8" (0.34 m) liner and hang at bottom of 18-5/8" (0.47 m) casing.
23. Run 13-3/8" (0.34 m) tieback to surface. Bottom of tieback will be in a cylindrical receptacle in the liner hanger that will allow vertical movement of the bottom of the tieback. Tieback will not be cemented at all; top of tieback will be hung in a receptacle in the wellhead that will be centralized and below the 24" (0.61 m) flange.
24. Remove BOPE and release rig.

3. WASTE CANISTERS

The waste canister design and handling procedures are required to provide a high level of assurance that radioactive materials will be completely contained in the waste canister during all phases of surface operations, emplacement in the deep borehole system, and at least until the borehole seals are in place. In addition, all surface operations would be subject to radiological and standard occupational health and safety standards.

3.1. Waste Canister Requirements

Technical requirements of the reference design include

- Waste canister design must provide a high level of assurance that no leakage of radioactive materials will occur during handling and emplacement of the waste canisters. Welding and sealing of canisters must prevent release of radionuclides in solid, liquid, or gaseous state.

- Waste canisters must maintain structural integrity during loading, transportation, and handling prior to emplacement.

- Waste canisters must maintain structural integrity during emplacement, sealing, and abandonment of the borehole disposal system. Waste canister design must provide a high level of assurance that the canisters can withstand fluid pressures, mechanical loads, and temperatures during emplacement and the remainder of the operational phase.

- Waste canisters must have an integrated system for connection to other waste canisters and to drill pipe for lowering to the disposal zone as a string of canisters. Connections must have sufficient strength to withstand mechanic loads during and after emplacement, and for potential retrieval during the operational phase.

- Internal length of the waste canister must be sufficient to accommodate most intact PWR fuel rods. Waste canister should have a minimum internal length of 4.2 m.

- Waste canisters should retain their integrity as long as practical. However, the deep borehole disposal concept does not rely on the waste canisters as a significant barrier to radionuclide release beyond the operational period.

- Design, handling, and emplacement of waste canisters must preclude any possibility of nuclear criticality.

Hydrostatic fluid pressure on waste canisters will be a function of depth and the fluid density within the borehole. Fluid density will be a function of salinity and temperature, which will also vary with depth. High salinity brines are expected to occur in the host rock at the depths of deep borehole disposal, but fluid composition within the cased borehole could be controlled to a certain extent during waste canister emplacement. The fluid pressure design requirement is conservatively based on an assumed salinity profile varying from fresh water at the surface to a

density of 1.1 x fresh water density at a depth of 500 m and varying from 1.1 x fresh water density at 500 m depth to 1.3 x fresh water density at a depth of 5000 m. The assumed temperature gradient is 25 ºC/km. The resulting fluid pressure at the bottom of the borehole is about 57 MPa (8250 psi) and this pressure is used as the canister design requirement.

The nominal mechanical load requirement for waste canisters is based on the assumption that the loaded canisters will be emplaced in strings of 40 canisters (approximately 200 m intervals). The maximum compressive force on the bottom canister in the string after emplacement will be equal to the maximum tensile force on the uppermost canister in the string while being lowered into the borehole. The mechanical load design requirement is based on a preliminary canister design in which each canister was assumed be loaded with 421 PWR fuel rods with a weight of 2.39 kg/fuel pin (calculated from data for reference nuclear fuel assemblies in DOE, 1997). The approximate total weight of the canisters and waste for 40 canisters is 69,400 kg (153,000 lbs). The final canister design contains fewer fuel rods (see Section 3.2) than used to estimate the weight given above, so the actual weight of the canister string would be less than this. Buoyancy in the fluid within the borehole is conservatively disregarded in this design requirement. Forces associated with the potential retrieval of waste canisters during the operational phase must be considered in the safety margin relative to this design requirement.

Two waste canister designs are developed for variations in heat output from waste and depth of emplacement. The strength of steel may be significantly degraded within the range of temperatures experienced by different waste canisters. Maximum values of temperature in this design requirement are based roughly on the peak simulated temperatures for disposal of used nuclear fuel and vitrified high-level radioactive waste from reprocessing documented in Brady et al. (2009). The lower-temperature, thinner-walled waste canister is designed for a maximum temperature of 160 ºC (320 ºF). The higher-temperature, thicker-walled canister is designed for a maximum temperature of 300 ºC (572 ºF).

3.2. Waste Loading into Canisters

The disposal system in the reference design is based on the disassembly of used nuclear fuel assemblies at the reactor sites (or at a centralized facility) and loading of individual fuel rods in the waste canisters. Although this procedure entails greater cost and effort in the loading of the waste canisters, it allows for a smaller diameter waste canister, a smaller diameter borehole, and greater operational assurance for the construction of the borehole to the required depth. The higher density of used fuel in the waste canisters also results in fewer total waste canisters, fewer boreholes, and lower transportation, drilling and operational costs. Fuel consolidation technology and costs have been analyzed in previous studies that are summarized in Gibbs (2010). Results of these studies indicate that dismantling assemblies and consolidating of fuel rods is technically feasible, costs are reasonable, and that the costs of consolidation would be offset by savings in number of canisters and drilling costs for deep borehole disposal. Individual fuel rods can be removed from most PWR fuel assemblies and many reactor sites have existing facilities that could be adapted for the disassembly of fuel assemblies in fuel storage pools. Additional reactor site facilities would likely be required for the sealing, shielding, welding and

handling of the loaded waste canisters. However, the engineering for such facilities should be relatively straightforward, given the modest size of the waste canisters.

Loading of the cylindrical fuel rods in the waste canisters is based on hexagonal close packing of rods that are assumed to be about 1 cm in diameter (DOE, 1997). The packing arrangement for the lower temperature canister design is illustrated in Figure 5. The lower-temperature canister design can contain approximately 367 fuel rods and the smaller inside-diameter, higher-temperature canister can contain 349 fuel rods. For comparison, a standard 17 x 17 PWR fuel assembly contains 268 fuel rods, so the consolidation of fuel rods in the lower-temperature canister constitutes a 37% increase in disposal capacity, compared to disposal of an intact fuel assembly. The higher density of packing used fuel rods in the reference waste canister design in this report results in an estimate of about 700 boreholes for the disposal of the projected waste inventory from the current fleet of nuclear reactors in the U.S. The estimated number of boreholes required for the disposal of intact fuel assemblies is about 950 boreholes (Brady et al., 2009).
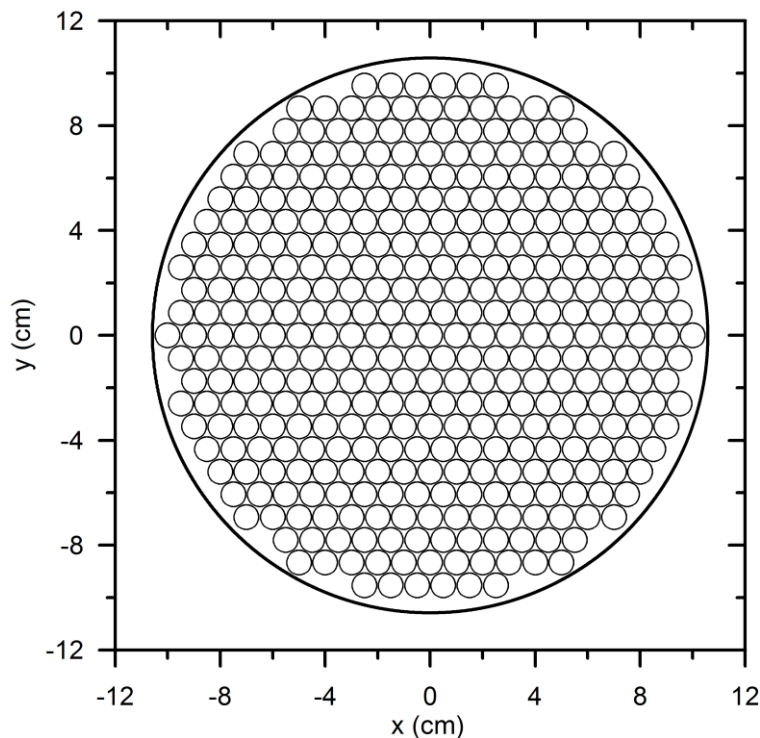
Figure 5. Loading of Fuel Rods in the Lower-Temperature Waste Canister.

Waste canisters are also designed for the disposal of vitrified DOE defense high-level waste or of vitrified waste from the reprocessing of commercial used nuclear fuel. Vitrified high-level waste could be poured as molten glass into a thin-walled steel container, which could then be placed into the waste canister. It should be noted that existing DOE high-level waste glass forms will not fit in the reference waste canister design.

