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Deep Borehole Disposal Concept: Development of Universal Canister Concept of Operations

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Sandia National Laboratories
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Abstract

This report documents key elements of the conceptual design for deep borehole disposal of radioactive waste to support the development of a universal canister concept of operations. A universal canister is a canister that is designed to be able to store, transport, and dispose of radioactive waste without the canister having to be reopened to treat or repackage the waste. This report focuses on the conceptual design for disposal of radioactive waste contained in a universal canister in a deep borehole.

The general deep borehole disposal concept consists of drilling a borehole into crystalline basement rock to a depth of about 5 km, emplacing WPs in the lower 2 km of the borehole, and sealing and plugging the upper 3 km. Research and development programs for deep borehole disposal have been ongoing for several years in the United States and the United Kingdom; these studies have shown that deep borehole disposal of radioactive waste could be safe, cost effective, and technically feasible

The design concepts described in this report are workable solutions based on expert judgment, and are intended to guide follow-on design activities. Both preclosure and postclosure safety were considered in the development of the reference design concept. The requirements and assumptions that form the basis for the deep borehole disposal concept include WP performance requirements, radiological protection requirements, surface handling and transport requirements, and emplacement requirements. The key features of the reference disposal concept include borehole drilling and construction concepts, WP designs, and waste handling and emplacement concepts. These features are supported by engineering analyses.

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Nomenclature

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BOP	Blowout Preventer
DBD	Deep Borehole Disposal
DBFT	Deep Borehole Field Test
DOE	Department of Energy
CFD	Computational Fluid Dynamics
DRZ	Disturbed Rock Zone
EZ	Emplacement Zone
FoS	Factor of Safety
ID	Inner Diameter
IDEQ	Idaho Department of Environmental Quality
LWT®	Legal-Weight Truck (transportation cask designation)
NAC	NAC International
OD	Outer Diameter
ORNL	Oak Ridge National Laboratory
R&D	Research and Development
RWCH®	Releasable Wireline Cable Head
SNL	Sandia National Laboratories
TBD	To Be Determined
UC	Universal Canister
US	United States
WP	Waste Package

1 INTRODUCTION

This report documents key elements of the conceptual design for Deep Borehole Disposal (DBD) of radioactive waste to support the development of a universal canister (UC) concept of operations. A UC is a canister that is designed to store, transport, and dispose of radioactive waste without the canister having to be reopened to treat or repackage the waste. This report focuses on the conceptual design for disposal of radioactive waste contained in a UC in a deep borehole.

The general DBD concept consists of drilling a borehole (or array of boreholes) into crystalline basement rock to a depth of about 5 km, emplacing waste packages (WPs) in the lower 2 km of the borehole, and sealing and plugging the upper 3 km (Figure 3-1). The emplacement zone (EZ) in a single borehole would contain up to about 400 WPs. A number of disposal options for radioactive waste were investigated in the 1980's in the United States (US), including DBD of commercial spent nuclear fuel. Research and development (R&D) programs for deep borehole disposal have been ongoing for several years in the US and the United Kingdom. These studies have shown that the DBD concept could be safe, cost effective, and technically feasible.

A valid conceptual design is one that is shown by limited analysis to be technically feasible and likely to meet requirements. The design concepts described in this report are workable solutions based on expert judgment, and are intended to guide follow-on design activities. The DBD conceptual design is supported by engineering analysis of several types: numerical stress analysis, finite element heat transfer modeling, thermal-hydrologic simulation, and fragility analysis for dropped package assemblies.

Waste Forms and Packaging Options

Small, medium, and large WP concepts were developed for maximum downhole hydrostatic pressure of 9,560 psi and maximum temperature of 170°C. The minimum required external pressure rating to meet a factor of safety (FoS) of 2.0 (against yield) is 21,250 psi. This specification is met for a set of configurations based on commercially available materials, as determined from: 1) numerical stress analysis of complete packages; and 2) vendor pressure ratings for threaded connections on top and bottom. Threaded connections would serve as backups for internal seals on the fill plugs used to load WPs. Selection of materials for WPs to be used for disposal will also need to consider containment lifetime in the expected downhole environment (e.g., hot brine).

Package Transfer and Wellhead Equipment

This report presents a concept for surface equipment to safely receive packages, transfer them to a double-ended cask, position the cask over a disposal borehole, and lower the packages into position at depth. The concept was developed assuming availability of the NAC International (NAC) legal-weight truck (LWT®) Type B transportation cask (or equivalent). The purpose-built transfer cask must be double-ended (operable openings at both ends) to lower packages into the borehole. The system is required to serve as part of the pressure envelope for well control, i.e., to contain a pressure "kick" during operations as a safety measure. The recommended concept meets the engineering challenge of removing or opening a radiation shield at the bottom of the transfer cask and attaching the cask to the wellhead, without using components that could compromise the pressure envelope capability.

The transfer cask would have removable shield plugs on both ends, and would receive a WP from the transportation cask in a horizontal position (which is safest). A side latch mechanism (internal to the transfer cask) would hold the WP in place until ready for lowering into the borehole. The wellhead configuration would include a rotating shield plate, and equipment operated remotely beneath it, to remove the lower shield plug and attach the transfer cask to a wellhead flange. Once fixed to the wellhead flange, the transfer cask and associated hardware would become part of the pressure envelope for well control, so that pressure transients encountered during emplacement operations would not necessarily require actuation of a blowout preventer (BOP).

Emplacement Method Options

Several methods for emplacing waste packages at the bottom of a 5-km borehole were considered: free-drop, electric wireline, coiled tubing, drill-string, and conveyance casing (on a drill string). The free drop method was judged to be impractical because of inherent risks, but the behavior of WPs that are accidentally dropped in a disposal borehole was extensively analyzed. Wireline emplacement was selected as the preferred option based on consideration of safety and costs that would be associated with DBD using the wireline method. Wireline emplacement is made more attractive by the availability of modern wireline cable and equipment, and the use of impact limiters.

Supporting Engineering Analyses

Engineering analyses were conducted to support the reference design for DBD. First, stress analyses were performed for four WP options. Second a detailed thermal analysis including internal package temperatures was conducted to investigate the temperature response of packages containing heat-generating waste. Third, coupled heat and fluid flow from a DBD containing Cs/Sr capsules was modeled. Fourth, the behavior of impact limiters that would be attached to the bottom of each waste package was evaluated.

2 BASIS FOR THE DBD AND DEEP BOREHOLE FIELD TEST DESIGN

This section summarizes the DBD safety case and expected preclosure and postclosure conditions. It also presents technical information, design requirements and design assumptions for the reference DBD concept. Requirements of particular relevance to the UC concept of operations include the packaging, requirements, package surface handling/transfer requirements and package emplacement and retrieval requirements.

2.1 Summary of Deep Borehole Disposal Safety Case

Preclosure and postclosure safety were considered in the development of the reference design concept (Arnold et al. 2011). Preclosure risks are associated with worker safety, accidents involving WPs, and the potential for operational failures (e.g., packages stuck in the borehole above the EZ). Postclosure risks are associated with potential releases of radionuclides and transport to the biosphere, generally in the far future. The most likely postclosure risks are thought to be related to thermally driven fluid flow and the effectiveness of seals above the EZ (Brady et al. 2009).

English units are used intentionally because of their prevalence in the oil and gas industry, without offering metric equivalents in order to avoid possible confusion. Metric units are used primarily in discussing the key transition depths in disposal boreholes, for convenience in describing force, torque, temperature, power and other quantities, and for discussing results published elsewhere.

2.1.1 Preclosure Safety

A deep borehole field test (DBFT) will support the development of the DBD preclosure safety case by means of engineering analyses and testing of important components of the disposal system including test packages, handling and emplacement equipment, and impact limiters. The scope of testing and demonstration includes surface handling equipment and procedures, emplacement equipment and procedures, borehole construction, and package integrity during emplacement operations prior to borehole sealing. Preclosure radiological risks for an actual disposal operation during normal operations, would be limited to radiation exposure of workers. Preclosure radiological risks for off-normal conditions would include worker exposure and radioactive contamination caused by package breach following an accident such as dropping a package, or by damage incurred during package recovery after one or more packages becomes stuck above the EZ. External events such as flooding, extreme weather, seismicity, and sabotage may also be factors in preclosure radiological safety, but are not planned to be addressed by the DBFT.

