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Handling and Emplacement Options for Deep Borehole Disposal Conceptual Design

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HANDLING AND EMPLACEMENT OPTIONS FOR DEEP BOREHOLE DISPOSAL CONCEPTUAL DESIGN

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ABSTRACT

This report presents conceptual design information for a system to handle and emplace packages containing radioactive waste, in boreholes 16,400 ft deep or possibly deeper. Its intended use is for a design selection study that compares the costs and risks associated with two emplacement methods: drill-string and wireline emplacement.

The deep borehole disposal (DBD) concept calls for siting a borehole (or array of boreholes) that penetrate crystalline basement rock to a depth below surface of about 16,400 ft (5 km). Waste packages would be emplaced in the lower 6,560 ft (2 km) of the borehole, with sealing of appropriate portions of the upper 9,840 ft (3 km). A deep borehole field test (DBFT) is planned to test and refine the DBD concept. The DBFT is a scientific and engineering experiment, conducted at full-scale, in-situ, without radioactive waste.

Waste handling operations are conceptualized to begin with the onsite receipt of a purpose-built Type B shipping cask, that contains a waste package. Emplacement operations begin when the cask is upended over the borehole, locked to a receiving flange or collar. The scope of emplacement includes activities to lower waste packages to total depth, and to retrieve them back to the surface when necessary for any reason.

This report describes three concepts for the handling and emplacement of the waste packages: 1) a concept proposed by Woodward-Clyde Consultants in 1983; 2) an updated version of the 1983 concept developed for the DBFT; and 3) a new concept in which individual waste packages would be lowered to depth using a wireline.

The systems described here could be adapted to different waste forms, but for design of waste packaging, handling, and emplacement systems the reference waste forms are DOE-owned high-level waste including Cs/Sr capsules and bulk granular HLW from fuel processing.

ACKNOWLEDGEMENTS

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ACRONYMS AND ABBREVIATIONS

BOP	Blow-Out Preventer
cm	centimeter
Cs/Sr	Cesium-137 and Strontium-90
DBFT	Deep Borehole Field Test
DBD	Deep Borehole Disposal
DOE	U.S. Department of Energy
FoS	Factor of Safety
ft	foot
HLW	High-Level radioactive Waste
in	inch
lb	pound
m	meter
NNSS	Nevada National Security Site
psi	pounds per square inch
R	rem
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
SOP	Standard Operating Procedure
TBD	To Be Determined
TD	Total Depth
WCS	Waste Control Specialists LLC

HANDLING AND EMPLACEMENT OPTIONS FOR DEEP BOREHOLE DISPOSAL CONCEPTUAL DESIGN July 22, 2015

1. INTRODUCTION

This report presents conceptual design information for a system to handle and emplace waste packages in boreholes 16,400 ft (5 km) deep or possibly deeper depending on future mission requirements. Its intended use is for a design selection study that compares the costs and risks associated with two emplacement methods: drill-string and wireline emplacement.

English units are used intentionally throughout much of this report, particularly for discussion of downhole construction and operations, because of their prevalence in the drilling industry.

Deep Borehole Disposal Concept and Deep Borehole Field Test

The deep borehole disposal (DBD) concept calls for siting a borehole (or array of boreholes) that penetrate crystalline basement rock to a depth below surface of about 16,400 ft (5 km). In this disposal concept, waste packages would be emplaced in the lower 6,560 ft (2 km) of the borehole, with sealing of appropriate portions of the upper 9,840 ft (3 km). The borehole seal system could consist of alternating layers of compacted bentonite clay and concrete (Arnold et al. 2011).

The DBD conceptual design has not been implemented or field tested, and a deep borehole field test (DBFT) is planned to test and refine the DBD concept. The DBFT is a scientific and engineering experiment, conducted at full-scale, in-situ, without any radioactive waste. Data from the DBFT will provide an opportunity to validate and improve waste package design, and the design of the handling and emplacement systems.

Scope of Handling and Emplacement

The scope of *handling* is defined here to begin with the onsite receipt of a purpose-built Type B shipping cask, that contains a waste package. It ends when the cask is upended over the borehole, locked to a receiving flange or collar. The scope of *emplacement* includes the activities to lower the waste packages from the cask to total depth (TD), and to bring waste packages back to the surface when necessary for any reason as part of emplacement operations.

The systems described here could be adapted to different waste forms, but for design of waste packaging, handling, and emplacement systems the reference waste forms are DOE-owned high-level waste (HLW) forms including: 1) Cs/Sr capsules from Hanford; and 2) bulk HLW in solid form such as the calcine waste from fuel processing at Idaho. The DBD concept may also be viable for commercial spent nuclear fuel (SNF; Arnold et al. 2011). We note that large-scale waste disposal operations could involve multiple boreholes and last for several years, so that it could be cost effective to purchase and/or fabricate dedicated equipment.

2. WASTE PACKAGE HANDLING AND EMPLACEMENT

This section describes three concepts for the handling and emplacement of the waste packages. The first was described at a high level by Arnold et al. (2011) and was proposed originally in a Woodward-Clyde (1983) report. The concept involves assembling waste packages into strings at the top of the borehole and lowering the strings to depth on a string of drill pipe.

The second concept is an updated version of the 1983 concept, developed for this study. The third is a new concept developed for this study, in which individual waste packages would be lowered to depth using a wireline.

The remainder of this section is organized as follows:

- Section 2.1 describes the waste packages that will be manipulated by the handling and emplacement systems.
- Section 2.2 gives an overview of the 1983 and 2011 reference emplacement concepts, which is the point-of-departure for the two systems described in more detail in this report (Sections 2.4 and 2.5).
- Section 2.3 details the activities associated with receipt of the purpose-built shipping cask, and also presents a brief description of that cask.
- Section 2.4 describes an updated version of the 2011 concept in which up to 40 waste packages are threaded together and lowered into the disposal zone on a string of drill pipe. There are three subsections, describing the equipment, handling steps, and emplacement steps.
- Section 2.5 describes the concept for emplacing waste packages by wireline.

A minimum factor of safety (FoS) is required for design of the waste handling and emplacement systems. The DBFT Requirements and Controlled Design Assumptions document (SNL 2015a) prescribes FoS $\geq$ 2.0 for waste packages and systems for handling and emplacement. The FoS should be reasonably conservative, and comparable to values used in other critical systems (e.g., pipelines, rigging, etc.). The consequences of an accident during the DBFT or during DBD operations could be significant even without a release of radioactive material.

2.1 Overview of the Waste Package

Waste packages will contain bulk waste material (e.g., granular solids) in a thin-wall canister that is used for upstream handling and storage, or they will be loaded with bulk granular waste directly. In either case, the overpack or package must withstand downhole temperatures and pressures, and provide a 1 atm internal environment for the waste, during emplacement operations and borehole plugging and sealing (until breach after permanent closure). Detailed waste package design considerations are described elsewhere (SNL 2015b). From the exterior, the directly loaded waste package and the disposal overpack for thin-wall canisters will be similar in appearance.

Waste forms such as the Cs/Sr capsules are radiologically hot and the unshielded contact dose rate at the outside of the waste package could be as high as several hundred rem per hour. Waste packages may also be thermally hot, for example a package of Cs/Sr capsules could radiate 100 to 500 W per meter of length, depending on the waste age and the mode of packaging.

Waste packages will be loaded and sealed by welding at a specialized nuclear material handling facility (hot cell). Thus, waste packages will be delivered to the disposal site sealed and ready for direct emplacement in the disposal borehole. Welding provides a permanent seal and has been a preferred closure solution for mined geologic disposal in repository programs.

Reference-size waste packages will have a maximum diameter of approximately 11 in. The overall external package length used in this report is 18.5 ft. Arnold et al. (2011, page 37) presented a reference external length of 15.75 ft; the additional length adopted here will increase the internal dimension of the waste cavity to 16.4 ft or 5 meters (controlled by SNL 2015a). It will add a 1-ft thick shield plug at the upper end (Figure 1), thicken the lower endcap for structural strength, and allow increased separation of welds from the connector threads to limit heat damage. The 18.5-ft overall length is a maximum, and the package length can be adjusted by varying the length of the tubular part. The handling and emplacement systems could accommodate shorter packages, with certain complications noted in Sections 2.4 and 2.5.