30

3.3. Waste Canister Testing

Waste canister testing prior to loading with waste would verify the dimensions of the canister and yield strength of materials used in their construction. Canister wall thickness would be measured to verify a manufacturing tolerance of ± 6 %. Integrity of threads for connections would be inspected and verified. Yield strengths of steel canister walls and connections would be tested at elevated temperatures to verify that design requirements had been met.

Welding of sealing plugs in the canister would be inspected using x-ray imaging following waste loading. Surface samples of the loaded waste canisters would be tested for any radiological contamination.

Drop testing of a mock up of the loaded waste canister will be conducted to demonstrate the ability of the waste canister design to withstand possible accidents during handling and emplacement. The loaded waste canister design should not leak after a potential fall from raising the shipping cask to a vertical position prior to rail transference to the borehole. Nor should a loaded waste canister leak if it strikes the bottom of the borehole at terminal velocity after the accidental release of a canister string in the borehole fluid (see Section 4.5).

3.4. Reference Design and Waste Canister Handling

The reference waste canister is designed to be relatively simple and to use materials and components available in the petroleum and geothermal industries.

The reference waste canister is designed to withstand hydrostatic pressure in the borehole without internal mechanical support. Canister wall thickness to withstand a maximum hydrostatic pressure of 8250 psi (57 MPa) is calculated based on API 5CT specifications for K55 seamless pipe and a safety factor of 1.2. Standard manufacturing tolerances for the wall thickness of API 5CT steel tubing is ± 12.5 % and collapse strengths are calculated in the minimum thickness within this tolerance. A higher level of confidence in waste canister integrity could be achieved if tubing manufactured to tighter tolerances than the API standard were used to construct the canisters. Waste canisters with a higher tolerance for wall thickness would also help insure that the maximum number of fuel rods could be packed into each canister.

The reduction in yield strength with increasing temperature has been estimated from various sources. ASME recommended design factors from boiler and pressure vessel code for carbon and low alloy steels at 300 ºC indicate a factor of 0.78. Various manufacturers provide estimates of this design factor. Tenaris reported an average number to use of 0.86 for their 55,000 psi (380 MPa) yield strength casing. Grant Pridco reported 0.74 and Hunting 0.82 for their 80,000 psi (550 MPa) yield strength casing. Canister wall thickness design is based on a retained yield strength factor of 0.82 at 300 $^{\circ}$C and 0.90 at 160 $^{\circ}$C. Manufacturers can be required to run yield strength tests at elevated temperatures as an acceptance criterion for the material used in the canisters. The resulting waste canister dimensions are shown in Table 3.

Table 3. Waste Canister Dimensions.

	Inside Diameter (inches)	Outside Diameter (inches)	Wall Thickness (inches)
Lower-Temperature Canister	8.33	10.75	1.21
Higher-Temperature Canister	8.05	10.75	1.35

Connections between waste canisters consist of "premium" threaded coupled connections with an outside diameter of 11.75 inches (0.30 m) and 5 threads per inch. A custom design for these connections with a wall thickness of 1.21 inches (3.07 cm) would be required to match the tubing used in the lower-temperature canister design. Data on existing connections with smaller wall thickness made from L80 grade steel have a coupled minimum yield strength of 80,000 psi (550 MPa).

The top of the assembled 200 meters of canisters would have a J-slot safety joint screwed into the last canister. The safety joint is an assembly that is easy to release once the canister string is on the bottom of the emplacement zone; allows for reengagement if retrieval is necessary; and, in some cases, will allow cementing operations to commence immediately after release without tripping out of the borehole. There are a number of slightly different designs, depending on the manufacturer, but all operate in a similar manner.

The canisters will be sealed by welding plugs below and above the waste. The bottom plug could be welded in place before the fuel rods are loaded into the canister and the connection threads are cut into the canister. The top plug would have to be robotically welded in place after the waste has been loaded into the canister. If welding of the top plug is conducted before the connection threads are cut in the top of the canister, then the upper threads would have to be cut robotically in a shielded environment. If the upper threads are cut before loading waste and welding of the upper plug, then the weld would have to be far enough from the threads to prevent distortion of the threads.

The reference design canisters will easily withstand the mechanical compressive and tensile mechanical loads from overlying canisters and from the weight of the canister string during emplacement. The lower-temperature, thinner-walled canister design would be more prone to these stresses. With a nominal wall thickness of 1.21 inches (3.07 cm) the canister walls have a cross-sectional area of 36.265 square inches (234 square cm). The resulting stress from an overlying (or underlying) weight of a 200-m string of canisters of 153,000 pounds (69,400 kg) is about 4,220 psi (29.1 MPa). This mechanical stress is much less than the thermally degraded yield strength of 55,000 psi (380 MPa) steel, resulting in a safety factor of greater than 10 for these mechanical loads.