2.1.2 Postclosure Safety

Several factors suggest that the DBD concept is a viable approach for very long-term isolation of radioactive wastes from the accessible environment (i.e., the biosphere and potential sources of groundwater). Crystalline basement rocks are relatively common at depths of 2 to 5 km in stable continental regions, suggesting that numerous geologically appropriate sites may exist. The bulk permeability of deep crystalline rocks is generally low and decreases with depth, as shown by studies of permeability as a function of depth in the upper crust (Manning and Ingebritson 1999).

DBD safety would rely on emplacing wastes in competent crystalline rock well below the extent of naturally circulating groundwater. Movement in groundwater is practically the only significant pathway for migration of radionuclides from a deep borehole to the biosphere. If the groundwater has not moved for millions of years, then transport is limited to the mechanism of aqueous diffusion, a slow process. Diffusion-limited transport is the principle of isolation for mined repositories proposed at depths of 500 m in clay or shale, and salt. However, in DBD, waste would be situated at 3 to 5 km depth in low-permeability granite or schist, so the radionuclide migration path distance would be an order of magnitude greater than for mined repositories (e.g., 1,000 m in the crystalline basement vs. 150 m natural barrier unit thickness for a mined repository in clay or shale). Hence, DBD offers the potential for exceptional waste isolation because, according to the mathematical model for diffusion, the time for diffusive release to the biosphere is proportional to the square of distance (Bird et al. 2002).

The key to proving the potential effectiveness of DBD is to carefully analyze the environment at depth, to determine the origin and residence time of deep groundwater, and to understand why it has remained isolated. Natural cosmogenic tracers with long half-lives such as Ar-isotopes and Kr-81 could be helpful because they can be used to estimate or bound the average time since a groundwater sample was at the earth's surface. Other tracers originate in the solid earth: accumulation of radiogenic He, and U-series equilibria, are indicators of long groundwater residence time. Recent studies have shown groundwater deeper than 2 km in the Precambrian basement to have been isolated from the atmosphere for greater than one billion years (e.g., Holland et al. 2013; Gascoyne 2004).

Another aspect of deep groundwater isolation pertains to the chemical composition of such waters, which are typically concentrated chloride brines with densities that range from 2.5% greater than pure water (seawater) to more than 30% greater than pure water (Park et al. 2009; Phillips et al. 1981). High salinity at depth indicates old groundwater and precludes the use of deep groundwater as a future drinking water source. Types of brine in the basement range from sodium chloride to calcium and magnesium chloride brines at higher density. Low permeability and high salinity in the deep crystalline basement at many continental locations suggest very limited interaction with shallower sources of useable groundwater (Park et al. 2009) which is the most likely pathway for human exposure.

Density stratification of brine would tend to limit the effects from future perturbations to hydrologic conditions such as climate change, or from early borehole heating by the waste. The density gradient (fresh near the surface, concentrated at depth) is stabilizing and inhibits vertical flow or mixing. The inhibitive effect is well known where seawater invades near-surface groundwater aquifers. Ancient brines have been found in crystalline basement rock over a large area of the northern plains of North America, an area subjected to glaciation during the Pleistocene epoch (e.g., as reported by Gascoyne 2004). The simple existence of concentrated chloride brines in the crystalline basement is a general indicator of great age, especially when no evaporites are present in the geologic setting. Absence of overpressured conditions at depth (so that *in situ* pressure cannot drive flow at the surface) is also expected at favorable locations for DBD. In addition, geochemically reducing conditions in the deep subsurface limit the solubility and enhance sorption of many radionuclides, leading to limited mobility in groundwater.

2.2 Preclosure and Postclosure Conditions for Deep Borehole Disposal

An overview of preclosure and postclosure conditions associated with DBD that could guide the selection of design solutions is presented below. The discussion at this stage is high-level, and a license application for DBD would have much more detail, including site-specific information.

2.2.1 Preclosure Conditions

Deep borehole disposal of limited-volume waste forms could involve a single borehole (e.g., for 1,936 Cs/Sr capsules), or an array of boreholes (e.g., for 4,400 m^3 of granular calcine waste). The location would likely be remote to accommodate geologic factors in siting, and to provide physical separation between disposal operations and members of the public. It is assumed for this conceptual design report that the site would be served by improved, graveled roads but not paved roads because extensive heavy truck traffic would make construction and maintenance prohibitive for short term service.

The prevalence of crystalline basement geology in potentially suitable locations means that DBD could conceivably be sited in various regions of the conterminous US. Thus, any reasonable conditions of temperature, precipitation, wind, aridity, vegetation, and wildlife could be encountered. Extreme weather such as tornados, blizzards, flooding, electrical storms, and hurricanes would be accommodated in the same manner as with conventional oilfield operations (i.e., with emphasis on event prediction, damage prevention, and suspension of activities as needed).

The site of each borehole would be secured by fencing and other measures. Until a disposal borehole is sealed and plugged, the activity area including parking and staging, would be manned and guarded on a 24-hour basis, consistent with the safeguard and security requirements associated with the proposed waste type.

Siting of DBD would include consideration of hydrologic and geochemical conditions that favor waste isolation, which includes lack of evidence for upwelling water. Thus, an upward hydraulic gradient is not expected, and fluid levels are expected to remain stable (below ground level) during emplacement operations. However, upward flow in a disposal borehole might occur, for example if a disposal borehole is inadvertently filled with fresher and less dense water than present in the host formation, so that brine inflow displaces the borehole fluid. Accordingly, the wellhead and transfer cask would be designed to maintain control of wellbore pressure during emplacement (Section 3.3).

The DBD facility would be designed to provide adequate radiation protection to workers and the public, and to provide the means for meeting package integrity requirements during all stages of waste handling. Should the regulating agency require monitoring of downhole conditions, the DBD facility would provide such monitoring, consistent with agency requirements. The proper placement of any downhole materials that are important to performance of the disposal system will be verified to the extent possible.

Off-normal events could occur during waste handling and emplacement, for example:

- Accidental dropping of a package during handling at the ground surface
- Accidental dropping of a package while lowering or raising it in the borehole

- Accidental dropping of foreign objects ("junk") into the borehole
- A package getting stuck in the borehole
- Breach of a package in the borehole prior to closure, and radioactive contamination of the emplacement fluid
- Boiling of emplacement fluid (for heat-generating packages stuck or otherwise residing above a depth of approximately 2.2 km)

Natural events such as seismic ground motion or faulting, extreme weather, or flooding have low likelihood or minimal consequences if standard construction and operational practices are followed. Other off-normal events such as a sabotage and theft are possible. These conditions and off-normal events would be addressed as part of the siting, design, and licensing of a DBD site.

2.2.2 Postclosure Conditions

The postclosure period for DBD would begin after packages are emplaced in a borehole and sealing and plugging of the borehole are complete (the regulatory definition of closure could also factor in completion of a confirmation program).

Pressure in the disposal zone will initially be determined by the weight of emplacement fluid in the borehole, but will equalize with the formation fluid. Some equalization must occur if the emplacement fluid has uniform composition, while the formation fluid density varies with depth. Formation fluid will likely contain NaCl and may also include Ca2+ ion dissolved from feldspars in the host rock. Chemical weathering of the host rock will have been ongoing for millions of years, and the impact on formation brine chemistry will be very slow. At the time of waste emplacement, the borehole fluid ("emplacement fluid") could be a brine that is similar to, or even denser than what is present in the formation, to facilitate recovery of the natural fluid density gradient. In addition, residues from drilling fluid, and organic admixtures (plasticizers, retarders) in cement could result in residues, including organic material, in the disposal environment.

For heat generating waste, temperature in the disposal zone would increase for a period of time that depends on the heat-generating radionuclides present. Example simulations (Section 4.3) show that for 137Cs (half-life = 30.17 years) and 90Sr (half-life = 29.1 years), which are the primary heat-generating fission products in spent nuclear fuel or high-level waste, temperature increases rapidly for a few months after emplacement, then approaches a peak in approximately 1 to 5 years. Boiling of fluid in the EZ is precluded by the pressures at depth. With exponential decay, cooldown to ambient in situ temperature will take roughly 10 times the longest half-life among significant heat-generating radionuclides (e.g., approximately 300 years for 137Cs and 90Sr). In general, temperature history will be predicted based on waste characteristics, thermal loading, and rock and fluid properties, and the disposal approach will be adjusted so that temperature limits are met. Initial calculations of this type are described for disposal of Cs/Sr capsules in Sections 4.2 and 4.3.