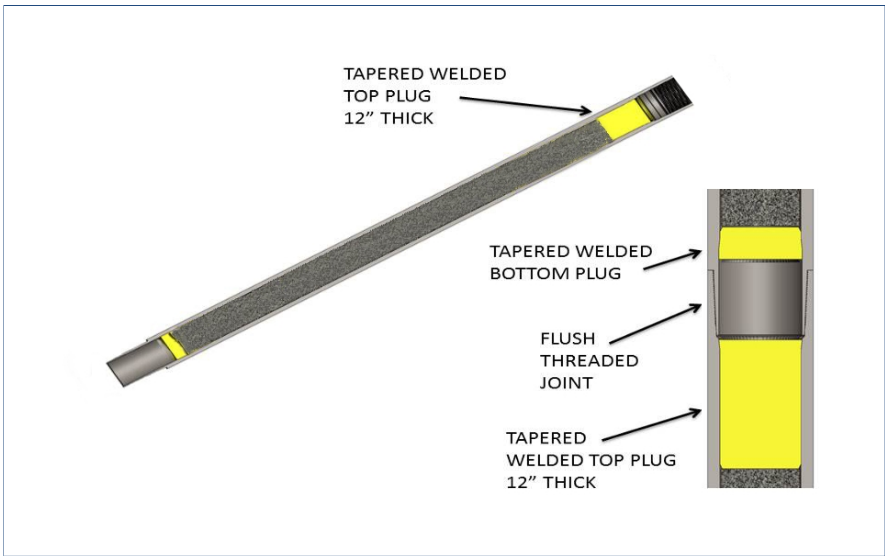

Figure 1. Waste package conceptual design.

The exterior of the waste package surface, including connections, will be free of exposed steps or ridges that could hang up on casing joints, hangers, etc., when moving upward or downward. All packages will have a detent or collar at the lower end that engages with the "elevator" ram to support the package string during assembly as discussed below. The depth of such detents (or the radial thickness of collars) will be approximately 0.5 in.

At TD the in situ temperature could be as high as 338° F (170°C). For heat-generating waste the peak package surface temperature could be 480°F (250°C, representing 80 C° rise). This latter temperature is based on thermal analysis from Arnold et al. (2014) for packages containing Cs/Sr capsules stacked end-to-end, with relatively high heat output, emplaced in 2020.

For design purposes it is assumed that borehole pressure will be less than or equal to that produced by a uniform fluid column with 1.3× the density of pure water, at up to 16,400 ft depth. The resulting design basis hydrostatic pressure at the bottom of the hole is 9,560 psi.

It is estimated that the loaded waste packages will have a dry weight of 4,620 lb (for the reference size package with 11-inch outer diameter). This is based on the following assumptions: the disposal overpack will be made of steel with a wall thickness of 1.2 in, length of 18.5 ft, solid steel ends 6 and 12 in thick, containing 367 pressurized water reactor fuel rods (consolidated, at 2.39 kg/rod). Granular waste forms would probably be less dense than closely packed fuel rods, and the package wall thickness could be smaller with higher strength material.

The displaced volume of the waste package is approximately 12.2 ft^3. The buoyancy is therefore 990 lb in drilling mud with density 1.3× that of pure water, and 760 lb in pure water. The buoyant weight of a loaded waste package will therefore be 3,630 lb in 1.3× drilling mud, or 3,860 lb in pure water.

In summary, the external characteristics of the waste package are

- Maximum outer diameter 11 in.
- Overall length 18.5 ft.
- Dry loaded maximum weight 4,620 lb.
- Maximum buoyant weight 3,630 lb in 1.3× drilling mud, and 3,860 lb in pure water at room temperature.
- Radiologically hot
- Thermally hot

Waste packages will be designed for a nominal lifetime of 10 yr (SNL 2015a) during which it may be exposed to brine containing chloride, Na, Ca, and possibly Mg ions.

Waste package configurations will differ for drill-string emplacement vs. wireline emplacement, as follows:

Packages for drill-string emplacement – Waste packages will have threaded joints at each end, for attachment to other waste packages. Joints between waste packages will have slightly larger or smaller external diameter, or they will have collars or detents, to give the waste handling equipment a positive grip. The "elevator" ram (discussed below) will be fitted to this diameter feature. Where possible, the inside of each threaded box-type connector will have a ridge or groove that can be engaged by internal fishing tools to provide an alternate method of retrieval.

Two sets of power tongs and one power slip will be available to make of strings of waste packages (Figures 2 and 3), the upper set of tongs could be eliminated for making up package strings, but without the upper tongs there would be no way to disassemble a package string if it were necessary to remove it from the borehole.

The first (lowermost) package in a string of packages to be emplaced will be an instrumentation package (e.g., caliper tool, look-ahead scanner for obstructions, and telemetry). Telemetry from the instrumentation package to the surface could be battery powered, pressure activated, and electromagnetic without cables. If a package string were lowered into collapsed casing and became stuck, the instrumentation package could have a "weak point" or shear pin to facilitate removal of the remainder of the string. The instrumentation package could serve other purposes: 1) initiate the process of threading together the string at the surface, as discussed below; and 2) bear any concentrated loads associated with setting the string down on the bottom, or onto a plug.