Engineering drawings of the low- and high-temperature waste canisters are shown in Figures 6 and 7.
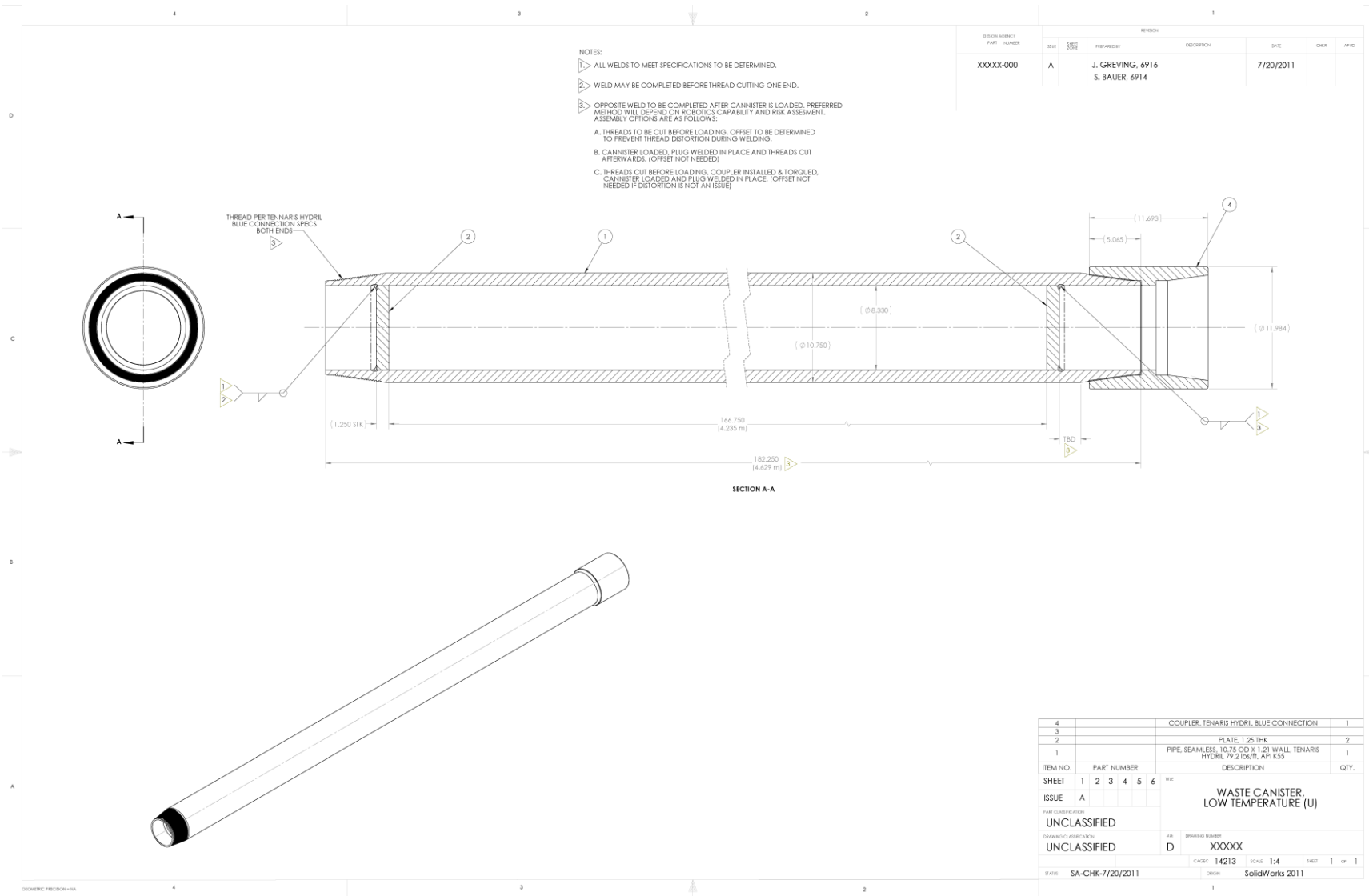
Figure 6. Low-Temperature Waste Canister Design.
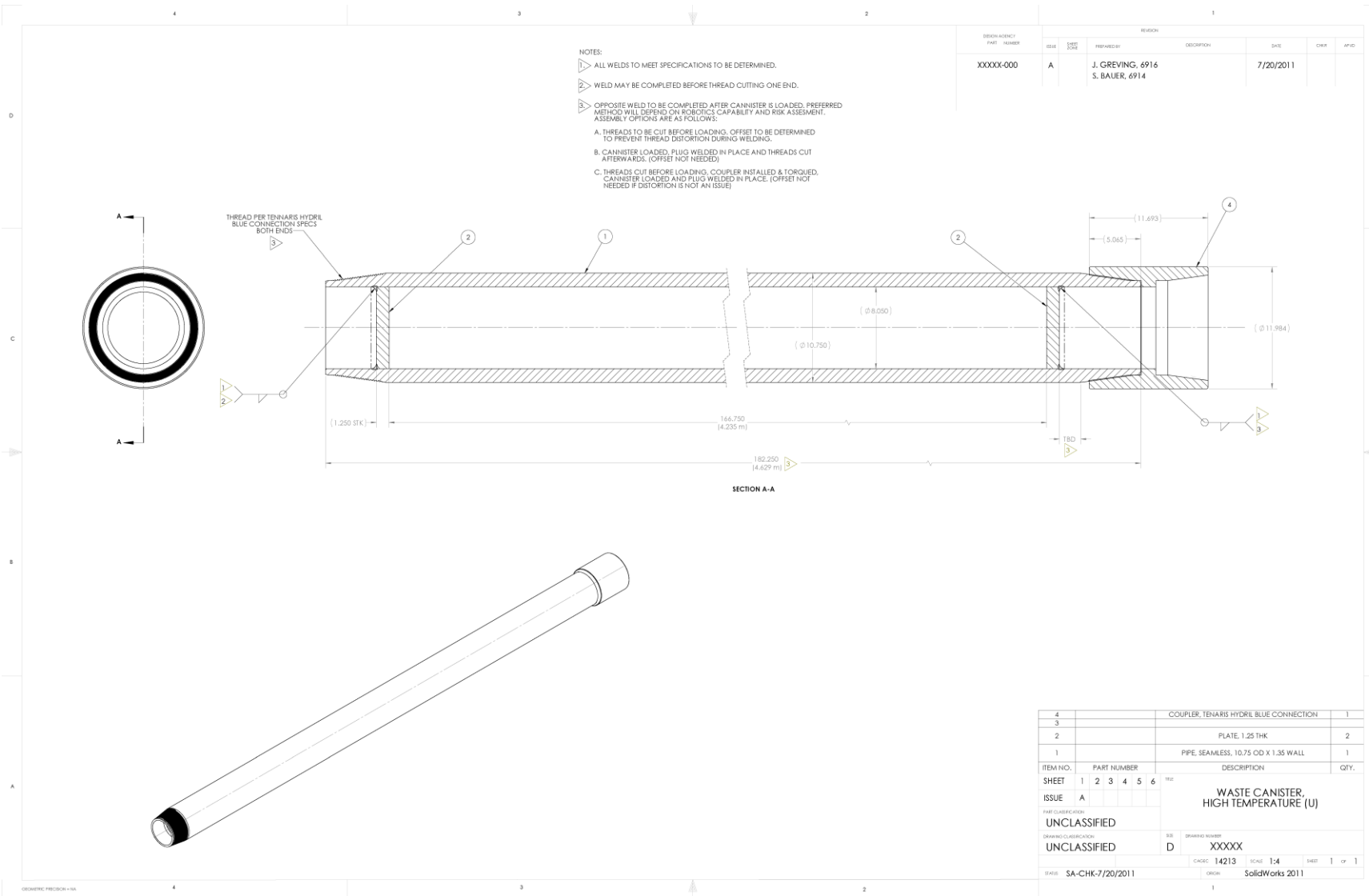
Figure 7. High-Temperature Waste Canister Design.

The mechanically robust nature of the reference waste canister design should preclude the need for special handling procedures during waste loading, transport, or preparation for emplacement at the borehole site. Used fuel rods would be loaded into the waste canister in the fuel pool at the reactor site or in a centralized storage facility. Vitrified high-level waste would be loaded into the waste canister at the reprocessing plant of at a centralized storage facility. Sealing of loaded waste canisters by welding would be subject to restrictions regarding the connection threads described above. All waste canister handling after loading with waste would be conducted in a shielded environment. Transportation of loaded waste canisters would occur in a shielded overpack that would protect the canister from design basis transportation accidents.

Nuclear criticality would be analyzed and avoided during all phases of the deep borehole disposal system using standard industry analytical methods and practices. Positioning of loaded waste canisters relative to fuel assemblies in the fuel pool and relative to other loaded canisters would be analyzed for loading, transportation, storage, and emplacement procedures. Nuclear interactions among used fuel in multiple boreholes would be negligible given the minimum allowable spacing of 50 m in the waste disposal zone specified in the borehole requirements (Section 2.1). Analyses of criticality risk for used nuclear fuel at Yucca Mountain (Sanchez et al., 1998) suggest that the risk of criticality within a loaded waste canister in the borehole disposal system would be negligible for the disposal of low-enriched uranium fuel rods from commercial nuclear reactors. The risk of criticality following corrosion and failure of the waste packages, in which the geometry of the fuel pellets would change unpredictably, is more uncertain. Yet, the maximum radius of an assembly of uranium fuel and its associated risk of criticality would be limited by the radius of the borehole in the disposal zone, decreasing the likelihood of a critical event. However, the duration of potential nuclear criticality in the deep borehole environment could be significantly greater than that analyzed in Sanchez et al. (1998), given the higher fluid pressure and the retention of liquid water acting as a neutron moderator at higher temperatures.

4. WASTE EMPLACEMENT

4.1. Waste Emplacement Requirements

Technical requirements of the waste emplacement include

- Waste emplacement procedures must provide a high level of confidence that radiation exposures to workers are acceptably low.

- Waste emplacement procedures must provide a high level of confidence that no leakage of radioactive materials will occur during operations.

- Waste emplacement procedures must provide a high level of confidence that waste canisters will not become stuck above the waste disposal zone in the borehole.

4.2. Surface Handling and Shielding

Loaded waste canisters would be transported to the deep borehole drillsite by tractor trailer using transportation casks similar to existing designs for the shipping of used nuclear fuel. Such casks provide shielding to workers and the public during transport, and protect the fuel from release in the event of an accident. Examples of existing shipping casks for transport on legal-weight trucks that could accommodate the reference canister design are the NLI-1/2 and NAC-1/NFS-4 cask models, with internal cavity diameters of 13.375 and 13.5 inches (0.340 and 0.343 m), respectively (Saling and Fentiman, 2001). The safety of these cask models would need to be reevaluated for the somewhat greater weight and radioactive inventory of the loaded waste canisters, relative to that of a single PWR fuel assembly for which these shipping casks were designed. A single deep borehole disposal reference canister could be shipped at one time in these casks. These cask models may have to be remodeled or redesigned to allow rotation to a vertical orientation, positioning over the borehole, and attachment of the waste canister to the drill string for emplacement in the borehole. The loaded waste canister would remain in a shielded configuration from the point that it is loaded into the shipping cask through the time that it is lowered into the borehole.

Surface handling of the loaded waste canisters at the drillsite would be conducted in a manner similar to that described in Woodward and Clyde Consultants (1983). The Woodward and Clyde system calls for rotation of the shipping cask to a vertical position from the tractor trailer adjacent to the emplacement rig onto a rail transporter. The cask containing the loaded waste canister would then be moved along a short rail system into an enclosed area beneath the elevated drill floor of the rig (see Figure 2). Remotely operated equipment would open the upper cover of the shipping cask, the drill pipe would be attached to the top of the canister, the canister would be lifted, the lower cover of the shipping cask would be opened, the canister would be lowered into shielded basement below the rail transporter, and the canister would be attached to the underlying waste canister that has been locked into place at the borehole collar in the

basement. The underlying waste canister would then be unlocked at the borehole collar, the waste canister string would be lowered by one canister length, and the new canister would be locked at the borehole collar. The drill pipe would then be unscrewed from the top of the canister, raised above the drill floor, the empty shipping cask would be moved away from the rig, and the process would be repeated for the next waste canister. All operations at unshielded locations would be performed remotely and monitored by video links.