The radioactive waste will emit some combination of alpha, beta, gamma, and neutron radiation, depending on its composition. Irradiation of water and other molecules can cause changes in chemical reactivity (e.g., redox potential, pH, radiolysis, and concentrations of reactive radicals), and possibly gas generation, that have the potential to affect the performance of the DBD system.

In addition to radiolysis, if the waste includes fissile radionuclides, the potential for nuclear criticality would also be assessed. Thermally driven convection is possible, and includes effects from fluid thermal expansion as well as buoyant convection. Fluid in the disposal zone would expand by approximately 5% to 16%, depending on brine composition. Some disposal concepts involve fluid-filled voids around packages or in the rock annulus. These volumes of fluid may convect, particularly where the vertical temperature gradient is greatest at the top and bottom of the EZ, near unheated parts of the borehole. Simulations show that cement plugs would tend to slow upward convection in the borehole, while the low permeability in the seal zone and the host rock around the borehole would attenuate buoyant convection. As heat generation decays, the potential for thermally driven convection would decrease also. When the system cools, fluid will be drawn back from the host rock and the seal zone, into the disposal zone.

In the vicinity of heat-generating waste, the guidance casing and the stack of packages would also expand. Potential expansion is approximately 0.08% to 0.14% depending on depth. Thermal expansion of the casing that occurs after the casing is cemented will produce axial thermal stress, and possibly some buckling where the casing is not constrained by cement. The stack of packages could adjust to thermal loads by further compressing the impact limiters attached to every package.

Thermal expansion of aqueous fluids varies more significantly with temperature. For NaCl brine of 1 molal and 4 molal concentration (Phillips et al. 1981) the maximum volumetric expansion at the top of the EZ would be approximately 16% and 10%, respectively (using temperature rise values discussed in Section 2.4.6). At the bottom of the EZ the maximum expansion would be approximately 8% and 5% at the same respective concentrations. Thermal expansion could thus vary from approximately 5% to 16%, depending on composition and initial temperature. Like casing expansion, these are bounds because some heating and expansion of the fluid will occur before cement plugs are set. One reason for casing perforations is to allow this expanded volume to dissipate in the host formation rather than building pressure against plugs and seals.

The existence of downward salinity gradients and concentrated brine in the deep crystalline basement has been extensively studied (for example, Lemieux and Sudicky 2010, Person et al. 2007, and Grasby et al. 2000). The density and viscosity of concentrated brines, along with low bulk permeability of the basement rock at depth, inhibit hydrologic circulation and flow in response to surface changes like continental glaciation. What this means for postclosure conditions in DBD is that the hydrologic and geochemical boundary conditions on the EZ will be stable (or at least slowly varying) over many thousands of years.

Concentrated chloride brines at elevated temperature are highly corrosive to steels and many other engineered materials that could be used for waste packaging. Package corrosion would eventually lead to exposure and dissolution of waste forms. The time scale of corrosion leading to degraded containment is uncertain, and could be from a few months to thousands of years depending on the material, fabrication methods, and specific characteristics of the environment.

Corrosion of iron and certain other metals in casing and packaging materials would cause reduction of aqueous hydrogen ions, producing hydrogen gas. If hydrogen gas were contained to a sufficient degree by the host rock, and plugs and seals, the gas pressure could increase significantly. At a pressure approximately equal to the minimum principal formation stress, the formation would fracture or pre-existing fractures would dilate, relieving the pressure. The concern with hydrogen gas generation that has been addressed by nuclear waste disposal R&D

programs internationally is that such behavior could occur within engineered barriers such as plugs or seals, at pressures less than the minimum principal stress. However, sustained corrosion would require transport of water from the host rock because the borehole initially contains enough water to corrode only a small fraction of the steel present. If there is sufficient permeability to pull water in, then hydrogen can disperse outward through the same permeability in dissolved or gaseous form. In summary, understanding of the gas generation process and the potential effects will be built on site-specific characterization, and can be addressed in selection of materials for casing and packages, and selection of an EZ completion option (Section 3.1.5).

Microbial activity in disposal boreholes is possible, because there are organisms that can survive and grow at high temperature in concentrated brines. However, the combination of thermophilic and halophilic behavior is rare. Further, the available metabolic pathways are limited. For example, there would be scarcity of electron acceptors such as sulfate and organic compounds in cement; when these are expended growth will stop. Ultimately, the safety case for DBD does not depend on long-term containment in packages, or on radionuclide sorption, so microbial processes may not be important.

There are several options for completing the EZ. Each of the options may affect the preclosure and postclosure conditions mentioned above (e.g., pressure, fluid flow, heat flow). For example, the use of cement to encapsulate packages could affect chemical conditions in the near-field. Cementing all void space in the borehole could couple the expansion of corrosion products, and any changes in formation stress, with the state of stress in the packages. Perforations in the guidance casing would be used for cementing during construction, and to relieve thermal expansion of emplacement fluid, but could also lead to a higher terminal velocity for a package that is accidentally dropped in the borehole. Selection of the EZ completion method for DBD will consider these preclosure and postclosure conditions.

Ultimately, over very long time periods the metals and cements used in DBD borehole construction would degrade, along with the waste itself, forming products that consolidate in the borehole. Molar volumes for metal corrosion products would increase, filling voids in the borehole. Corrosion products would generally be less dense than the primary materials, and some would be granular and non-cohesive. As corrosion of engineered materials and waste forms proceeds, consolidation could eventually result. The time frame for such degradation is highly uncertain, but could be extended by material selections made in design. Ultimately, consolidation in disposal boreholes would likely have no significant impact on waste isolation performance because the crystalline basement host rock and hydrogeologic setting is an effective barrier.

Radionuclides in the waste would eventually be available for transport away from the borehole via convection and/or diffusion. The rate of transport for any radionuclide would depend primarily on solubility and sorption, and whether transport is dominated by molecular diffusion (not advection).

For the long time scales over which the performance of a DBD system would be assessed, other possible postclosure events would be considered such as tectonics, seismicity, volcanism, erosion, hydrothermal activity, climate change, and other hydrologic changes. Events such as erosion could have no significant effect because of the depth at which the waste is emplaced. Other events such as tectonics and volcanism would be addressed in selecting a DBD site. All types of events which have been addressed by nuclear waste repository R&D programs would be considered for a DBD license application.

2.3 DBD Functional and Operational Requirements

Requirements for DBD that represent the engineering challenges associated with future waste packaging, handling, transport, transfer, emplacement, and possible retrieval for DBD are presented. Some requirements apply to the characterization borehole and/or the field test borehole that are planned to be drilled as part of the DBFT. In these cases, the results obtained from the DBFT will help guide the development of requirements for DBD.

2.3.1 Waste Packaging Requirements

For DBD, WP containment is required through all phases of disposal operations, until the borehole is sealed. Additional containment longevity may be required depending on the disposal environment, radionuclide half-life, and other properties of the waste. The DBFT will demonstrate that packages can be designed, fabricated, loaded, sealed, emplaced and retrieved without loss or leakage.

To achieve containment of the waste for the specified period of time, the WPs must maintain mechanical integrity; that is, it must provide sufficient resistance to external hydrostatic loading, combined with axial tensile and compressive loads, and bending loads if present. Waste packages may be loaded in tension during emplacement, retrieval, or during fishing operations to recover packages (if they become stuck). Packages may be loaded in compression when package strings or stacks are set on the bottom or on a plug. Specific mechanical loads for WP design are to be determined (TBD).

Hydrostatic loading combined with axial and bending loads constitute the maximum loading condition. The maximum design hydrostatic pressure for test packages is based on an assumed maximum depth-averaged fluid density in a 5-km column. The minimum hydrostatic pressure at the bottom of the borehole is based on the density of pure water (ignoring temperature effects on density). The maximum pressure for actual WPs is TBD because it depends on the properties of the emplacement fluid selected for disposal, and whether that fluid is uniformly distributed in the borehole (or layered with another fluid).