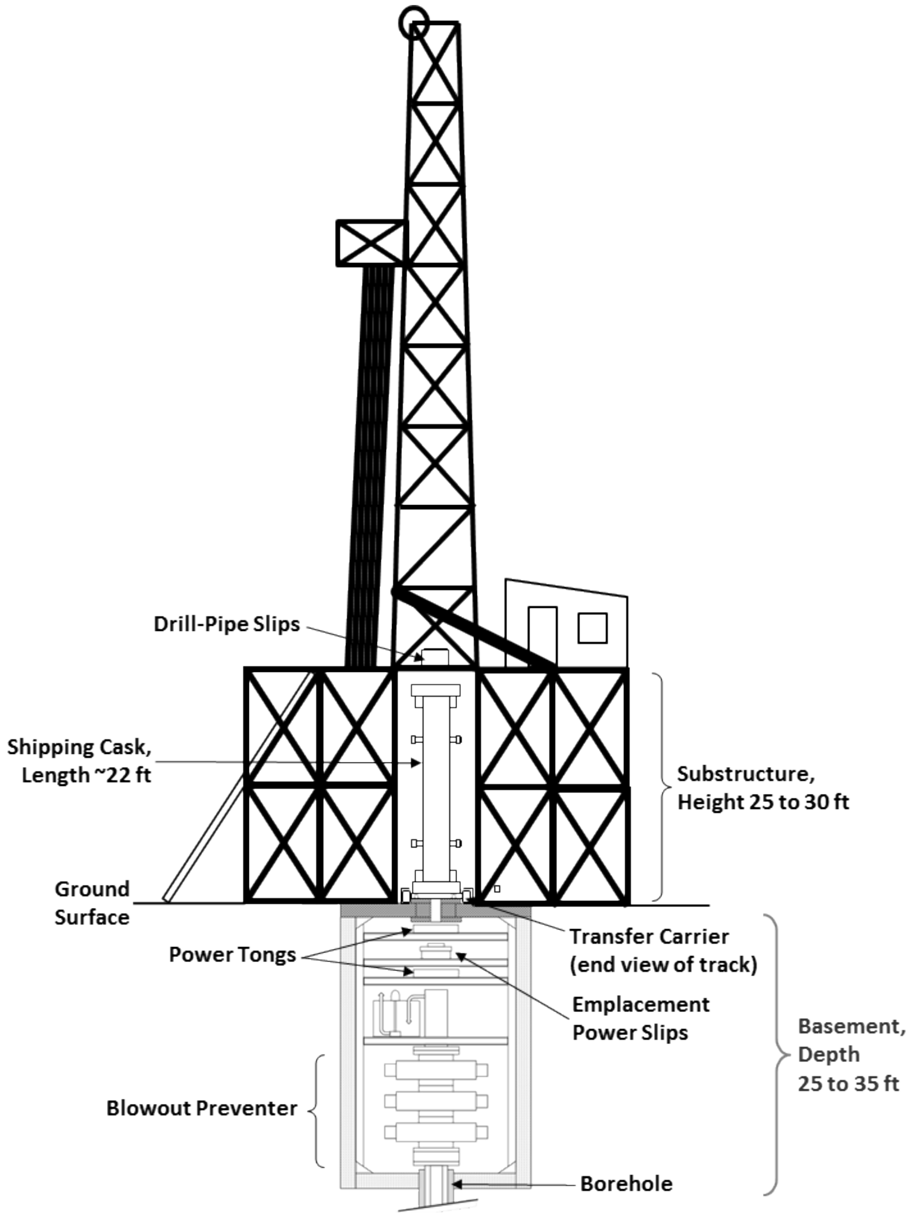

Figure 2. Schematic of emplacement workover rig, basement, transport carrier, and shipping cask in position for waste emplacement (not to scale).

A J-slot safety joint (Arnold et al. 2011) will be threaded onto the topmost waste package in each string to be lowered. This safety joint is readily released once the package string is resting on the bottom in the disposal zone and allows for re-engagement if retrieval is necessary.

Axial loads are a minor contribution to waste package loading (which is dominated by hydrostatic pressure), so package breach would be unlikely even if the string is accidentally set down hard on the bottom, for example, at the drill-string lowering speed.

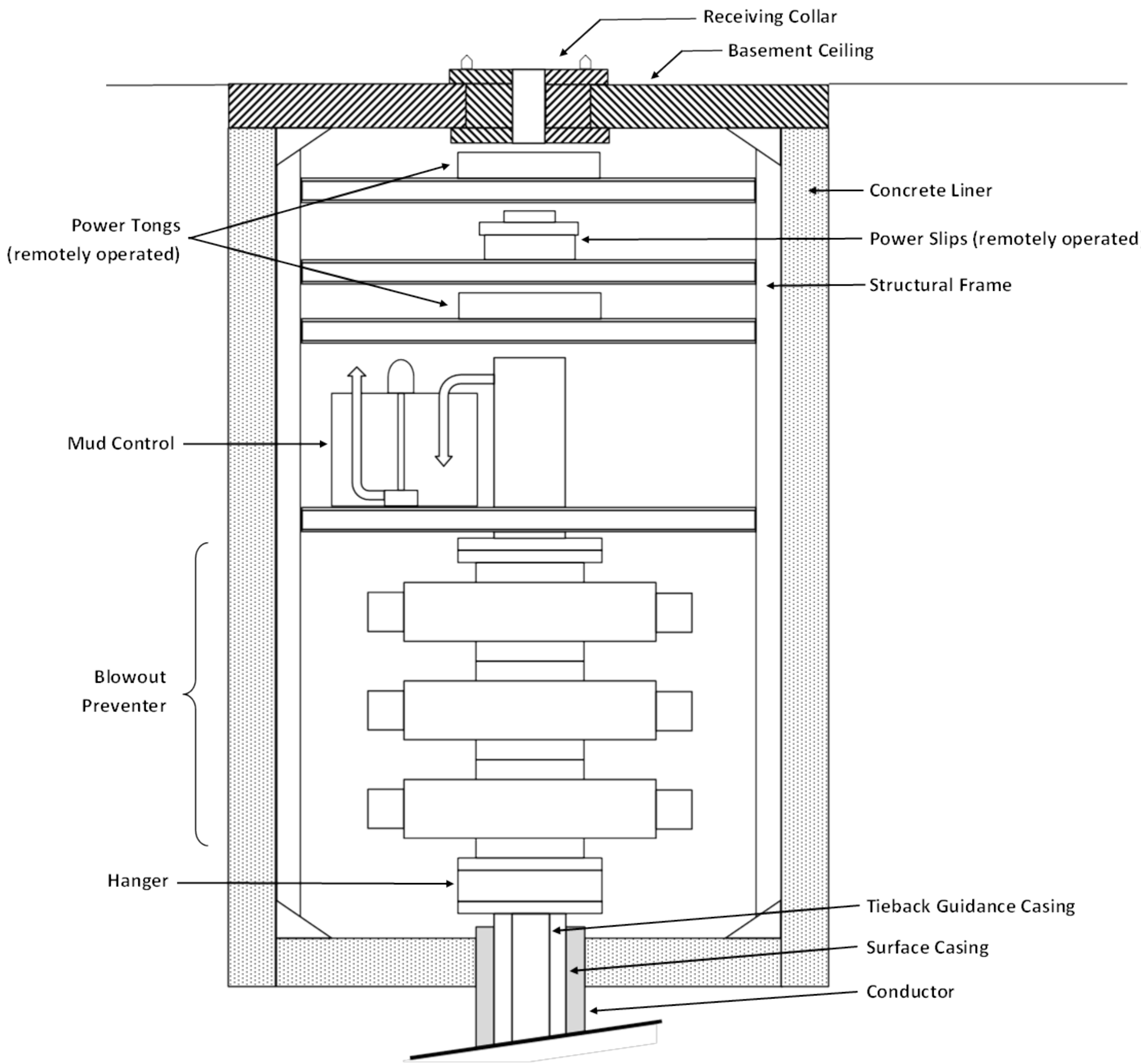

Figure 3. Basement concept for drill-string emplacement (not to scale).

Packages for wireline emplacement – Waste packages for wireline emplacement will essentially be the same, but emplaced individually on an electric wireline. They will have the same threaded joints discussed above, but specialized subs will be threaded on the top and possibly the bottom. The upper sub will have a neck that mates with an electrically actuated releasable cable head. The lower sub, if used, will have a threaded connection for attachment of instrumentation and/or a shock-absorbing assembly ("crush box"). Mechanical loads on these connections will generally be smaller than for drill-string operations. However, the upper and lower subs must be configured to sustain the static compressive load of a string of up to 40 stacked packages during emplacement.

2.2 Earlier Reference Concepts for Handling and Emplacement

The 2011 reference design for waste handling and emplacement (Arnold et al. 2011) is based loosely on a previous study (Woodward–Clyde 1983). The previous work followed the Spent Fuel Test-Climax (SFT-C) at the Nevada National Security Site (NNSS, formerly the Nevada Test Site), conducted from 1978 to 1983. The SFT-C was an operational demonstration in which 11 canisters, each containing one irradiated PWR fuel assembly, were transferred through a 1,365 ft (416 m) deep borehole into the Climax Mine. The SNF was stored underground for three years, then retrieved through the same borehole (Patrick 1986).

In the 2011 presentation of this design, the waste packages are lowered to emplacement depth through a guidance liner. The guidance liner has nominal outer diameter of 13-3/8 in. (34 cm) and internal (drift) diameter of 12.46 in (31.7 cm) (Arnold et al. 2011, Table 2). The upper length of guidance liner (tieback) hangs from the surface to 9,840 ft (3 km) and is contiguous with a slotted guidance liner that hangs from 9,840 ft to TD at 16,400 ft (5 km). The interface between the two is a casing hanger that is anchored to the intermediate casing (Arnold et al. 2011, Figure 4). The guidance liner is retained in the updated reference design described in Section 2.4.