The Woodward and Clyde Consultants (1983) waste handling system calls for use of a standard drill rig to drill and construct the borehole, and a separate specially designed emplacement rig for emplacing the waste canisters and performing borehole plugging and sealing operations. This strategy has the advantage of freeing up the drill rig for drilling and construction of the next borehole at the same site, while waste is simultaneously being emplaced by the emplacement rig. It has the disadvantage of requiring the capital investment in a specialized, dedicated emplacement rig that probably lacks the full capability and capacities of a deep drill rig. A deep drill rig probably would be better equipped to deal with unplanned events, such as a lodged waste canister string. Alternatively, it may be more effective to modify an existing deep drill rig to drill the borehole and to emplace the waste and perform borehole sealing and plugging operations. Fully evaluating these alternatives is beyond the scope of this study, but the reference design and operations described here are for use of a single, modified drill rig for both drilling and emplacement operations.

4.3. Waste Canister Emplacement

Waste canisters would be emplaced in the disposal zone of the borehole in strings of 40 canisters, with a total length of about 192 m, based on the waste canister design presented in Section 3. Each waste canister string would be lowered to the waste disposal zone and would rest on the bottom of the borehole in the case of first string or on the bridge plug and cement emplaced above the previous waste canister string for subsequent canister strings. The waste canister string would then be disengaged from the drill pipe using the J-slot assembly, as described in Section 3.4. A bridge plug and cement would be set above the waste canister string prior to the emplacement of the next waste canister string. The bridge plug would be set some distance above the top of the uppermost canister in the string to allow for differential thermal expansion of the steel waste canister string from the heat generated by the waste. Using a value of 13×10^{-6} per °K for the coefficient of linear thermal expansion of carbon steel, the 200 m canister string would increase in length by about 0.08 m and 0.44 m for increases in temperature of 30 °C and 170 °C, respectively. The differential thermal expansion of the waste canister string relative to the granite host rock would be less than these values because of corresponding expansion of the granite near the borehole. Perforations or slots in the liner casing in the waste disposal zone would allow flow due to thermal expansion of borehole fluid into the surrounding host rock and prevent the buildup of fluid pressure around the waste canister string once the that section of the borehole has been sealed by the overlying bridge plug and cement.

One issue of concern is the maximum temperature rating for commercially available bridge plugs and the temperature increases from the radioactive waste. Several standard designs for bridge plugs that would fit the 13-3/8 inch (0.34 m) casing in the disposal zone are rated up to 400 °F

(204 ºC).   This   maximum   temperature   rating   is   sufficient   for   close   proximity   to   the representative used nuclear fuel analyzed in Brady et al. (2009) and the low-temperature canister design described in Section 3.   However, this maximum temperature rating for bridge plugs could   be   exceeded   within   one   year   near   waste   canisters   that   contain   the   higher   heat   output vitrified high-level waste.   This problem would be addressed by a waste loading strategy that places the higher heat output waste canisters in the middle of canister strings.   This would increase the distance between the hotter waste canisters and the bridge plugs, protecting them from exceeding their maximum temperature rating.

4.4. Waste Canister Grouting and Bridge Plugs

A synthetic oil base mud containing bentonite will be used in the waste disposal zone during waste canister emplacement.   Although the waste canisters will not be cemented in place, the high concentration of bentonite in the mud will provide some degree of grouting around the canisters over time.   Injection of higher-viscosity grout, such as cement, around the waste canister string is not possible to accomplish effectively from above after the canister string has been   lowered   into   place.   The   emplacement   mud   will   also   provide   lubrication   to   assure emplacement at the desired depth and facilitate retrieval of the canisters if necessary.

Each waste canister string will be separated by a bridge plug and overlying cement plug.   The primary function of the bridge plug is to provide a base upon which the thicker cement plug can be   emplaced.   Together   the   bridge   plug   and   cement   plug   must   support   the   weight   of   the overlying waste canister string.   The cement plug would also invade the annulus between the perforated casing liner and the borehole wall, and provide a barrier to fluid migration within this annulus between waste canister string intervals.   Due to incompatibility between the oil base mud and cement, any oil base mud in the borehole above the bridge plug will be flushed out prior to setting the cement plug.

Bonding recommendations are made on the basis of the compressive strength of the set cement and on the assumption that the material satisfying the strength requirements will also provide an adequate bond. In a wellbore, the shear bond is typically used to determine the weight of pipe the cement can support. The shear bond force divided by the cement/casing contact area yields the shear bond stress. Smith (1989) presents a relationship for the support capacity of the cement sheath outside a casing to support the weight of the casing:

$$F = 0.969(S_c)(d_p)(h_c)$$

where F is the force or load to break cement bond (pounds), S_c is the compressive strength of the cement (psi), d_p is the casing diameter (inches), and h_c is the height of cement column (feet). The typical strength of a Class H cement at 15,000 ft (4570 m) depth is conservatively taken as 4000 psi for the anticipated temperatures and pressures (Smith, 1989, Table 4.8).   Using an inside diameter of the casing of 12.459 inches (0.316 m) (see Table 2) and the weight of the overlying canister string of 153,000 lbs (69,400 kg), the length of the cement plug required is about 3.2 ft (0.98 m).   The bond properties of the cement to the casing is highly dependent on the cement job, age of casing, surface finish of casing, amount of time the cement has had to cure,

and the type of fluid in the borehole amongst other possible factors. Taking these unknown factors into consideration and the desire to infiltrate and form a barrier in the annulus between the casing and the borehole wall, a cement plug of 10 m is recommended.

Numerous bridge plug types are commercially available for use in the waste emplacement procedure. Both mechanical and inflatable designs are available. Some inflatable, packer-style bridge plugs can be filled with cement for permanent installation. Two example bridge plugs are: 1) Weatherford PBP bridge plug and 2) TechTool high-pressure bridge plug. Both of these designs are rated for temperatures up to 400 ºF (204 ºC) and for a casing size of 13⅜ inches (0.34 m).

4.5.   Operational Safety Assurance and Monitoring

Operational safety for waste emplacement would be assured through routine monitoring and planning for potential unexpected conditions or events. Radiological monitoring would include badging of all workers and visitors on site and during transportation of waste canisters. Equipment would be routinely sampled and monitored for radioactive contamination using standard radiation safety procedures. Real time monitoring of radiation levels in working areas of the drill rig would be conducted and connected to an alarm system during waste emplacement operations. Fluids circulated in the borehole would be continuously monitored for radiation levels and periodically sampled for analysis of radionuclide concentrations.

One unplanned scenario of concern would be that a canister string becomes lodged in the borehole at some depth shallower than the disposal zone. A number of measures in the reference design and operations makes this scenario highly unlikely. The borehole will be fully cased from the surface to the bottom during waste emplacement operations. The casing will be surveyed using a caliper tool prior to waste emplacement to detect deviations in inside diameter, bending, shearing, or any other obstructions that could cause the waste string to become lodged. A guide shoe with rounded nose will be on the first canister in the string. The formation testing prior to waste emplacement will provide information concerning the potential for rock breakout during operations potentially compromising the casing. Additional assurance could be achieved by using a disposable caliper tool that would be attached below the lowermost waste canister in the string. This tool would send real-time measurements of the casing inside dimensions to operators via telemetry. Lowering of the drill string would be stopped if a potential obstruction is encountered ahead of the waste canister string, preventing it from becoming stuck. If a waste canister string becomes lodged in the borehole, considerable force could be applied by the drill rig to pull, push, or rotate the canister string, based on the strength of the waste canisters and the connections between them (see Section 3.4). If the waste canister string could not be dislodged, then a bridge plug and cement plug could be set above the canister string. Waste emplacement could continue if the lodged waste canister string is located in the waste disposal zone. The borehole would be grouted, sealed, and abandoned if the waste canister string is lodged above the disposal zone and cannot be retrieved. Other retrieval methods may be possible for a waste canister string that is lodged at a very shallow depth.