A minimum FoS of 2.0 with respect to yield strength for numerical analysis of deformation in response to combined loading at assumed bottom-hole temperatures (Section 2.4.2) is used for test packages. Previous analysis indicates that the maximum compressive stress, and the onset of yielding, would occur at the inner surface of the tubular portion of the WP (SNL 2015). The FoS should be reasonably conservative, and comparable to other critical applications in pressurized systems (e.g., pipelines, 49 CFR 192). Factors of safety for typical oilfield casing applications are approximately 1.2 (see Arnold et al. 2011), and this has been built into casing tables so that collapse and burst pressures can be used directly. Also, American Petroleum Institute (API) “5CT” collapse ratings take into account -12.5% variation of wall thickness (Arnold et al. 2011).

The FoS should be reevaluated for new applications, which warrants a conservative approach for DBD. The FoS should be related to the consequences of failure. For example, the consequences of accidental breach during operations include radiological contamination of the borehole, surface equipment, and the basement rock unit. For actual WPs, the design FoS will depend on results obtained in the DBFT.

Reference package sizes (Arnold et al. 2014) were determined using common casing sizes (for guidance casing and tubing that could be used for packages). Three sizes for test packages are being considered for the DBD: small, intermediate, and the large or reference size (Table 2-1).

The guidance casing sizes shown are consistent with API casing sizes, and there are size options available that could increase or decrease the radial gap, for a given size package.

Table 2-1. Casing, nominal package diameter, and radial gap for small, medium and large (reference size) packages

	Small	Medium	Large
	Cs/Sr Capsules (slim)	**Cs/Sr Capsules (3-packs)**	**SNL Reference (e.g., granular waste)**
Borehole Diameter (m) **(nominal) (in)**	0.216 8.5”	0.311 12-1/4”	0.432 17”
Guidance Casing OD (m) **(nominal) (in)**	0.178 7”	0.273 10-3/4”	0.340 13-3/8”
Guidance Casing ID (m) **(nominal) (in)**	0.162 6.366”	0.245 10.050”	0.321 12-615”
Package OD (m) **(nominal) (in)**	0.127 5”	0.219 8-5/8”	0.279 11”
Radial Gap (m) **(nominal) (in)**	0.017 11/16”	0.017 11/16”	0.021 13/16”
Capsules per Layer	1	3	(not evaluated)

Notes:

1. English measurements are ±1/16”.
2. Casing and package dimensions are nominal (do not account for drift or ovality, or package protrusions as allowed by design requirements).
3. Number of capsule layers in a single package is limited by the overall package length.
4. DBFT boreholes can support small or large size packages.
5. Data source: API Casing Table Specification (www.oilproduction.net).

The diameter of WPs depends on the diameter of guidance casing, and the specified radial clearance. Radial clearance between the packages and the casing inner diameter (ID) controls the potential for packages to become stuck and affects the terminal velocity if packages were to fall unsupported down the borehole, which is also related to the speed at which packages can be lowered or raised.

Several different radial clearance configurations have been proposed in the past. Hoag (2006) proposed radial clearance of 0.9 inches for packages with 13-3/8 inch diameter. Arnold et al. (2011) proposed minimum radial clearance of approximately 0.25 inches which was controlled by off-the-shelf buttress-type connectors with outer diameter (OD) of 12.1 inches. For this analysis, the radial clearance for reference-size large test packages is set to 13/16 inches, giving a nominal package diameter of 11 inches, within 13-3/8 inch casing. Applying an 11/16 inch radial clearance to small packages the nominal package diameter is approximately 5 inches for the ID of 7-inch casing (Table 2-1). Radial clearance for WPs used in DBD will be determined using experience from the DBFT. Other package dimensions such as overpack IDs are discussed in Section 3.2.

Note that radial clearances for different size packages are given as nominal values in Table 2-1. Deviation from these values could result in slower or faster terminal sinking velocity during emplacement. Slower sinking velocity could impede emplacement operations by wireline, for which emplacement speeds are limited to terminal sinking velocity. Faster sinking velocity could increase the potential for damage if a package is dropped in the borehole. The radial gap also has a moderate effect on pressure surge pressure during package lowering and raising.

Waste packages should have smooth external surfaces, with API standard threaded connections at the ends. The smooth exterior is intended to prevent hang-up on casing joints, shoes, collars, etc. Small protrusions on the package surface may be permissible if they do not interfere with emplacement or terminal velocity of free-falling packages, or cause other requirements to be violated.

For wireline emplacement, DBFT test packages will have threaded connections to be used for a releasable latch /fishing neck on top, and an impact limiter on the bottom. The connection on the bottom could also be used for other hardware such as instrumentation, centralizers, alternative impact limiters, etc. Waste package fittings for DBD are not yet determined.

Package connections will have sufficient strength to withstand mechanical loads during emplacement, retrieval, and fishing of stuck packages. Thrust and rotation conditions required to engage or disengage connections downhole must be consistent with the capabilities of the delivery system (wireline) and fishing method (a drill rig using fishing tools on drill pipe, if necessary).

The reference size WP overall length will be up to approximately 5.6 m, with internal cavity length of up to 5 m to accommodate various waste forms. Limiting package length limits the weights of both the transportation cask and transfer cask, which permits LWT® transport of these components. On the other hand, longer packages make more efficient use of borehole volume by limiting the proportion of total borehole volume that is used for package end fittings, couplers, impact limiters, etc.

Waste packages will have negative buoyancy in emplacement fluid of the maximum density so that they do not float after they are emplaced, and so they can be more readily emplaced (e.g., on a wireline, which requires that packages sink). Assumptions regarding WP weight and buoyancy are discussed in Section 2.4.3.

2.3.2 Radiological Protection Requirements

Actual disposal operations will be conducted in a manner to ensure that radiological exposures comply with appropriate regulations (e.g., 10 CFR 20), including the requirement that worker doses are as-low-as-reasonably-achievable. The particulars of such a program are beyond the scope of the DBFT and deep borehole disposal, and are TBD.

2.3.3 Package Surface Handling/Transfer Requirements

Shielding is required for future DBD operations, but the level and design of the shielding depends on the waste form. Shielding will be designed to meet requirements specified in appropriate US Department of Energy Orders and regulations (e.g., DOE Order 458.1 and 10 CFR 835).

Oil-and-gas wells typically have BOPs at the surface, and overpressured fluids (gas and liquid) possible at depth. The pressure is managed using a drilling fluid with sufficient weight that the wellbore can stand open at the surface for drilling, logging, completion, etc. If a pressure transient ("kick") occurs during drilling or development activities, the well can be rapidly shut in using the BOPs. When the well is completed for production, it is temporarily plugged and the

BOPs are replaced with wellhead valves and piping. The well is under control at all times, with the capability to contain pressure transients.

For DBD and DBFT boreholes, which are drilled into crystalline basement rock and sealed off from the overburden by cemented casing, pressure transients are unlikely. However, as a safety requirement (e.g., imposed by a permitting authority) DBD and DBFT boreholes may be required to handle pressure transients. One example could result from decrease of borehole fluid density for any reason, causing downhole pressure to become under-balanced. Handling and transfer equipment must be capable of operating under these conditions. This means that the transfer cask must withstand internal pressurization, including the connection to the wellhead flange, and the upper closure on the cask where the wireline enters. In other words, the transfer cask and its attachment to the well, and provisions for accessing and lower packages, must be capable of being made part of the well control pressure envelope. For example, the transfer cask should be designed with interchangeable attachments to the top of the cask, that can provide well control at different pressure levels. Specific well control requirements for the transfer cask and associated surface equipment for DBD and for the DBFT are TBD.

For the DBFT, test packages will be transport by LWT®s. For DBD, the means of transport of WPs has not yet been determined.

2.3.4 Package Emplacement and Retrieval Requirements

The foremost requirements are that packages will not be dropped or become stuck during emplacement or retrieval. A corollary is that packages will be emplaced at the intended depths.

For DBD boreholes, retrieval could involve removal of all cement, plugs, and other obstructions, as necessary to access the EZ. Package retrieval could be performed using a different method than used for emplacement (e.g., emplaced by wireline, retrieved using a drill string). Regulatory requirements for retrievability of waste from DBD are TBD.