In abbreviated form, the 2011 handling and emplacement system lays out the following steps:

- A waste package arrives in a purpose-built Type B shipping cask on a trailer (tractor-trailer).
- The Type B shipping cask (referred to as a "cask transporter" in the Woodward–Clyde study) has two lids or doors, one on each end.
- Equipment on the trailer rotates the Type B shipping cask into a vertical orientation using hydraulic cylinders.
- Handling equipment on a rail transporter grasps trunions on the Type B cask, and pulls the vertical cask on to the rail transporter.
- The rail transporter consists of a car with a steel frame, that is supported by four railcar trucks that run on steel rails. The rails are part of a large steel frame that is aligned to the borehole and bolted down to a reinforced concrete pad.
- The rail transporter is self-propelled and moves the vertically oriented cask along the track, under the drill rig floor, to a position directly over the borehole.
- The rail transporter locks in position with the shipping cask centered on the borehole.
- The upper door on the shipping cask is opened and drill pipe is connected to the top of the exposed waste package. (The integrated shielding plug on the top end of the waste package greatly reduces the gamma shine upward, toward the rig floor.)
- The waste package is lifted slightly to remove the weight from the lower door on the shipping cask.
- The lower door is opened and the first (lowermost) waste package is lowered through the shipping cask, and gripped by a set of powered slips located in a shielded, remote-handling "basement" that houses the wellhead. For subsequent packages, the new package is lowered onto, and threaded into the previous one lodged in the slips.

- The drill pipe is disconnected from the package and hoisted out of the way, and the Type B shipping cask is returned to the trailer.
- The above steps are repeated, creating a string of waste packages hanging in the borehole.
- When as many as 40 waste packages are connected together, the string is lowered by extending sections of 4-1/2 in (11.4 cm) drill pipe, using redundant means to hold the pipe during operations (e.g., a pipe ram and a set of slips optimized for the drill pipe). The string is brought to rest at the appropriate elevation in the disposal zone. The first string will rest on the bottom of the hole, while subsequent strings will rest on cement plugs installed to support the weight.
- The drill pipe is disconnected from the waste canister string using a J-slot device, and the drill string is tripped out of the hole.
- A bridge plug and cement are set above the waste canister string to support emplacement of the next waste canister string. A cement plug of 33 ft (10 m) is recommended (Arnold et al. 2012).
- Approximately 400 waste packages are placed in each borehole (e.g., 10 strings of 40 packages each).

After all waste packages have been emplaced the borehole is sealed by introduction of materials such as cement and bentonite slurry. The guidance liner tieback (above 9,840 ft) is removed, and the uncemented interval of intermediate casing (from approximately 6,560 ft to 9,500 ft) is cut and removed to expose the borehole wall for sealing purposes. Sealing procedures and equipment are beyond the scope of this report.

Similar steps and the associated general layout are adopted for the updated concept described in Section 2.4, with changes to the surface handling equipment and the basement configuration, and addition of a leading instrumentation package in each string.

2.3 Receipt of the Shipping Cask

Each waste package would arrive at the site in a purpose-built Type B shipping cask, on a purpose-built trailer. Only one waste package can be carried in a shipping cask. This is a departure from the Woodward–Clyde study which brought three canisters containing chopped SNF to the site, attached together in a rigid carrier and transferred as one to the borehole. Even though the Woodward–Clyde waste packages would have been shorter (less than 4 m overall length), the resulting triplet of packages would have required a longer transfer cask, higher elevation of the rig floor, and a deeper rig basement.

Based on operational experience at Waste Control Specialists (WCS) site in Andrews, Texas, only one shipping cask and one package containing highly radioactive waste can be handled per day. At the WCS site it takes 4 days to complete an emplacement cycle, but one shipping cask can be unloaded and released for reuse every 24 hours (Britten 2013).

The purpose-built shipping cask will be a hollow, right circular cylinder with doors on each end that can be operated remotely by connection to an external power supply. These doors could be electrically operated with worm gear drives. The doors will have locking pins or bolts that restrain the doors in either the open or closed position (important for wireline emplacement as discussed below). The inner diameter of the shipping cask will be a clearance fit with the waste package, which will limit gamma shine emanation from the gap when the upper door is open.

The cask will also have permanently fixed range-limiting pins or bolts at the top that prevent inadvertent lifting of the waste package up and out of the cask. Lifting a package out of the cask could expose all rig workers to strong gamma radiation. These pins will have greater strength than the breakaway sub used in drill-string emplacement (or a weak-point in the wireline) so that the lifting mechanism fails first. Spacing of the pins will allow passage of drill pipe or a wireline cable head, but not the waste package.

The shipping cask will also have a set of radial restraint bolts at the lower end that restrain the waste package during transport, and keep it from turning as drill pipe is initially threaded into it. The bolts will provide enough reaction torque to achieve a firm connection with the drill pipe, so that the package can be lowered a few feet out of the cask and threaded into the previous package. Once the drill pipe is connected the radial restraint bolts will be backed out slightly, releasing the package. These bolts will be designed to shear if the full joint makeup torque is applied, thereby limiting damage to the cask and the waste package. They will be located near the bottom of the shipping cask (engaging the bottom endcap of the waste package) where they can be readily accessed for manual operation. These radial restraining bolts would not be used with wireline emplacement, and could be replaced by shorter bolts for shielding.

When each shipping cask arrives at the DBD facility (Figure 4) it will be radiologically surveyed. After check-in activities, the impact limiters will be removed from the ends (Figure 5). A crane and associated equipment will be required. After removal of the impact limiters, the tractor-trailer with the shipping cask will be directed to the disposal borehole. This receipt procedure, and the shipping cask configuration, would be same for both drill-string and wireline emplacement.

Analogous shipping cask for SFT-Climax – The Spent Fuel Test-Climax developed and deployed a purpose-built surface transport cask similar to that described above (DOE 1980). The SFT-Climax cask was not certified as a Type B shipping cask, however, its design provides an analogue for DBD application. The top lid of the Climax shipping cask was made of steel approximately 7 in (18 cm) thick, attached by means of a hinge. The top lid was opened and closed by a double-acting hydraulic cylinder attached to the cask body. The bottom lid was a sliding door assembly with steel doors approximately 18 in (46 cm) thick. The sliding doors were electrically actuated, and moved on lubricated slides driven by lead screws. The Climax shipping cask was made mostly of steel, and weighed approximately 90,000 lb (45-inch outer diameter, 18-inch inner diameter, and 18 ft length).

Figure 4. Example Typical Type B shipping cask (photo courtesy of Waste Control Specialists).

Figure 5. Removal of typical impact limiters (photo courtesy of Waste Control Specialists).

2.4 Drill-String Handling and Emplacement of Strings of Waste Packages

2.4.1 Handling and Emplacement Components

After drilling and construction of the disposal borehole is complete, and the drilling rig is moved off, a number of modifications will be made to create the integrated facilities needed to emplace waste packages. Modifications will be made in several phases: basement construction, surface pad installation, transfer carrier installation, emplacement workover rig setup, and installation of the control room and ancillary surface equipment. The following paragraphs describe modifications for a reference-size borehole (17-inch diameter in the disposal zone), but similar facilities would be used for disposal boreholes of different sizes.

Basement construction – The basement will serve two main functions: 1) provide a shielded facility to house the BOP and other control equipment for handling waste packages, and 2) reduce the height requirement for the shipping cask, emplacement rig, and related equipment.

A reinforced-concrete basement excavation will be constructed around the conductor and surface casing (Figures 2 and 3). The choice of construction methods, basement cross section, and other details will depend on site conditions (e.g., deep unconsolidated soil vs. bedrock). The basement structure will need to withstand loading at the ground surface by the emplacement workover rig (see discussion of surface pad below). The rig will exert forces on the order of 10^6 pounds at various locations close to the excavation. The basement could be circular or rectangular in cross section, and lined with steel or concrete. The basement floor will be reinforced concrete with footings to support load-bearing structural components (i.e., either the walls, or an internal structural frame).

To facilitate construction of the basement the borehole casings (conductor and surface) will be temporarily plugged and the BOP removed (the BOP is installed on the surface casing, nominally 24-inch diameter). If the BOP is also required during emplacement and sealing operations, it will later be re-installed in the basement, and the basement design will be approximately 10 ft deeper (e.g., 30 ft instead of 20 ft, for waste packages nominally 18.5 ft long).