Another potential accident scenario is premature release of the waste canister string during emplacement, in which the canister string falls or sinks to the bottom of the borehole. Waste canisters could be ruptured upon impact at the bottom of the borehole if the velocity of the waste canister string is high enough. A possible design feature to prevent dropping the canister string if the slips at the borehole collar fail is a set of automatically activated hydraulic rams that would grasp the canisters, as suggested by Woodward and Clyde Consultants (1983). Furthermore, the terminal velocity of the waste canister string sinking in the fluid within the cased borehole would be limited by viscous forces of the fluid flowing past the waste canisters. This terminal velocity is related to the annulus between the inside diameter of the liner casing (12.459 inches, 0.316 m) and the outside diameter of the connections on the waste canisters (11.984 inches, 0.304 m) by the equations given in Bates et al. (2011). Conservatively assuming that the effective outside diameter of the canister is equal to the diameter of the body of the canister (10.75 inches, 0.273 m), the terminal velocity of the sinking canister string would be about 4 m/s. It is likely that the canisters would not be ruptured by the impact at the bottom of the borehole at this relatively low velocity.

Detection of excessive radiation in the borehole fluid from either of the accident scenarios described above or from failure of a waste canister for unknown reasons would cause immediate suspension of waste emplacement. In addition, storage capacity for contaminated fluids would be part of the rig design and actions would be taken to securely store any contaminated fluids produced at the surface.

4.6. Reference Design and Operational Sequence

The reference design and operational sequence for waste canister emplacement includes unloading the shipping cask from the tractor trailer, positioning the cask over the borehole, attaching the waste canister to the canister string, lowering the canister string to the disposal zone, and emplacement of bridge plugs and cement. Waste canisters would be emplaced as 10 canister strings consisting of 40 waste canisters per string. Each canister string would be separated by a bridge plug and cement plug that would bear the weight of the overlying waste canister string and isolate the individual canister strings. An additional bridge plug and cement plug would be emplaced above the last canister string.

The general operational sequence for waste canister handling and emplacement would be as follows:

1. Position loaded tractor trailer for unloading of shipping cask.
2. Raise loaded shipping cask to a vertical position on the rail transference system.
3. Transport the shipping cask on the rail system to the shielded room beneath the elevated drilling floor of the rig.
4. Position the shipping cask over the borehole collar.
5. Close the doors on the shielded room.
6. Open the shielding door above the borehole collar.
7. Remotely remove the upper cap on the shipping cask.

8. Remotely attach the drill pipe to the Tenaris Blue connection on the upper end of the waste canister.
9. Lift the waste canister with the drill string to take the weight off the lower cap of the shipping canister.
10. Remotely remove the lower cap from the shipping cask.
11. Lower the waste canister and attach it to the underlying waste canister that is locked in the slips at the borehole collar. Note: if this is the first canister in the string, it will be attached to a guide shoe rather than underlying canister.
12. Lift the waste canister string, unlock the slips at the borehole collar, and lower the waste canister string by the length the newly added canister.
13. Lock the uppermost canister with the slips at the borehole collar.
14. Close the shielding door above the borehole collar.
15. Open the shielded room doors, move the rail transference platform back to the tractor trailer and lower the empty shipping cask onto the trailer.
16. Repeat steps 1 to 15 for each waste canister until the 40 canister string has been assembled in the borehole.
17. Lower the waste canister string to the bottom of the borehole or to the top of the cement plug emplaced over the preceding waste canister string.
18. Release the waste canister string and trip out of the borehole.
19. Lower and set the bridge plug via wireline and remove wireline from borehole.
20. Trip back into the borehole with drill string and emplace cement plug above bridge plug.
21. Deploy oil-based bentonite mud in lower 200 m of borehole in preparation for emplacement of the next waste canister string.
22. Trip out of the borehole.
23. Repeat the above sequence until 10 waste canister strings have been emplaced in the waste disposal zone of the borehole.

After the last canister is placed, including the bridge plug and cement:

1. Remove the 13-3/8" (0.34 m) guide casing from the well.
2. Run in the hole with a casing cutter and cut the 13-3/8" (0.34 m) casing just above the cement.
3. Pull out of the hole with the casing cutter
4. Run in the hole with a spear and engage the 13-3/8" (0.34 m) casing. Pull the casing stub to the surface and lay it down.
5. Place a cement plug to the top of the cemented section of the 18-5/8" (0.47 m) casing.
6. Run in the hole with a casing cutter and cut the 18-5/8" (0.47 m) casing just above the cement.
7. Pull out of the hole with the casing cutter
8. Run in the hole with a spear and engage the 18-5/8" (0.47 m) casing. Pull the casing stub to the surface and lay it down.
9. Fill the bentonite placement tool with bentonite and run into the hole and place the first bentonite plug on top of the cement, then pull the tool out of the hole
10. Repeat until the bentonite fill reaches inside the 24" (0.61 m) casing at 1,500m

5. BOREHOLE SEALING AND ABANDONMENT

5.1. Borehole Sealing Requirements

Technical requirements of the reference design include

- Borehole seals must provide a low permeability barrier to fluid flow within the borehole. The overall permeability of the material used in the seal zone above the waste must be less than 1×10^{-12} m^2 (Herrick et al. 2011). However, the present reference design requires an overall permeability less than 1×10^{-16}.m^2.

- Borehole seals must 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.

Figure 8 illustrates the primary components of the borehole sealing system which are described later in the text. In the lower sealing section, the components correspond to those which will be emplaced in the unlined borehole above port collar in the 18-5/8 inch (0.47 m) Intermediate 2 liner, which is to be cutoff and pulled during sealing (Figure 4). Figure 8 also shows the components to be emplaced in the upper sealing section in the 24 inch (0.61 m) Intermediate 1 casing. The majority of the borehole will be filled with cement or cement with sand and finely crushed rock which will act as both plugging and backfill materials. In the lower, uncased section the seals will act directly against the rock surface after removal of the Intermediate 2

casing above the port collar. In certain places, two cement plugs will bracket a bentonite or bentonite and sand mixture seal. A ballast of silica sand or crushed rock will be emplace between the cement and bentonite to minimize chemical interaction. In the upper cased section, bridge plugs will be installed to create an API-type plug or to partition off the segments of cement plugs and/or backfill. The lower part of the 24 inch (0.61 m) Intermediate 1 casing will be supported by a cement seal.
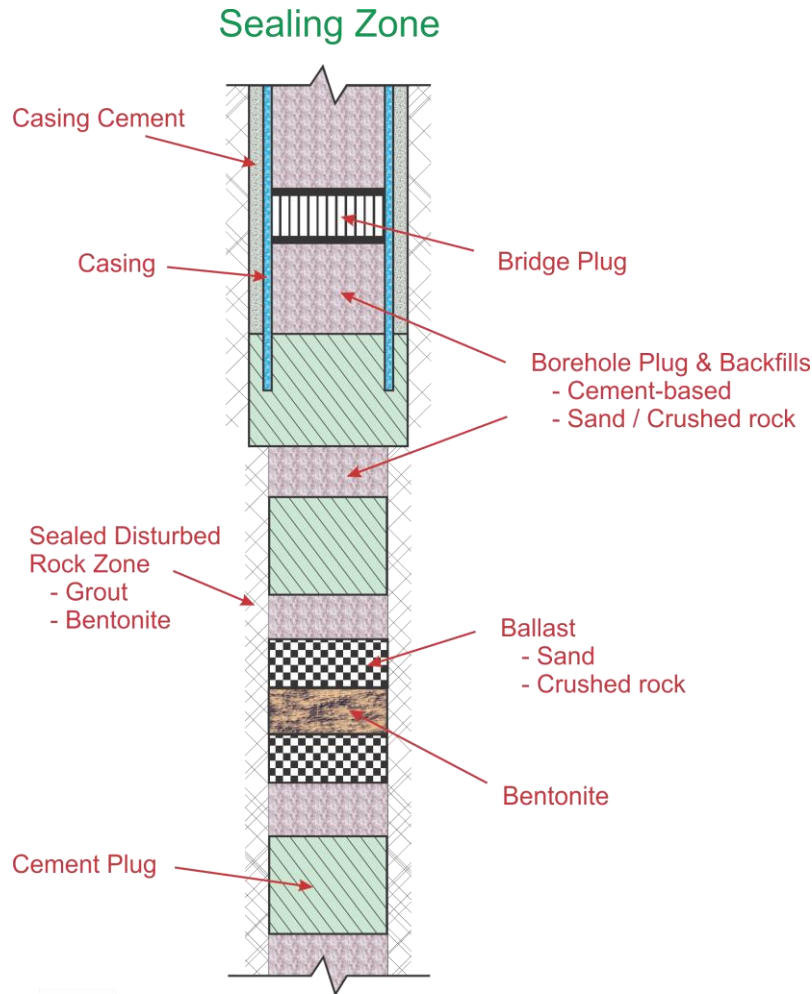
Figure 8. Schmatic Drawing of Seal Components in the Lower Unlined and Upper Lined Sections a Borehole above the Waste Disposal Zone and Port Collar of the Pulled Intermediate 2 Liner.