One of the technical criteria for site suitability for waste disposal is no significant upward flow of groundwater from the EZ due to natural hydraulic gradients. This could mean that there is no significant upward gradient from the EZ to the ground surface. In that case BOPs would not be needed, unless required by permit or regulation. Nevertheless, requirements for BOPs for the DBFT and on waste disposal boreholes will depend on site-specific conditions and history of nearby drilling activities. During emplacement operations WPs will be connected to the emplacement equipment (wireline), and transferred from a transfer cask into the borehole. Redundant mechanisms will secure the package in the transfer cask until it is ready for emplacement, and block the wellbore during preparations for emplacement. Redundancy will be designed so that, to the extent practical, single-point electrical, hydraulic or mechanical failures, or instances of human error, do not directly cause a package to be dropped in the borehole.

The composition and properties of the fluid in the borehole affect many aspects of borehole operation and package emplacement: terminal sinking velocity, the need for a BOP, WP buoyancy, borehole completion options, hydrostatic pressure, etc. The minimum density of any fluid in the borehole at any location when WPs are being emplaced shall be that of water, and the maximum density is TBD. The exact composition of the fluid has not yet been determined for either the DBFT or DBD.

When emplacing a WP the wireline tension must not exceed the service limit of the cable and the equipment that is being used to emplace the waste. Wireline tension is the sum of maximum buoyant weights for the cable (fully deployed to the bottom of the hole), WP, and wireline tool string. An appropriate FoS must also be included. For the DBD, the weight limit is not known. For the DBFT the wireline tension shall not exceed 12,000 lb, which is the published limit using Tuffline® cable without a capstan for spooling and unspooling (SLB 2016). A maximum package weight has been assumed (Section 2.4), and wireline cable properties are known, so this requirement limits the maximum buoyant weight of the wireline tool section.

2.4 Design Assumptions for Disposal System

The following discussion supports the assumptions for the DBD system that are relevant to the UC concept of operations.

2.4.1 Borehole Depth

For the DBFT, boreholes are assumed to be5 km deep to facilitate design of test packages and emplacement/retrieval equipment. The actual depth of the characterization borehole and field test borehole may be slightly different depending on the geologic setting. For waste disposal, borehole depth would depend on site characteristics, drilling capability, and the engineering design of the disposal system.

2.4.2 Bottom-Hole Temperature for the DBFT and Disposal of Heat-Generating Waste

Maximum ambient bottom-hole temperature is assumed to be 170°C, based on mean annual surface temperature of 20°C, a typical continental geothermal gradient of 30°C/km, and depth of 5 km. For heated packages a maximum WP wall temperature of 250°C is assumed, which is needed to limit thermal degradation of WP material yield strength (Section 4). For thermal expansion calculations it is assumed that the ambient bottom-hole temperature is 170°C and the ambient temperature at the top of the EZ is 110°C. Thus, the maximum temperature rise is 80°C at the bottom of the hole and 140°C at the top of the EZ.

2.4.3 Maximum Package Weight

An assumption on maximum package weight is provided for handling system, emplacement system, and canister design. Beginning with the reference design (Arnold et al. 2011) the loaded large package will have a total dry weight of approximately 4,620 lb based on the following dimensions for a steel WP: nominal OD 11 inches, wall thickness 1.2 inches, length 18.5 ft, and solid endcaps 6 and 12 inches thick. For bounding the weight, the waste contents are assumed to be 367 pressurized water reactor rods (at 2.39 kg/rod).

Displaced volume for this geometry is ~12.2 ft^3. The buoyancy would be 990 lb in emplacement fluid with density of 1.3× pure water (and 760 lb in pure water at ambient temperature and pressure). The net buoyant weight of a loaded package in emplacement fluid would therefore be approximately 3,630 lb (3,860 lb in pure water).

Using higher strength tubing for the package body would reduce the wall thickness, thereby reducing weight (see options in Section 3.2). Also, the DOE-owned, granular high-level waste forms are much less dense than reactor spent fuel. Thus, the assumed maximum dry weight of 4,620 lb is a reasonable bound that allows for connectors and adapters attached to the ends, impact-absorbing attachments, etc., with less dense waste forms. Note that consolidated rods are mentioned here only as the basis for a reasonably bounding calculation on package weight, and that the DBFT is not intended to investigate spent fuel disposal in boreholes, nor to promote rod consolidation as part of a disposal a solution.

For the small packages (Table 2-1) the dry weight and buoyant weight of each package is 880 lb and 690 lb, respectively, assuming that each package contains eight Cs/Sr capsules, each capsule weighs up to 44 lb including a thin-wall canister or basket (the weight of each capsule is approximately 10 kg or less; Randklev 1994), and the emplacement fluid density is 1.3× the density of water.

2.4.4 Package Stacks

Package stacks are assumed to be limited to 40 or fewer, consistent with the reference design (Arnold et al. 2011). This assumption impacts package loading and design for mechanical and containment integrity during the operational period. For waste disposal this assumption determines how many packages will be supported by separate plugs in the EZ. Emplaced packages will load the lowermost package in a stack or string. While a simple calculation indicates a small contribution to combined loading of packages, a conservative approach limiting stacks to 40 is appropriate because of uncertainty as to uniformity of loading, and dynamic loading during emplacement.

2.4.5 Year in Which DBD Could Begin

For thermal analyses (Sections 4.2 and 4.3) an emplacement date of 2050 is assumed for disposal of Cs/Sr capsules. This date was selected to maintain peak WP temperature below the maximum temperature assumed above; there is no regulatory or legal basis, and the date of emplacement of waste in a DBD is not yet determined.

2.4.6 Formation Conditions

Temperature and *in situ* stress conditions in the host rock at the top and bottom of the EZ are used to evaluate thermal expansion of casing and the potential for cement injection pressure to exceed formation breakdown pressure. For lithostatic pressure the density of a 2-km overburden layer is assumed to be 2.30 g/cc, and that of the underlying crystalline basement 2.65 g/cc. These densities correspond to vertical stress gradients of approximately 1.0 and 1.1 psi per foot of depth, respectively. Using them the vertical stress at 3 km (top of EZ) and 5 km (bottom) are calculated (Table 2-2).

Table 2-2. Summary of conditions assumed for evaluating EZ completion options

Summary of Initial Generic Conditions in EZ (detailed in text)	(top of EZ) 3 km	(bottom of EZ) 5 km
***In situ* Temperature (reasonable bound)**	110°C	170°C
Temperature Rise (for thermal expansion calculations)	140°C	80°C
Vertical Lithostatic Stress	10,330 psi	17,900 psi
Hydrostatic Pressure in Formation	4,690 psi	8,385 psi
Hydrostatic Pressure in Borehole (using 1.3× density of pure water)	5,540 psi	9,650 psi
WP Design Hydrostatic Load (not including factor of safety)	9,650 psi	9,650 psi
Fracture Breakdown Pressure (at 0.7 psi/ft)	6,900 psi	11,500 psi
Lightweight cement (0.70 psi/ft for full column height)	6,900 psi	11,500 psi

For formation fluid pressure, a simple scheme is used with brine (1.3 g/cc) in the 3 km of crystalline rock and fresh water (1.0 g/cc) in the 2 km of overburden. For borehole fluid pressure, the average borehole fluid density is assumed to be 1.3× that of pure water.

The *in situ* fracture gradient is important because injection of cement and thermal expansion of fluids in the EZ could conceivably generate pressures sufficient to fracture the host rock. For vertical stress of 17,900 psi, formation pressure of 8,385 psi (Table 2-2) and Poisson's ratio of 0.25, Eaton's equation (www.glossary.oilfield.slb.com/en/Terms/f/fracture_gradient.aspx) gives a fracture gradient of 0.7 psi/ft. This equation does not account for variations in host rock tensile strength, borehole geometry, or effective stress that could impact actual fracture pressure. The importance here is not the exact magnitude, but the observation that fracture could occur with borehole fluid pressure that is only moderately greater than planned for emplacement fluid in the borehole, and well below the vertical lithostatic stress.

2.5 Waste Types

Two waste types are possible candidates for DBD: cesium and strontium capsules and calcine waste. There is no current plan to dispose of these wastes using deep boreholes; they are mentioned here because they have been considered to be good candidates for disposal in a deep borehole (DOE, 2014). These wastes are described briefly below.