The basement will have a mud surge tank, sump pump, mud lines to the surface, and equipment for handling mud surge during operations. The basement surge tank, plus additional mud storage capacity at the surface, will have capacity at least equal to the displacement of the drill string plus 40 waste packages (~8,000 gallons). It is anticipated that the basement surge tank would be smaller than this (e.g., 1,500 gallons) with pumps to move mud back and forth between the borehole and a larger surface tank. The basement sump could be used for emergency surge (e.g., in the event of pump failure during emplacement operations).

After basement construction the surface and conductor casings will be cut off and reconfigured for the basement equipment. This equipment (i.e., "elevator" ram, BOP if required, any additional valves required, slips, tongs, and other monitoring and control equipment) will be lowered and assembled in place. Worker access to the basement will be through the ceiling as discussed below, with ceiling plates removed.

Taken together, the basement stack (Figures 2 and 3) may include: 1) a blind-ram to close the borehole when waste packages are not being emplaced; 2) a 4-1/2 in (11.4 cm) pipe ram used to seal around the drill pipe during emplacement operations; 3) an "elevator" ram configured as a pipe ram to grip package strings at the joints; and 4) any other valving or preventer hardware required by permits. Shear rams or other closure systems that could damage waste packages or cause the drill string to part if inadvertently actuated, will not be used or will be disabled during emplacement operations.

The basement will have a ceiling at grade level that shields the rig above from gamma radiation emanating from waste packages when they are located in the basement interval. The ceiling will also support the shipping cask during waste package transfers. It will consist of two or more movable plates of steel or prefabricated reinforced concrete. The plates will be keyed and bolted together in place, forming a load-bearing platform with a central hole (Figures 2 and 3).

The basement will be constructed to allow worker access and ventilation in the event that there is an equipment problem during emplacement operations. Access will be provided by a shielded door in each half of the basement ceiling. The basement ceiling plates and collar can be disassembled and removed for greater access. In the unlikely event that waste packages get stuck in the basement interval, the cause will be malfunctioning wellhead equipment, and remote operations will be used to operate or repair the equipment.

A receiving collar will be installed in the central hole in the ceiling, aligned with the borehole. The functions of the receiving collar are to: 1) anchor the shipping cask and transporter platform over the borehole; 2) guide the shipping cask into position over the borehole; 3) provide shielding between the basement ceiling and the shipping cask; and 4) provide a central hole for access to the borehole, that is a clearance fit with the waste package upper end to limit radiation leakage. The receiving collar and basement ceiling will support weight of the shipping cask (approximately 66,000 lb), and the waste package, at an appropriate factor of safety (see SNL 2015a). The shipping cask will be present only when assembling or disassembling strings of waste packages. The receiving collar and basement ceiling will also resist an inadvertent upward pull by the rig hoist, sufficient to release the breakaway sub (approximately 200,000 lb; see Section 2.4.3).

Emplacement power slips will be installed below the receiving collar and above the BOP (Figures 3 and 6). The function of these slips will be to grip the package string and prevent vertical movement during string assembly (or disassembly if required). The power slips will be remotely and hydraulically actuated. A separate set of slips at or just below the rig floor will be used to hold the drill string as pipe joints are made up or broken down during trips into/out of the borehole.

Figure 6. Example of power slips (courtesy of National Oilwell Varco).

A remotely operated power tong will be installed just below the power slips to prevent rotation of the package string when making joints in the string. Breaking of joints in the package string (e.g., if the string must be removed from the borehole) will require an additional power tong above the power slips (Figures 2 and 3).

The breakaway sub will be long enough to extend from the emplacement power slips, to the “iron roughneck” above the rig floor, in one piece. The breakaway sub will include load and torque sensors integrated with the interlock system on the cask doors, emplacement power slips, basement tong, “elevator” ram, drill pipe ram, and blind ram. The interlock system will also include sensors that monitor for rotation of the waste package string in the basement and the borehole, when threaded connections are made up.

In the Woodward–Clyde (1983) concept the emplacement power slips were supported by structural links attached to the basement ceiling plate, which in turn was supported by the basement walls. This arrangement would complicate removal of the ceiling plates for inspection, maintenance, or disassembly. In this updated concept, the emplacement power slips would be supported either by a structural frame anchored to the basement walls and floor, or by structural beams anchored in the walls. As noted above the power slips would support only a single string of packages (less than 200,000 lb; see weight calculations below) plus dynamic loads associated with engagement and disengagement of the slips. Supporting these slips with an independent structural frame would simplify loading conditions in the wellhead. Regardless of how the emplacement power slips are supported, it is likely that a steel frame structure would be erected in the basement to provide ladders and work decks for access to equipment, and for lateral support of the wellhead stack.

The “elevator” ram would be located below the power slips at a distance corresponding to the length of one package (approximately 18 ft center-to-center).

The tieback guidance liner will hang from the surface casing below the stack, consistent with the reference design of Arnold et al. (2011, Figure 4). Thus, the waste packages will run in a 24-inch bore for a short distance down to the tieback, approximately 30 ft below grade. Guides will be provided in this interval to ensure that packages pass freely. These guides would be removed after waste emplacement, for borehole plugging and sealing operations.

All systems will be tested after fabrication, and after assembly on-site, using the instrumentation package and empty (“dummy”) waste packages. Standard operating procedures (SOPs), maintenance procedures, and contingency procedures will be developed.

The basement and wellhead equipment will be designed for removal after waste emplacement, sealing, and plugging operations are complete. The borehole would be cemented up to the level of the basement floor. Equipment removal would be accomplished in the reverse order of installation. Casings would be cut off and removed. The basement would then be backfilled to the surface.

Surface pad installation – A surface pad will be constructed from reinforced concrete to serve two main purposes: 1) transmit support loads to the emplacement workover rig, and 2) anchor the transfer carrier track and align it over the borehole. Whereas heavy concrete pads are not typically used for workover rigs, the close proximity of the rig and the basement excavation require close control of load paths and deformations.

Transfer carrier installation – Following the Woodward-Clyde (1983) concept, a track-mounted transfer carrier will deliver the shipping cask over the last 50-ft distance to the borehole. It will consist of a platform mounted to four wheel trucks that run on a steel track. The wheel trucks will grip the track both above and below so that they cannot be derailed. The track will be part of a rigid steel frame that is anchored to the surface pad. The track will be approximately 6 ft wide, straddling the borehole, precisely aligned. Details of the transfer carrier are to-be-determined (TBD).

Other options considered for cask transfer include providing sufficient room within the rig substructure to drive the semi-trailer through, and up-ending the shipping cask directly from the trailer. Use of a boom-type crane directly under the rig would require significantly more vertical clearance, further elevating the rig. A bridge or gantry crane could be set up within the rig substructure, but would also require additional vertical clearance and could be difficult to align. A high-capacity forklift would require significantly more horizontal clearance under the rig floor. The pre-fabricated track option is compact and precise alignment could be accomplished during setup and prior to waste handling operations.

Emplacement workover rig setup – After the basement, surface pad, and transfer carrier track are installed and tested, the emplacement rig will be assembled above the borehole. It will be used to assemble waste packages into strings, lower the strings to emplacement depth, set bridge plugs and cement plugs, remove casing, and seal the borehole.

The emplacement rig floor will sit well above ground level, standing on a steel-frame substructure. A dimensioned open space within the rig substructure and around the wellhead will be required for the transfer carrier. The substructure will have sufficient height to allow the shipping casks to be positioned vertically over the hole under the rig floor. An opening in the substructure that is approximately 7 ft wide and 26 ft high will provide passage for the transfer carrier and shipping cask.

The emplacement rig will be similar to a drill rig but lighter and less costly. It will have the capacity to emplace 40 waste packages with approximately 15,660 ft of drill pipe. Drill pipe will be used to lower strings of waste packages, set cement plugs, remove casing from the seal zone, and seal the borehole. Pipe will likely be handled in 90-ft stands; whereas "quad-rigs" are available the extra size and cost may not be justified.