5.2. Compacted Bentonite Seals

Bentonite and other smectitic swelling clays installed in a dry condition should swell through water uptake to form a low permeability (10^{-20} m^2) zone by completely filling void spaces and exerting a swelling pressure against the surrounding rock. 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.

Bentonite can be placed to shallow depths using a grout pump, or using a tremie pipe to emplace bentonite pellets into water. At great depth bentonite plugs must be emplaced by extrusion from a container which is moved to the appropriate depth (bentonite in the container can be an intact plug or bentonite pellets); or by placement of a perforated tube holding the bentonite.

Bentonite expansion is inhibited, and seal permeability increased, by chemical conversion of the bentonite to non-swelling clays (e.g. illites and chlorites) caused by high ionic strengths and/or calcium. Calcium can come from cement leachate and high ionic strength fluids can come from ambient fluids. A saturated density of at least 1600 kg/m^3 is needed for a sodium bentonite to attain sufficiently low permeabilities in contact with salt water (Pusch and Ramqvist 2007, Pusch 2008).

5.3. Cement Seals

Cements have low permeability, can penetrate small fractures (Onofrei et al. 1992), can be very durable, and the methods to emplace the materials downhole are quite mature (Pusch 2008, API 2000). Fluid transport that would bypass the cement seal only occurs through the interface between the cement and the adjacent rock (Stormont and Finley 1996) 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., Neville, 1995; Onofrei et al., 1992; and Smith, 1989). Shrinkage, fracturing, or chemical alteration may increase this value. Field values can be two or three orders of magnitude higher (Greer and Crouthamel 1996, SKB 1987).

The longevity of cement seals is based on a concrete longevity analysis performed for the Waste Isolation Pilot Plant by Thompson et al. (1996). In that analysis, the durability of cement plugs in boreholes was analyzed in terms of the number of pore volumes that can be passed through the cement mass. Their analysis showed that more than 100 pore volumes of leachants (they considered both fresh water and brine) must pass through the concrete before there is chemical evidence that the matrix is being attacked. Thompson et al. (1996) consider this a conservative approach because this is the critical volume of flow needed before breakdown of the calcium-silicate-hydrate (CSH) matrix is expected to begin. Failure of the plug is taken to occur when a sufficient volume of water has passed through the concrete mass that the CSH matrix undergoes measurable alteration. At this point, it is assumed that the matrix has degraded significantly, and the plug is subject to unconstrained microfracturing and physical failure. The time required for this volume to pass through the concrete mass can be calculated using Darcy's law, plug characteristics, and site-specific conditions. 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).

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, API 2000, Lyons and Plisga 2005). The final cement mixture and emplacement method will depend on the recommendation of the cementing contractor based on borehole conditions.

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).

5.4. 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.

5.5. Reference Design and Operational Sequence

Figure 9 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 short 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 borehole. 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.
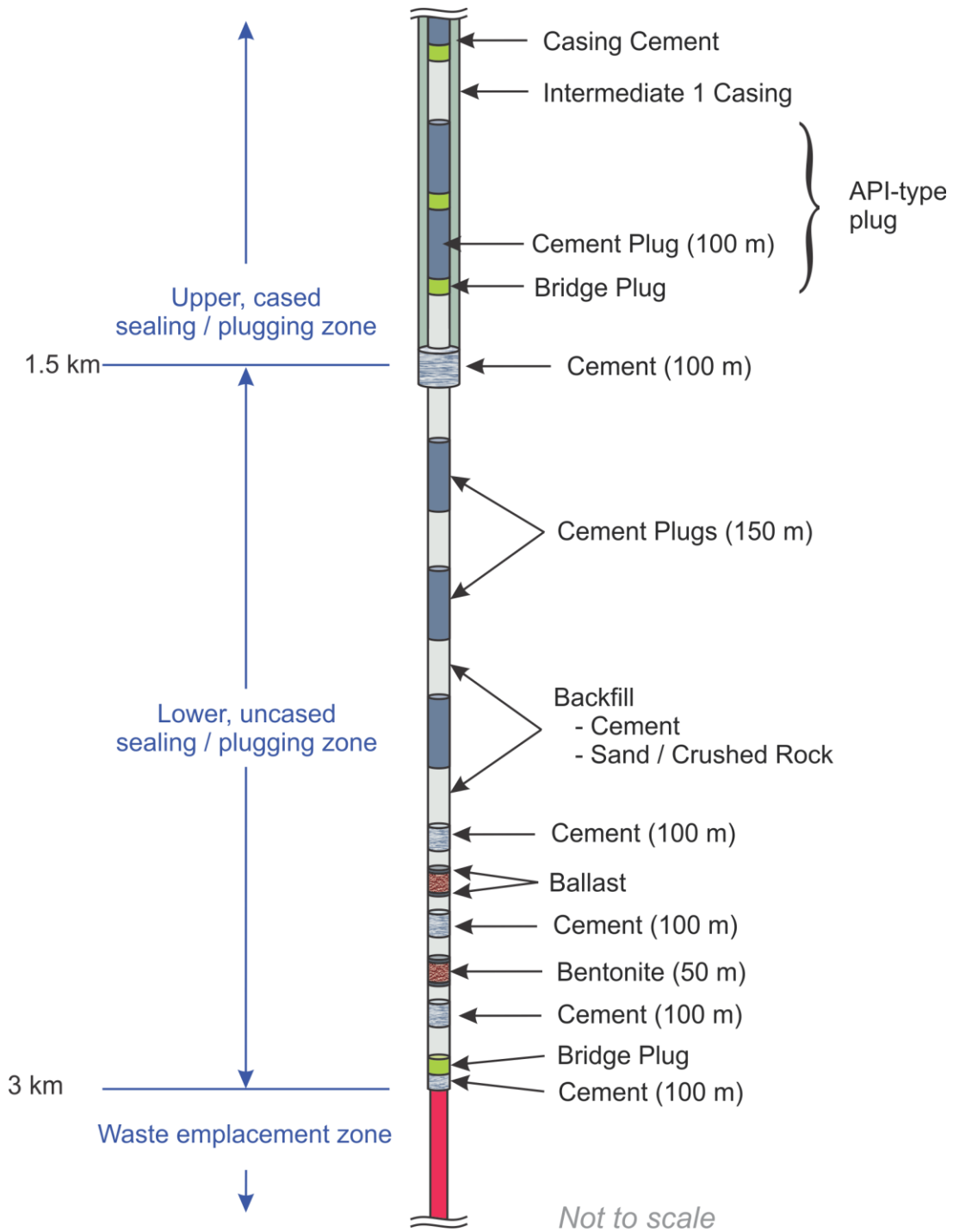
Figure 9. Borehole Sealing, Plugging, and Backfilling Reference Design Schematic.

Table 4 provides the post-waste emplacement operational sequence.

Table 4. Borehole Seals Operational Sequence.

Activity	Detail
Waste closure	Complete waste emplacement, pull Intermediate 2 casing, backfill to first keyed seal location
First Seal	Cement lower section. Emplace lower sand buffer, then bentonite or bentonite-sand mixture, followed by an upper sand buffer. Cement upper section. Backfill to next seal location
Second Seal	Cement lower section. Emplace lower sand buffer, then bentonite or bentonite-sand mixture, followed by an upper sand buffer. Cement upper section. Backfill to next seal location
Third seal	Cement lower section. Emplace lower sand buffer, then bentonite or bentonite-sand mixture, followed by an upper sand buffer. Cement upper section. Backfill to first cement plug location
First plug	Cement job
Second plug	Cement job
Third plug	Cement job
Cement bottom Intermediate 1 casing	Cement job
First API-type seal	Place lower bridge plug, continuous cement job for 30 m, place upper bridge plug, then second 30 m cement job. Backfill.
Second API-type seal	Place lower bridge plug, continuous cement job for 30 m, place upper bridge plug, then second 30 m cement job. Backfill.
Third API-type seal	Place lower bridge plug, continuous cement job for 30 m, place upper bridge plug, then second 30 m cement job. Backfill.