There are a total of 1,936 cesium and strontium capsules; most of them are doubly encapsulated (i.e., a capsule within a capsule). The 1,335 cesium capsules contain cesium chloride (CsCl) and the 601 strontium capsules contain strontium fluoride (SrF_2). The capsules are constructed of either 316L stainless steel or Hastelloy C-276, are between 19.05 and 21.825 inches long, and are between 2.625 and 3.25 inches in diameter. As of January 1, 2016, the average cesium capsule generated about 120 watts of power, while the average strontium capsule generated about 160 watts of power. The unshielded surface dose rate from a cesium capsule is over 600,000 rem/hr, while the unshielded surface dose rate from a strontium capsule is almost 30,000 rem/hour (Price et al. 2015), also as of January 1, 2016. The radionuclides of concern are ^{137}Cs (half-life = 30.17 years), ^{135}Cs (half-life = 2,300,000 years), and ^{90}Sr (half-life = 29.1 years).

The capsules are currently stored in a pool at the Waste Encapsulation and Storage Facility at the Hanford Site, although the process to move the capsules into dry storage has been initiated. The design of the dry storage facility is not yet known. The capsules are considered to be mixed waste by the State of Washington (Washington Department of Ecology, 2008).

The calcine waste is stored in multiple storage bins that are housed within six concrete vaults at the Idaho Nuclear Technology and Engineering Center. The calcine waste is a granular solid with an average bulk density of 1.4 g/cc; the total volume of calcine waste is about 4,400 m^3. While most of the radioactivity derives from ^{90}Sr and ^{137}Cs, most of the radionuclide mass derives from various isotopes of uranium and plutonium. As of January 1, 2016, the thermal output of the calcine varied from 3 W/m^3 to 40 W/m^3. The calcine waste is considered to be mixed waste by the State of Idaho (Idaho Department of Environmental Quality; IDEQ 2006).

3 REFERENCE DISPOSAL CONCEPT

This section describes the key features of a reference disposal concept, based on earlier work (Arnold et al. 2011, 2014) but with modifications proposed.

3.1 Borehole Drilling and Construction

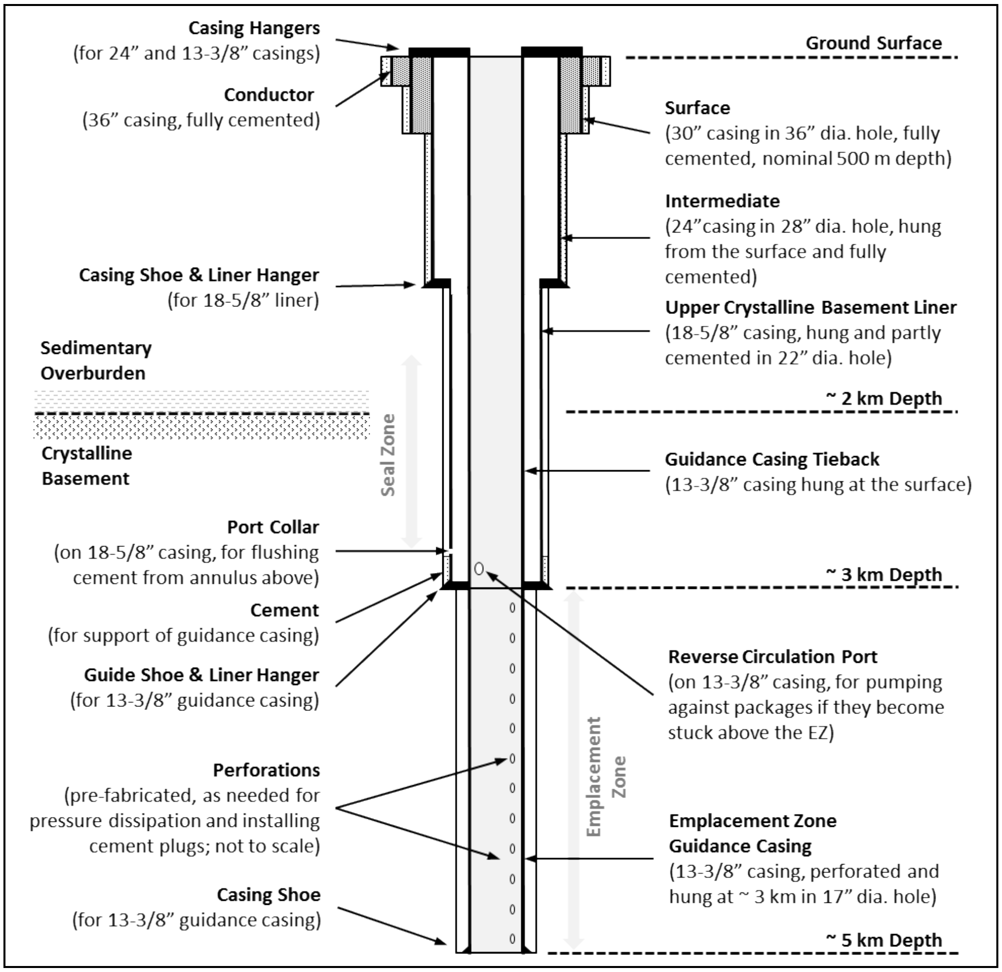
Borehole drilling and construction will be based on currently available technology that can be accomplished at reasonable cost. The goal is to achieve total depth with the maximum diameter that can be completed with reasonable certainty in the depth range 3 to 5 km. Assessment of geothermal drilling experience in crystalline rocks has concluded that this diameter is 17 inches (Arnold et al. 2011).

The reference drilling fluid would be brine, designed with ionic composition similar to formation fluid in the EZ to promote return of the natural salinity gradient after borehole closure. Drilling fluid could be slightly underbalanced with respect to formation fluid pressure, to limit invasion by organic viscosifiers and other additives. Brine (clear fluid) without organic additives would be used for emplacement fluid.

Disposal boreholes would be designed from the bottom up to the surface casing using a telescoping plan (Figure 3-1, Table 3-1). The expected depth and diameter of the EZ would determine the wellbore geometry and casing program, and most of the drilling equipment and casing selections would follow from those criteria. The drift diameters shown in Table 3-1 are less than the nominal IDs and account for ovality of the casing. Further discussion of borehole drilling and construction is provided by Arnold et al. (2011). Casing material selection would be based on longevity required for the site-specific chemical environment, taking into account the potential for damage from gas generation, and any requirement for containment after sealing and plugging of the borehole.

Table 3-1. Typical disposal borehole casing specifications

Interval	OD (inches)	Wall Thickness (inches)	Drift Diameter (inches)	Weight (lb/ft)	Tensile Strength (psi)	Collapse Pressure (psi)
Surface	30	0.75	28.0	235	56,000	772
Intermediate	24	0.688	22.4	174	125,000	1,170
Upper Basement	18-5/8	0.693	17.05	136	125,000	1,140
Guidance Tieback	13-3/8	0.375	12.46	54.5	56,000	1,130
Emplacement Zone Guidance Casing	13-3/8	0.375	12.46	54.5	56,000	1,130
See Arnold et al. (2011) for casing specifications and discussion of required fluid levels.						



Note: Seal Zone and Disposal Zone refer to the reference concept of Arnold et al. (2011); no permanent seals or radioactive waste will be included in the DBFT.

Figure 3-1. Disposal borehole schematic; hachured patterns indicate cement.

Collapse pressure is shown with other casing specifications in Table 3-1. Formation pressure is not expected to be high enough to collapse casing filled with pure water, given the desired characteristics of DBD sites. However, the occurrence of especially heavy formation brine (e.g., containing concentrated $CaCl_2$) could increase the density to 1.3× the density of pure water or greater, in which case the weight of drilling or emplacement fluid would be adjusted to prevent collapse (Table 3-1).

The reference casing plan (consistent with Table 3-1) would be as follows:

3.1.1 Surface Casing

Surface casing would be set in a 36-inch hole, as required by drilling permits to a depth considered suitable for initial well control (500 m; Figure 3-1).

3.1.2 Intermediate Casing

Intermediate casing would be set in the overburden, from the surface to a depth to be determined from site characteristics, in a 28-inch hole (and within the surface casing). The intermediate casing would be fully cemented.