The combined weight of waste packages and drill pipe will be approximately 468,000 lb based on 153,000 lb buoyant weight for 40 waste packages in pure water, and 315,000 lb for 15,660 ft of drill pipe at 20 lb/ft. The heaviest lift for the emplacement workover rig will be removal of the guidance liner tieback (approximately 550,000 lb, assuming 10,000 ft of 13-3/8 in casing at 54.5 lb/ft).

In deep boreholes the weight of drill pipe hanging in the borehole is an important consideration. Woodward–Clyde (1983) selected 4-1/2 in (11.4 cm) drill pipe, which is available with tensile yield strength ranging from 330,600 to 824,700 lb depending on the weight and type of material (Grant Prideco 2003). Pipe joint strength generally exceeds that of the pipe because of increased wall thickness. Several approaches are available to deal with the weight of drill pipe while maintaining an appropriate FoS, including: 1) use lighter weight pipe (e.g., 16 lb/ft or less in steel or aluminum) in the lower part of the hole, and heavier pipe (20 lb/ft) in the upper part; and/or 2) lower fewer waste packages at a time in the lower part of the hole, since waste packages will comprise about a third of the total string weight.

Making and breaking threaded drill pipe joints is one of the riskiest tasks in a drilling operation from the standpoint of worker safety and improperly made joints. Accordingly, it is recommended that an "iron roughneck" (Figure 7) be used to make and break drill pipe joints. Iron roughnecks clamp the bottom pipe section while a rotary wrench turns the top section. The example shown stands about 10 ft tall in the stowed position, and handles pipe from 3½ to 10 in diameter with maximum make-up torque of 100,000 ft-lb and break-out torque of 120,000 ft-lb. It is pedestal mounted to the rig floor. The "iron roughneck" is not fully automated; an operator stands at a control panel. It does not necessarily increase the speed of pipe joint operations but it improves safety and reliability by reducing variability and the potential for human error. Whereas modern fully automated rigs are available, the "iron roughneck" represents a compromise that can be used with a wide range of rig types and could achieve similar reliability in joint tending.

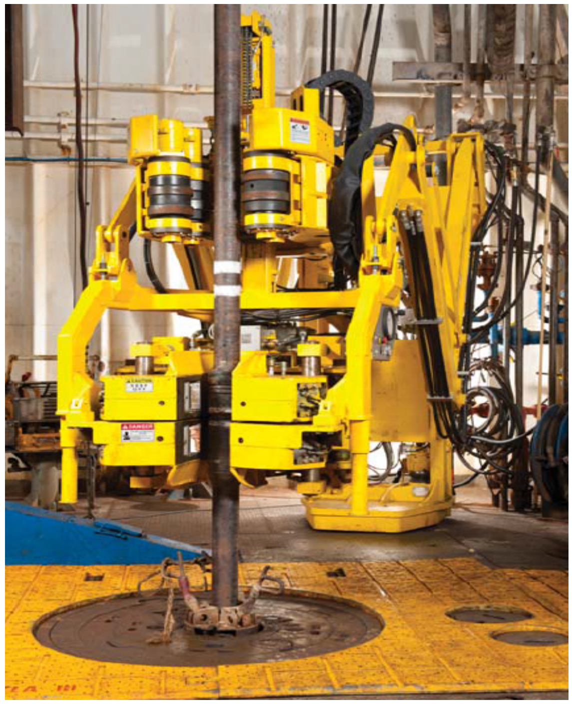

Figure 7. Mechanical "iron roughneck" pipe joint tender (Wrangler Roughneck 120 ™).

Control room and ancillary equipment – Waste handling operations will be controlled from a dedicated control room located on the rig floor, near the driller. Ancillary equipment associated with the emplacement rig will include generators, pipe handling, hydraulic pumps, cement and mud handling equipment, waste handling equipment laydown, a warehouse, a shelter and comfort facilities.

2.4.2 Handling Steps

Before the shipping cask is placed over the borehole, a caliper log will be run to ensure safe condition of the borehole. A crane will lift the shipping cask by one end from the trailer and lower it onto the transfer carrier (Figure 2). The shipping cask will be aligned using index pins, and bolted onto the transfer carrier. The transfer carrier will slowly move down the track and position itself over the borehole receiving collar (Figure 2). Additional steel guides high in the rig substructure may be used to stabilize the cask in its vertical orientation. The transfer carrier wheels, track, and drive mechanism can be optimized for safety and control. Kneeling jacks at each wheel of the transfer carrier can lower the cask down onto the receiving collar. where it is clamped or bolted in place.

2.4.3 Emplacement Steps

After the shipping cask has been bolted/secured to the receiving collar, the following steps will be used to make up a string of waste packages in the borehole and then use drill pipe to lower the string of packages to the emplacement interval in the borehole. The number of packages in a string is TBD based on logistical and safety analyses.

1. Remotely open the upper door on the shipping cask (shielding is provided by the shield plug integral to the waste package).

2. Attach the breakaway sub (for use in making up waste package strings, see text) to the rig hoist (e.g., using an elevator device).
3. Verify radial restraining bolts on lower end of shipping cask (restrain waste package from spinning when threading on drill string).
4. Remotely attach the breakaway sub (pin) to the threaded connection on the upper end of the waste package (box) inside the Type B shipping cask, with minimum torque sufficient for picking up the waste package (without shearing the rotation restraining bolts).
5. Back out the rotation restraint bolts from lower end of shipping cask (free the waste package).
6. Slightly lift the waste package with the breakaway sub (permanently fixed range-limiting blocks or pins will prevent waste package from being withdrawn beyond the shield).
7. Check status of breakaway sub, cask doors, basement power slips, basement tong, “elevator” ram, drill pipe ram, and blind ram (these are interlocked).
8. Remotely open the lower door on the shipping cask.
9. If this is the first (lowermost) instrumentation package (see text), then remotely lower the instrumentation package so it is in the correct position, grip it with both the power slips and the “elevator” ram, engage the basement tong (prevents rotation), and apply weight to set the slips.
10. Remotely open blind ram and drill pipe ram.
11. If this is a subsequent waste package in a string, remotely lower the package onto the previous package in the slips.
12. Rotate the breakaway sub/waste package using the automated tender at the rig floor, and make the threaded connection with the previous package.
13. Verify threaded connection between packages (e.g., log makeup torque).
14. Disengage basement tong and “elevator” ram.
15. Slightly lift the package string to disengage the emplacement power slips.
16. Lower the string so it is in correct position, grip it with both the power slips and the “elevator” ram, engage the basement tong, and apply weight to set the slips.
17. Disconnect the breakaway sub and raise it back through the shipping cask.
18. Close upper and lower shipping cask doors.
19. Reverse handling steps (Section 2.4.2) to remove shipping cask.
20. Repeat handling steps (Section 2.4.2) and steps 1 through 18, to add additional waste packages to the string.
21. After final waste package is added, reverse handling steps (Section 2.4.2) to remove shipping cask.
22. Remove the breakaway sub and attach the J-slot device to the first stand of drill pipe.