6. COST AND SCHEDULE ANALYSIS

6.1. Drilling, Casing, and Borehole Completion

Drilling costs (where "drilling" is taken to comprise all the activities in drilling, casing, cementing, coring, logging, testing, and completing the hole) will be highly variable for at least two reasons. First is the variation in requirements for different hole configurations: the first hole in a location has much more time devoted to coring and testing than subsequent holes in that location, and there is also a possibility of having a smaller\-diameter hole for the site-evaluation function. These differences in design criteria have significant impact on cost.

More generally, drilling costs are unpredictable because so many metrics of drilling performance differ from hole to hole, and sometimes even in the same hole at different depths. Some specific aspects of drilling with a major impact on well cost are described below.

- *Well design*: Well design is a "bottom-up" process. Desired depth of the waste disposal zone determines the well's overall length, and the canister size determines diameter at the bottom of the hole – the well's profile above that zone is then set by iteration of the successively larger casing strings required by drilling or geological considerations. Because of the large diameters required by the canisters, however, casing and cementing form a relatively large share of the cost, and the ability to eliminate one string of casing would have a major impact.
- *Directional Drilling:* The need for directional drilling is dictated by the hole trajectory criteria that the holes maintain a certain minimum spacing in the disposal zone. These are important factors in cost. While there is no choice about these requirements, there is usually quite a bit of choice in the method used to meet those requirements. The method chosen can have a large effect on the cost of the well and the success in meeting the directional objectives.
- *Drilling Hazards*: "Trouble" is a generic name for many sorts of unplanned events during drilling, ranging from minor (small amounts of lost circulation) to major (BHA stuck in the hole and the drill string twisted-off). In some cases, experience in the same or similar stratigraphy will give a hint that certain types of trouble are likely, but at other times events are completely unexpected. It is difficult, therefore, to estimate a precise budget for trouble, but all well expenditure planning must contain some contingency funds, and this number is often taken to be around 10-15% of the total budget.
- *Rate of penetration (ROP)*: Many of the costs attributed to drilling are time-dependent (primarily related to the rental rate on the rig and service company expenses) so it is clear that anything that speeds up the hole advance without compromising safety, hole stability, or directional path is beneficial. (Keep in mind, however, that increased ROP at the expense of more trips, or lower tool life, is usually not effective. See the next paragraph.) It is not always easy to optimize the performance with a new bit design drilling an unfamiliar formation. The three parameters that can be easily changed for any bit/formation combination are rotary speed, weight on bit (WOB), and hydraulics (combination of jet size and flow rate) and it often takes some experimentation to determine the best combination of these values. Bit performance data from offset wells in the same formations, and with the same hole size and bottom-hole assemblies can often be very useful.

- **Bit and tool life**: Much of the commentary above about ROP applies to bit and tool life. Improved tool life means, of course, that the expense of replacing a bit or other piece of equipment can be avoided or delayed, but time is also saved if trips can be eliminated. This becomes more important as the hole gets deeper and the trips take more time. The three factors that most affect bit and tool life are lithology, drilling parameters (including well path), and bottom-hole assembly design. The drilling engineer has little or no control over lithology, but significant improvements can sometimes be made by changes in the latter two factors.

Having presented these caveats, however, cost estimates for three hole configurations are given below. These estimates were prepared using industry averages for most raw costs – no attempt was made to select a specific drill rig, or to solicit quotes on a particular casing string, but these estimates should provide a reasonable approximation of drilling cost and, perhaps more importantly, show the effect on cost of different hole configurations. Assumptions on bit performance (rate of penetration and bit life) are conservative and a 15% contingency is included in each estimate. All of the holes are assumed to be trouble-free. Finally, the cost of rig time for coring, logging, and drill-stem testing is included in estimates for holes A and B, and for logging in hole C, but the additional fees paid to service companies for those activities are not included. The three hole configurations for which estimates are provided are the following:

- A: A smaller (bottom-hole diameter 8.5 inches, 0.22 m) hole that would allow complete characterization of the local conditions through the coring, logging, and testing defined in Table 1, all using commercially available tools. The smaller hole size would preclude any waste storage in it.
- B: The hole design shown in Figure 4, with all coring, logging, and testing required for the initial borehole from Table 1. To allow coring and logging with commercially available tools in the three upper (largest) intervals of the hole, each interval would be drilled by first making a pilot hole approximately 12.25 inches (0.31 m) diameter. Coring and logging would be done in the interval's pilot hole and it would then be reamed to the final diameter.
- C: Again, the Figure 4 hole design, but with the reduced testing requirements required in Table 1 for subsequent boreholes. There is no coring or drill-stem testing, and no allowance for size-limited logs. This is the nominal cost for drilling the Figure 4 design without consideration of which logs might be problematic.

Table 5. Estimated Drilling, Casing and Completion Costs

HOLE DESIGN	A	B	C
Interval costs			
Drilling time cost	$3,906,016	$7,421,582	$4,882,520
Tripping time cost	$2,446,664	$5,905,986	$3,058,330
Bit cost	$631,322	$3,861,709	$1,753,587
Other BHA	$315,661	$1,930,855	$876,793
Mud cost	$1,159,941	$1,732,607	$987,607
Casing cost	$1,183,200	$4,777,425	$4,777,425
Cementing time cost	$372,500	$790,625	$790,625
Cementing mat'l cost	$1,356,829	$2,339,904	$2,339,904
Trouble time	$0	$0	$0
Trouble cost	$0	$0	$0
Directional drilling	$467,850	$1,475,040	$951,165
Logging time	$645,000	$806,250	$806,250
Logging service	$200,000	$200,000	$200,000
Wellhead time	$120,000	$225,000	$225,000
Other costs	$1,612,500	$2,015,625	$0
Total interval costs	**$12,804,983**	**$33,482,609**	**$21,649,206**
Additional costs and time			
Mobilization/De-mob	$800,000	$1,000,000	$1,000,000
Site prep, cellar, conductor	$100,000	$100,000	$100,000
Pre-spud engineering	$300,000	$300,000	$300,000
Casing hangers, port collar, packers	$300,000	$500,000	$500,000
Wellhead equipment	$300,000	$500,000	$500,000
Contingency (15%)	$1,920,748	$5,022,391	$3,247,381
Total well cost	**$16,525,731**	**$40,905,000**	**$27,296,587**
Total project time, days	**160.7**	**211.0**	**139.2**

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

6.2. Waste Canisters and Loading

The costs of dismantling used fuel assemblies have been estimated by Gibbs (2010), based on previous detailed studies of nuclear fuel consolidation in EPRI (1990) and DOE (1993). These costs of fuel dismantlement vary significantly from $3.24/kg heavy metal (HM) (2009) to $12.38/kg HM (2009). The lower cost estimate corresponds to a larger-scale facility that might be operated at a centralized storage facility and the higher cost estimate are for fuel consolidation at a smaller-scale facility, such as the fuel pool at a reactor site. The cost estimates shown in Table 5 assume the higher cost of dismantling the used fuel assemblies, a total of 268 fuel rods removed from 17 x 17 PWR fuel assemblies, and a total of 367 fuel rods per waste canister. Given the dominant role of fuel assembly dismantlement and canister loading costs in the total cost, reduction of these costs associated with a centralized storage and processing facility would reduce the overall costs significantly.

Welding of the waste canister plug after loading with waste would be conducted remotely within the open ended interior of the steel tubing. There is large uncertainty in the cost of this

procedure, given the specialized nature of this welding operation and the custom robotic equipment needed. Similarly, inspection of the weld after waste loading and within the strong gamma radiation field near the canister may require specialized methods. Welding and inspection of the first canister plug would be conducted prior to loading the waste and would be significantly less costly. A rough estimate of $1,000 for welding and $1,000 for inspection per canister is assigned to the cost estimate shown in Table 6.

Table 6. Estimated Waste Canister and Loading Costs.

	Cost per Waste Canister	Cost per Borehole
Waste Canister Materials	$7,750	$3,100,000
Thread Cutting	$1,000	$400,000
Tenaris Blue Connection	$500	$200,000
Fuel Assembly Dismantlement and Canister Loading	$7,824	$3,129,600
Canister Welding	$1000	$400,000
Weld Inspection	$1000	$400,000
Total		**$7,629,600**

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

6.3. Waste Emplacement Operations and Materials

The costs associated with waste emplacement operations include the surface handling of waste canisters, assembly of strings of canisters at the top of the borehole, lowering waste canister strings to the disposal zone, setting bridge plugs between canister strings, and setting cement plugs between the canister strings. Most of the cost for waste emplacement operations is for the rig time needed.