3.1.3 Upper Crystalline Basement Liner

The upper basement liner would be hung from the intermediate casing, extending approximately 1 km into the basement. This liner would be uncemented (for later removal) except the lowermost 100 m. To facilitate cementing of only 100 m, an 18-5/8 inch port collar would be installed as indicated in Figure 3-1. The port collar would allow flushing the rock annulus after cementing, by pumping down the casing with return up the rock annulus and into the intermediate casing.

3.1.4 Guidance Casing Tieback

The guidance tieback casing would consist of about 3 km (10,000 ft) of 13-3/8 inch casing hung from the intermediate casing at the surface (Figure 3-1). At the lower end of the tieback, above the shoe, a reverse-circulation port would be installed to allow fluid to be pumped down the intermediate casing and the upper basement liner, through the port and back up the tieback toward the surface, if one or more packages becomes stuck above the EZ.

In addition, a guide shoe would be used at the top of the guidance liner to make a slip-fit with the bottom of the tieback, to ensure an internally smooth path for package emplacement and to accommodate thermal expansion. Thermal expansion of 0.08% to 0.14% (depending on depth) is estimated for steel casing due to emplacement of heat-generating waste. This much expansion could occur over only the part of the guidance liner that is not constrained by cement plugs. Hence, differential expansion of the guidance tieback casing and guidance liner at the top of the EZ during emplacement operations would be on the order of 2 to 3 m, or less depending on how the casing is cemented, how much heating occurs before cementing, and how much heat migrates upward into the guidance tieback above the EZ.

3.1.5 Emplacement Zone Guidance Casing and Completion

The guidance casing would consist of slightly more than 2 km (6,560 ft) of 13-3/8 inch casing hung from the bottom of the upper crystalline basement casing (Figure 3-1). The functions of guidance casing in the EZ include

- Provide a clear, smooth path for package emplacement
- Prevent rock or cement debris from falling in the path
- Help to control surge pressure when packages are lowered or retrieved
- Align packages as they are stacked (limit offset loading)
- Facilitate placement of cement plugs and bridge plugs if used
- Limit terminal sinking velocity if a package is accidently dropped
- Facilitate recovery of packages in case of an accident (alignment and protection from rock debris; also recovery of stuck packages by pulling casing)

Once the casing is installed, emplacement fluid would be circulated throughout the EZ. Approximately 40 WPs would be emplaced (Section 3.4) and a bridge plug would then be set above the top waste package. A squeeze packer would then be set 10 meters above the bridge plus, and cement would be injected under pressure through the packer (a multi-purpose cementing tool run on coiled tubing). Casing perforations in the interval between the bridge plug and the squeeze packer would allow cement to flow into the annulus between the casing and the rock wall and upward, following the path of displaced fluid. Any excess cement would remain in the annulus where there would be ample volume available and no need for flushing after the cement job. Small perforations, about 2 cm in diameter, spaced every 50 meters would provide for fluid and gas pressure relief while still limiting the terminal velocity of a dropped package. In addition, at least one larger perforation would be needed near the bottom of each cemented interval to enable the placement of the cement under pressure. This perforation could be created *in situ* after the waste has been emplaced. The final state of the EZ would have emplacement fluid around the WPs and in the annulus between the rock and the casing next to the WPs, and 10-meter cement plugs between stacks of WPs.

3.2 Waste Packages

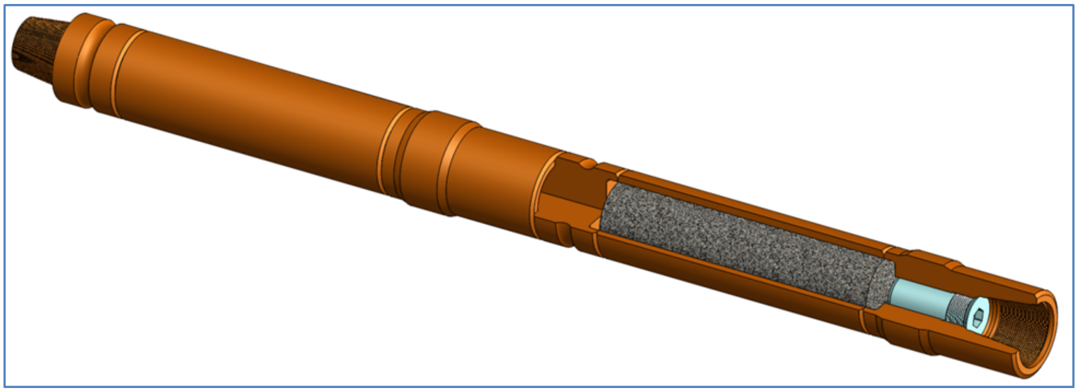
Two basic packaging concepts are presented here, either of which could be scaled to nominal ODs of 5, 8 and 11 inches (identified as small, medium, and large in Table 2-1):

- Flask-type WP for bulk waste
- Internal semi-flush type package for canistered waste

The corresponding guidance casing size and radial gap for these packages are given in Table 2-1.

3.2.1 Flask-Type Packages

Each end of the flask-type package would be a plug with integral API connections (Figure 3-2). The upper shield plug would have a filling plug with its own seal, and provision for a sealing weld. The thickness and mass of the top plug might allow for a sealing weld with small cross-section, as a final step after waste loading, without subsequent heat treatment. The lower plug would be a simple structural plug. The end plugs would be attached to the tubular package body via friction welding, which is commonly used to fabricate the ends on drill pipe. The plug region of each end would be long enough to isolate critical connection threads from the heat of friction welding.



Notes: Two packages are shown with aspect ratio shortened for illustration. Upper end shown to the right. Waste packages would not be attached to each other, as shown, if emplaced by wireline.

Figure 3-2. Flask-type waste package concept, shown loaded with bulk waste.

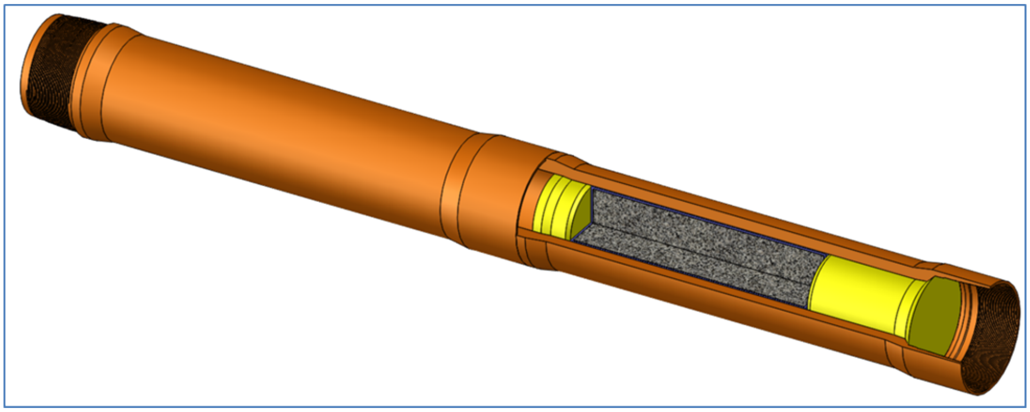
The package would have a box thread on top and a pin thread on the bottom. For the 10-3/4 inch OD package design, an API NC-77 or equivalent thread could be used. This arrangement would provide a smooth exterior package profile. Granular waste could be loaded through the fill port on the upper (box) end of the package. A tapered, threaded plug with a metal-metal seal would then be threaded into the port for initial containment of the waste. A cover plate would be welded over the plug.

Advantages identified for the flask-type concept include: 1) relative ease of manufacturing and assembly; 2) heat treatment of structural welds is possible before waste loading; 3) standard API tool joints are designed for repeated makeup/breakout, providing more flexibility for rework during package preparation; 4) the external surface is smooth; and 5) gripping features can be machined into the end plugs. Disadvantages include: 1) welds in the axial load path (for fishing of stuck packages); and 2) the most robust types of pipe joints require pipe dope which is a potential contaminant in the borehole environment.

The geometry for small packages Table 2-1) would allow sufficient wall thickness for a flask-type package to be loaded with the smaller size of Cs/Sr capsules (2.6-inch OD; Josephson 2004). A basket to hold the capsules would be built into the package during initial assembly and welding.