23. Thread the J-slot device into the top waste package using an extension sub if necessary to reach the box thread in the emplacement power slips. Torque the connection.
24. Verify threaded connections between drill string and package string (e.g., log makeup torque).
25. Disengage basement tong and "elevator" ram.
26. Slightly lift the package string to disengage the emplacement power slips.
27. Lower string into position for adding a stand of drill pipe.
28. Actuate the drill pipe slips (on the rig floor) and basement pipe ram (and/or emplacement power slips).
29. Add another stand of drill pipe; make the joint with the "iron roughneck."
30. Disengage the basement pipe ram.
31. Slightly lift the string and disengage the drill pipe slips (and emplacement power slips if used).
32. Lower string into position for adding another stand of drill pipe, or lower string into emplacement position (if on bottom).
33. Repeat steps 28 to 32 until emplacement depth is achieved.
34. With the string secured in the drill pipe slips, attach a rotation device (e.g., kelly).
35. Disengage the basement pipe ram.
36. Slightly lift the string and disengage the drill pipe slips (and emplacement power slips if used).
37. Gradually lower the string until the force on the bottom is within specification to operate the J-slot safety joint.
38. Disengage the canister string using the J-slot safety joint.
39. Hoist the string into position for removing the rotation device.
40. Actuate the drill pipe slips, basement pipe ram, and emplacement power slips if used.
41. With the string in the slips, remove the rotation device.
42. Disengage the basement pipe ram.
43. Slightly lift the string and disengage the drill pipe slips (and emplacement power slips if used).
44. Hoist the string into position for removing another stand of pipe.
45. Actuate the drill pipe slips, basement pipe ram, and emplacement power slips if used.
46. Remove another stand of drill pipe, breaking the joint with the "iron roughneck."
47. Repeat steps 42 to 46 to trip out of hole.
48. Remotely close the blind ram.

2.5 Wireline Handling and Emplacement of Single Waste Packages

2.5.1 Handling and Emplacement Components

After the drill rig is moved off of the borehole and before wireline emplacement can begin, a number of modifications will be performed. Construction is divided into several sub-systems: surface pad, BOP shield, hoist and wireline, cable head, boom-type crane, ancillary surface equipment, and a control room. After waste emplacement, a completion/sealing workover rig will be used for final sealing and plugging.

Surface pad – A steel-reinforced concrete pad, approximately 25 feet on a side, will be poured around the wellhead at grade level, as a base for the BOP shield and other items.

BOP shield – Note that the following description is written for an emplacement borehole with a remotely operated BOP on 24-inch surface casing. If no BOP is required, and the wellhead consists of a simple remotely operated valve, then the BOP shield could be scaled down in both diameter and height. The hanger for the 13-3/8 in guidance liner tieback is located in the surface casing at or just below grade level.

A robust radiation shield will be constructed around the BOP (Figure 8). The shield will consist of two concentric, large diameter, corrugated metal culverts set up vertically and coaxially with the BOP. The height of the culverts will be just taller than the BOP. The culverts will be assembled from curved, corrugated structural plates, with flanges that are bolted together. The inner culvert will have flanges on the inside, and the outer culvert will have flanges on the outside, to access bolts for disassembly.

Figure 8. Schematic of BOP shield, top plate and shipping cask in position for waste emplacement (not to scale).

The annular space between the culverts will be filled with radiation shielding material. Inner culvert diameter (14 ft or sufficient for clearance around the BOP) and outer culvert diameter (20 ft) will provide at least 3 ft of shielding. Fill material will be selected (composition, density) to provide necessary shielding performance. Low-density non-reinforced concrete is recommended, with form-release compound or plastic sheet on the culvert surfaces to facilitate disassembly. Filling the culverts with concrete will ensure the desired mechanical strength to support the waste shipping cask discussed below.

A top plate on the shield will be made in two semi-circular sections, pre-fabricated from reinforced concrete. The pieces will form a hole at the center for the surface casing, and they will be keyed together to limit radiation leakage. The plates will be bolted down to the shield walls described above. The top plate pieces will have shielded doors for ventilation and worker access. A heavy, cylindrical steel receiving collar will fit into the hole and bolt to a flange on a section of 24-inch casing that is attached to the wellhead stack (Figure 9). The receiving collar will provide an interface to the shipping cask and a clearance fit for insertion of waste packages (limiting gamma shine through the gap). The culverts and collar will support the weight of the shipping cask (nominally 66,000 lb) and the waste package, with an appropriate FoS. Functionally, this receiving collar will be identical to that described for drill string emplacement. The shipping cask inside diameter will also be a clearance fit with the waste package, to limit radiation leakage as the package is lowered into the borehole. The BOP shield, top plate and collar will be designed for removal after waste emplacement operations are complete.

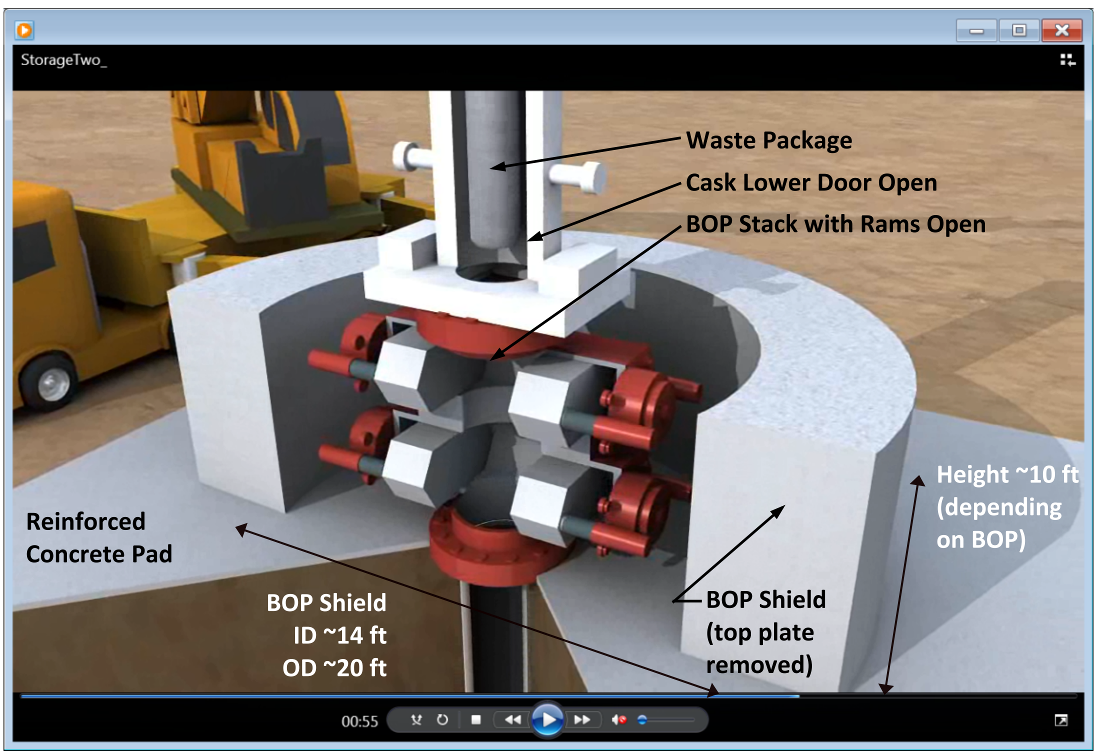

Figure 9. Detail of wellhead inside BOP shield, with doors opening in preparation for lowering waste package (mud handling equipment not shown).

Mud control piping will run from the wellhead through the BOP shield, to a surge tank and pump located outside. The surge during emplacement is expected to be on the order of 500 gallons.

Hoist and wireline – A standard truck- or skid-mounted wireline with 20,000 ft of 0.488" double-armored 7-conductor electric wireline can be used for emplacing waste packages. Typical service limit of 12,000 lb is 50% of breaking strength (approximately 24,000 lb). Buoyant weight of the wireline is approximately 5,800 lb (350 lb per 1,000 ft, at 16,400 ft TD), and the maximum buoyant weight of a reference waste package is approximately 3,860 lb, giving a total maximum wireline tension of 9,660 lb, plus the weight of the cable head and any additional logging tools, and subs used on the waste package (i.e., upper wireline latch, and a lower sub containing instrumentation or a "crush box").

Alternatively, a more modern wireline such as the Schlumberger Tuffline® may used. This example has 7-conductors, and uses corrosion resistant, low-stretch, synthetic polymer material for torque balanced armor, so that "seasoning" is not required. It has a breaking strength of 27,000 lb and a working load limit of 18,000 lb. According to a Schlumberger description, the 18,000-lb system does not require a dual-capstan device if tension is less than 12,000 lb. Figures 8 and 9 depict such a setup without one or more additional guide sheaves that could be used.