It should be noted that estimates of waste canister transportation costs are beyond the scope of this study and not included in the analysis. Transportation costs would be a significant economic component of any high-level radioactive disposal system. However, transportation costs could vary tremendously for differing locations of borehole disposal sites relative to the locations of nuclear power plants or centralized used fuel storage facilities.

The cost estimates presented in Table 7 are based on several underlying assumptions and estimates. The daily rig rate is estimated to be $75,000, based on the assumption that the deep rig used for drilling the borehole would also be used for the waste emplacement operations. It is estimated that waste canister shipping casks could be unloaded from trucks, oriented vertically, positioned over the borehole, and canisters attached to the canister string at a rate of two per hour. This operational rate assumes that waste canisters would be available on site and have undergone necessary testing in sufficient numbers to be efficiently available for loading into the borehole. The cost analysis assumes that 10 trips in and 10 trips out of the borehole would be required for: (1) lowering the waste canister strings, (2) setting the bridge plugs, and (3) setting

the cement plugs. It is assumed that tripping in and out of the borehole for lowering the waste canisters and setting the cement plugs would be done with drill pipe (at 1,000 ft/hour, 305 m/hour) and that faster wireline methods (at 6,000 ft/hour, 1830 m/hour) would be used to set the bridge plugs. The material costs of the bridge plug and cement plug sets are roughly estimated to be $10,000 per set.

Table 7. Estimated Waste Canister Emplacement Costs

	Rig Time (hours)	Cost per Borehole
Surface Handling and Canister String Assembly	200	$625,000
J-Slot Assembly	-	$135,000
Canister String Emplacement	240	$750,000
Setting Bridge Plugs	60	$187,500
Cement Plugs Emplacement	300	$937,500
Bridge Plugs and Cement	-	$140,000
Total	800	**$2,775,000**

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

6.4.   Borehole Sealing Operations and Materials

The costs for sealing the borehole above the waste emplacement zone include rig time for the emplacement operations and material costs. Although the exact design for the emplacement of the bentonite seals in the lower uncased seals zone is uncertain, it is assumed that each of the 50 m bentonite seals would be emplaced in 5 m segments by wireline methods, with trips in and out of the borehole required for each segment. Cement plugs would be emplaced through drill pipe and backfill would be emplaced directly into the borehole at the surface. Estimated borehole sealing costs are summarized in Table 8.

Table 8. Estimated Borehole Sealing Costs

	Rig Time (hours)	Cost per Borehole
Lower Uncased Sealing and Plugging Zone		
Cutting and Pulling Casing	20	$62,500
Cement Plugs Emplacement	146	$455,000
Cement Plugs Materials		$768,000
Bentonite Seals Emplacement	57	$177,083
Bentonite Seals Materials		$46,700
Backfill Emplacement	20	$62,500
Backfill Materials		$7,800
Upper Cased Sealing and Plugging Zone		
Bridge Plugs Emplacement	8.5	$26,563
Cement Plugs Emplacement	44	$137,500
Cement Plugs Materials		$630,000
Backfill Emplacement	20	$62,500
Backfill Materials		$14,000
Total		**$2,450,146**

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

7. SUMMARY AND CONCLUSIONS

A reference design and operational procedures for deep borehole disposal of high-level radioactive waste have been developed and documented in this report. The reference design is relatively simple and feasible with current engineering technology and materials. Preliminary indications are that the reference design for deep borehole disposal meets anticipated regulatory requirements for safety and limitations on long-term risk to the public, when implemented in an appropriate geological setting.

Objectives of developing the reference design and operations include updating the reference design presented in Brady et al. (2009), evaluation of feasibility, consideration of design alternatives, establishing a design basis for performance assessment analyses, and providing more accurate cost estimates. 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.

7.1. Reference Design and Procedures

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.

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. A list of logging and testing is presented in the reference design and this list distinguishes between the more detailed geological and hydrological characterization required for the initial borehole at a site and the less detailed characterization needed for subsequent boreholes. One difficulty identified in this study is that geophysical logging tools may not be available for some of the tests in the large-diameter

segments of the borehole. Similarly, periodic coring in the initial borehole would be impossible or prohibitively expensive at the larger diameters. One solution is to drill a smaller-diameter pilot hole for some segments of the borehole, conduct the logging and testing, and then drill out the hole to the larger diameter. Alternatively, a smaller-diameter exploratory borehole could be initially drilled at the site and the needed logging and testing conducted in that borehole. The exploratory borehole would be plugged and abandoned without emplacing any waste in it.

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, consistent with the cost analysis methods of Polsky et al. (2008). This conclusion is evident in the alternative cost estimates presented in Table 5. 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 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 (see Table 6), 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 in this study; 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. 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.

7.2. Costs and Schedule

The cost and schedule analysis presented in Section 6 of the report includes the major elements of the deep borehole disposal system, with the exception of waste transportation. There are significant uncertainties in the cost and schedule analysis due to alternative design choices that might be employed in the system, the inherent variation in well construction cost at any given time, uncertainties in regulatory requirements for testing and characterization, and the unique nature of engineering and operational practices involved. Nonetheless, the cost and schedule analysis constitutes the most comprehensive synthesis available to date, provides a basis for comparison of relative costs among elements of the disposal system, and gives a rough idea of costs for a pilot or demonstration project. Overall, the costs in this analysis likely are overestimates because of various conservative assumptions in the reference design and lack any formal optimization of the design and procedures.

The estimated system costs per borehole are summarized in Table 9. 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 9 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 9. 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.

The estimated drilling, casing, and borehole completion costs shown in Table 9 are for configuration C, as described in Section 6.1. 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. As discussed earlier, the borehole costs for logging, coring, and testing constitute an important component of the total cost and a more cost effective method of conducting initial characterization of the deep subsurface at a site may be to do so in a smaller-diameter, exploratory borehole.

The costs of dismantling the fuel assemblies and loading used fuel pins 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. report.

7.3. Conclusions and Recommended Additional Work

Overall, the results of the reference design development and the cost analysis support the technical feasibility of the deep borehole disposal concept for high-level radioactive waste. Drilling and borehole construction methods required for deployment of the disposal concept are within the envelope of capabilities for deep drilling and can be accomplished at acceptable costs. A relatively simple canister design with consolidation of used fuel pins provides sufficient waste capacity and reasonable assurance of canister integrity during loading, handling, and emplacement of the waste canisters. The higher density of packing used fuel rods in the reference waste canister design results in an estimate of about 700 boreholes for the disposal of the projected waste inventory from the current fleet of nuclear reactors in the U.S. The estimated number of boreholes required for the disposal of intact fuel assemblies is about 950 boreholes (Brady et al., 2009). The operational procedures for waste emplacement and sealing of the borehole can be accomplished with standard, or reasonably envisioned modifications of standard, borehole equipment.

The reference design and operational procedures can be used as the basis for planning a pilot or demonstration project of the deep borehole disposal concept. Several aspects of a pilot project can be patterned on the reference design, including:

1. The details of logging, coring, and testing in the deep borehole environment for characterizing the geological and hydrogeological conditions relevant to safety and performance of the deep borehole disposal concept. The tools and methods used in such characterization are common in the petroleum and geothermal industries, but are not commonly used for the purposes and at the depths of borehole disposal. Equipment and methods may require adaptation for use in large-diameter boreholes.

2. Mockups of waste canisters for use in testing. Testing of loading, welding, and handling of waste canisters could be done as part of a pilot project. Corrosion testing under deep borehole conditions would provide confidence that waste canisters would retain their integrity on operational time scales. *In situ* heater testing using waste canister mockups could be used to validate numerical modeling of coupled thermal-hydrologic-mechanical processes and to provide confidence in seal integrity.

3. Seals emplacement operations and performance. Operational procedures for emplacement of seals and plugs could be refined and demonstrated in a pilot project. The mechanical and hydrologic integrity of seals could be tested under deep borehole conditions.

4. Engineering systems for surface facilities. Specifically, the system for handling shipping casks, positioning them over the borehole, and lowering waste canisters into the borehole could be developed and demonstrated. Other engineering systems associated with

emplacement and monitoring operations would require alteration for specific application to deep borehole disposal and could be tested in the pilot project.

The reference design should be used to update the performance assessment analyses presented in Brady et al. (2009). Borehole configuration and canister dimensions in the reference design are somewhat different from those used in the previous performance assessment. The waste loading and thermal output from used nuclear fuel are significantly higher than the baseline calculations performed in Brady et al. (2009). The reference design in this report provides a much more detailed design for the types, dimensions, and number of borehole seals and plugs that should be incorporated into modeling for the performance assessment calculations.

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