Note that the emplacement concept described here could, in principle, use coiled steel tubing for waste package emplacement instead of an electric wireline. Coiled tubing offers an advantage that could be important for emplacement operations, that waste packages could be pushed into the hole (e.g., to free stuck packages). However, the fatigue life of coiled tubing is on the order of a few hundred trips at most, particularly if they are deep trips that use most of the tubing in a coil. Thus, multiple coils would be needed for emplacing waste and completing a single deep disposal borehole.

Another advantage of coiled tubing compared to wireline emplacement, could be the greater strength of coiled tubing that could allow emplacement of several waste packages at a time. However, emplacing more than one package a time necessitates the construction of a basement similar to that needed for drill-string emplacement (Section 2.4) with facilities for threading packages together and supporting the string.

The additional cost and potential safety implications associated with detecting and replacing damaged tubing, and the expense of a basement for connecting multiple packages, mean that coiled tubing operations would be significantly more costly than wireline operations, and potentially more risky considering limited tubing life. Note that even with wireline emplacement operations, coiled tubing would still be used to set cement plugs as discussed below.

Coiled tubing could be considered for waste package emplacement, in variants of the drill-string method (which includes a basement), or the wireline method (for single packages). Coiled tubing is available with electrical conductors (at additional cost) which could operate an electrically actuated releasable cable head. For the drill-string method, coiled tubing could replace the rig for emplacement operations, whereas for the wireline method it would replace the wireline hoist.

Cable head – An electrically actuated cable head will release packages in the emplacement position. Examples of this type of equipment include the Haliburton RWCH® (releasable wireline cable head) and the Schlumberger SureLOC® 12000. Off-the-shelf tool designs may need to be modified to minimize the length and cost of the hardware left in the hole with each package.

Boom-type crane – Alignment and support of the wireline sheave over the borehole will be provided using a telescopic boom-type crane. The same or a similar crane will be used to hoist shipping casks onto the BOP shield receiving collar, and to support the coiled-tubing rig.

Ancillary surface equipment – During waste emplacement, cement plugs in the disposal zone will be set using a coiled tubing truck, with separate mud handling and cement handling systems. Bridge plugs (to locate the cement) can be set using either the coiled tubing or the wireline.

Other equipment associated with the completion/sealing rig will be organized on the surface, including generators, cement and mud handling equipment, a warehouse, a shelter and comfort facilities.

Completion/sealing workover rig – A workover rig will be used to remove the guidance liner tieback (approximately 550,000 lb as discussed previously) and the intermediate casing section from the seal zone (approximately 3,000 ft of 18" casing). The same rig will be used for seals emplacement and plugging of the disposal borehole.

Control room – Waste handling operations will be managed from a control room.

All systems will be tested after fabrication, and on-site with empty ("dummy") waste packages prior to operations. Standard operating procedures (SOPs), maintenance procedures, and contingency procedures will be developed.

2.5.2 Handling Steps

Before the shipping cask is placed over the borehole, a caliper log will be run to the next waste emplacement position, to ensure safe condition of the borehole.

A crane will be used to lift the shipping cask by one end from the trailer and place it in vertical orientation in the receiving collar. The shipping cask will be secured/bolted to the receiving collar in preparation for emplacement.

2.5.3 Emplacement Steps

After the shipping cask has been bolted/secured to the receiving collar, the following steps will be used to lower individual waste packages to the emplacement interval by wireline:

1. Remotely open the upper door on the shipping cask (shielding is provided by the shield plug integral to the waste package).
2. Manually set restraints on the upper door to prevent inadvertent closing on the wireline.
3. Attach the cable head to the upper end of the waste package, either remotely or accessing the top of the waste package using a portable worker platform.
4. Slightly lift the waste package with the wireline (permanently fixed, range-limiting pins prevent the waste package from being withdrawn beyond the shield).
5. Remotely open the lower door on the shipping cask.
6. Manually set restraints on the lower door to prevent inadvertent closing on the wireline.
7. Remotely open the blind ram inside the BOP shield.
8. Proceed to lower the waste package to emplacement position, verifying position using geophysical logs.

9. Disconnect cable head on electrical signal.
10. Hoist and re-spool wireline.
11. Remotely close the blind ram.
12. Manually release the restraints holding the upper and lower shipping cask doors open, and close the doors.
13. Repeat handling steps (Section 2.5.2) and steps 1 through 12 above, to emplace additional waste packages.

14.

3. EMPLACEMENT DISCUSSION

3.1 Drill-String Emplacement Rate-of-Progress

Drill pipe will be used to lower the string of disposal overpacks to the desired depth, up to 15,600 ft (plus the length of a package string). Assuming the crew can make up or break down one 90-ft stand of drill pipe every 5 min, the rate of emplacement is about 1,000 ft/hr (the rate referenced in Arnold et al. 2011). Thus, lowering a string of waste packages will take approximately 15 hr, and the round-trip time will be approximately 32 hr (15-hr trips and 2 hr for package release).

3.2 Wireline Emplacement Rate-of-Progress

Reference rate for lowering waste packages would be comparable to lowering bridge plugs (6,000 ft/hr or 1.7 ft/sec; Arnold et al. 2011). The rate of waste package emplacement will be controlled by the maximum waste package sink rate, which in turn depends on: 1) radial clearance (minimum 0.7 inches, SNL 2015a); 2) borehole fluid viscosity (temperature dependent); and 3) waste package buoyant weight. Assuming a sink rate of 1.7 ft/sec is feasible, and that the wireline would be respooled at twice this rate, the round-trip time for wireline emplacement would be approximately 6 hr.

3.3 Logistical Controls on Emplacement Schedule

As discussed in Section 2.3, it is optimistically assumed that one shipping cask/waste package can be managed per day at a DBD facility. This estimate is based on operational experience at the WCS site in Andrews, Texas. A paper describing the operation (Britten 2013) states that their initial handling rate was one package every four days, which was later improved to one package every three days (verbal communication). Three or more packages are active in the process, giving a throughput of one per day.

The proposed operations at a DBD facility will likely be faster because: 1) there is no need for intermediate waste transfers to other vessels prior to emplacement; and 2) waste packages will have no external contamination. However, DBD operations will be limited by the frequency of waste package deliveries to the disposal site, estimated to be one per day with three shipping casks and three tractor-trailer rigs. It is estimated above that approximately 32 hours will be required to lower one string of 40 packages to the emplacement interval, but it will take approximately 40 days to accumulate the 40 packages. In addition, placing a bridge plug and a cement plug will require additional equipment and two to three days per interval.

This rate of emplacement (averaging approximately one per day) has implications for logistics at a DBD facility. For the reference borehole, 400+ workdays will be required to emplace the 400 waste packages and 10 cement plugs. Additionally, there will be holidays and weather days (e.g., an additional 5%). A similar rate of emplacement will be achieved with wireline emplacement, particularly if operations are limited to daylight hours. Thus, 450 to 470 calendar days will be required to load 400 waste packages in a 16,400-ft emplacement borehole.

3.4 Self-Emplacement

With a guidance liner running from the surface to TD, and the borehole filled with an emplacement fluid with controlled properties, it could be possible to allow waste packages to sink freely into disposal position. Terminal velocity was estimated by Bates et al. (2011) to be on the order of 8 ft/sec for waste packages with diameter of 13.4 in, radial clearance of 0.93 in, and water as the emplacement fluid. Waste package weight in the analysis was the same as the maximum weight estimated here. A package moving at this speed could be stopped over a distance of 1 ft with average deceleration of 1 g and average force of approximately 20 kN. Expressed over an area of 0.06 m^2 (93 in^2), such a force would require a pressure of 0.33 MPa. Controlled pressures of this magnitude are readily obtained from crushable materials such as aluminum honeycomb. Note that if slotted casing is used in the disposal zone, the waste package terminal velocity could be significantly greater.

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