3.2.2 Internal Semi-Flush Type Packages

The internal semi-flush type package would be built around a section of external-upset semi-flush threaded casing (Figure 3-3 and Table 3-2). The threaded connection would be a Tenaris MAC II® or equivalent. These specially shaped threads provide a tight seal against external pressure, but are not ideal for repeated makeup/breakout. The lower structural plug and the seat for the fill plug would be installed at the mill where the casing is fabricated (e.g., by friction welding). To prevent heat damage to connection threads from welding, any welds used to seal the fill plug would be recessed beyond the threaded portion of the body tube. Alternatively, the fill plug could be sealed using the same type of high-performance metal-metal seal used on casing connections.



Notes: Two packages are shown with aspect ratio shortened for illustration. Upper end shown to the right. Waste packages would not be attached to each other, as shown, if emplaced by wireline.

Figure 3-3. Internal semi-flush package concept.

Table 3-2. Inner and outer dimensions for representative small, medium and large packages.

WP Type	Waste Type	Casing Grade [A]	Tube OD (in)	Tube ID (in)	Tube D/t Ratio	Connection		Casing Size [B] (in)	Casing ID [B] (in)	Radial Gap [C] (in)
						ID (in)	OD (in)			
Internal semi-flush	Cs/Sr capsules (end-to-end)	P110	5.000	3.876	8.9	3.795	5.000	7.000	6.366	0.683
Internal semi-flush	Cs/Sr capsules (3-packs) [D]	P110	8.625	6.751	9.2	6.671	9.044 [E]	10.750	10.05	0.503
Flask-type	Bulk waste (e.g., calcine)	Q125	10.750	8.650	10.2	4.750 [F]	10.75	13.375	12.615	0.933

Notes:

[A] Casing and connection data from Tenaris-Hydril® (http://premiumconnectiondata.tenaris.com/tsh_index.php).

[B] Guidance casing selected for mechanical support and minimal differential pressure.

[C] Minimum gap along the length of a package including end connections, based on nominal dimensions, for use with sinking velocity calculations.

[D] Universal canister (3-pack) OD assumed to be 6.500 inches.

[E] This selection from Tenaris has a connector OD that exceeds the nominal overpack OD from Table 2-1.

[F] Inner dimension for API NC-77 thread.

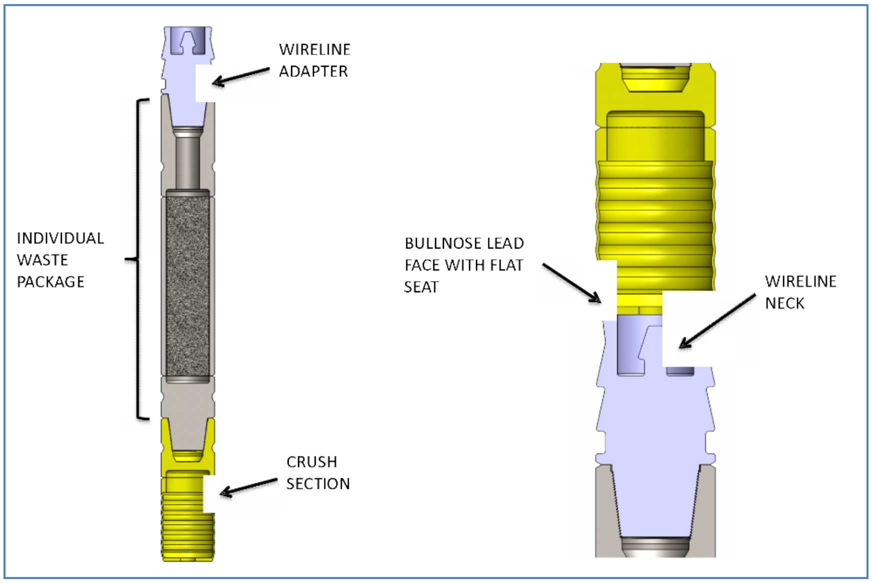
Canistered waste would be loaded through one end, then contained by a slightly tapered plug, with a seal or sealing weld. The OD of pre-canistered waste for the concept shown here would be limited to approximately 8.5 inches (for the large size package). Note that for a 10-3/4 inch nominal casing OD, the external upset diameter would be 11.23 inches (for the MAC II® connection with 1.000-inch wall), providing approximately 11/16 inches radial clearance compared to nearly 15/16 inches for the 10-3/4 inch tube section (data from http://premiumconnectiondata.tenaris.com/tsh_index.php).

Advantages identified for this internal semi-flush package concept include: 1) uses standard size casing and casing connections; 2) no welds in axial load path; and 3) metal-metal dovetail casing threads provide good backup sealing (in addition to the fill plug seal) against external pressure. Disadvantages include: 1) the combination of casing size and material grade (e.g., 10-3/4 inch OD with 125 ksi yield strength) could require a custom mill run; 2) dovetail threads are not designed for repeated makeup/breakout; and 3) the external upset could increase flow resistance during emplacement, slowing the process and contributing to pressure surge.

An internal semi-flush option could be developed in the small size that would accommodate the largest Cs/Sr capsules (Type W, up to 3.3-inch OD; Josephson 2004). The concept is based on commercial casing with a 5-inch OD and 4-inch ID. The connection would be a Tenaris Wedge 513® which uses dovetail shaped threads, and is both internally and externally flush. The rated collapse pressure for the casing is 19,800 psi. After capsules (or small waste canisters) were loaded, a slightly tapered plug would be inserted and sealed.

3.2.3 Package Connections and Attachments

Package connections for wireline emplacement of single packages would include a releasable latch and fishing neck at the top, and an impact limiter attached at the bottom (Figure 3-4). While multiple packages might be emplaced with a wireline while meeting service load limits, it would require a means to thread packages together at the surface, which would increase cost and complexity and is not included as part of the wireline emplacement option (Section 3.4).



Note: Package aspect ratio shortened for illustration.

Figure 3-4. Package assembly for lowering individually on wireline.

Impact limiters would be designed to limit the deceleration of any accidentally dropped packages to a few g's on impact. They would also be loaded progressively as packages are stacked, and a graduated crush force profile would moderate dynamic loads during stacking and help to distribute stack loads uniformly at the contacts between packages. Impact limiter performance (Section 4.4) is important in the risk analysis. It will be further developed and tested as part of the DBFT demonstration, as it could significantly reduce the probability of package breach associated with dropping a package. In addition to the progressive loading profile, other design questions include venting of borehole fluid during crushing, and materials (e.g., all metal) that can perform in the downhole physical and chemical environment.

For wireline emplacement, an electrically actuated cable head would release each package in the emplacement position. Examples of this type include the Haliburton RWCH® and the Schlumberger SureLoc® 12000. Off-the-shelf tool designs would be reviewed and potentially modified to: 1) interface with the package design; 2) minimize the length and cost of the hardware left in the hole with each package; 3) ensure appropriate load rating; and 4) include safety features as appropriate, such as the function of release only without load.

Fishing could be needed if a package becomes stuck, particularly during wireline emplacement. If the wireline itself fails to free a stuck package, it can be released and potentially reconfigured for greater pull (e.g., with a stronger weak point if stuck near the surface) or a workover rig could be mobilized. A fishing neck would be provided to facilitate removal using fishing tools run on drill pipe.

3.2.4 Package Dimensions

Oilfield tubing or casing is used to the extent possible in the packaging concepts presented here for the tubular portions of the packages. Test packages meeting requirements for the DBFT will generally have greater wall thickness than typical oilfield tubulars, especially in the large size (Table 2-1).

For example, for large packages with nominal OD of 11 inches, a typical tubing size would be 10-3/4 inch OD × 1-inch wall thickness, but larger wall thicknesses (e.g., 1.050 inches) are also available. For packages with nominal OD of 5 inches, a casing size of 5-inch OD × 3.876-inch ID is available, but greater wall thicknesses (and greater ODs) may be used if additional strength is needed.

The nominal package ODs shown in Table 2-1 might be approximated using API casing sizes, or they could require use of structural steel pipe or high-strength steel tubing. Machining the ID or OD may be an option to accommodate canistered waste or to adjust the radial gap.

Waste package length for DBD has not been finalized. The overall external length used in this report for the DBFT is 14.5 ft, which includes an internal waste cavity length of about 11 ft, an upper shield plug and lower end plug, and connecting threads. This overall length fits in the transportation cask discussed in Section 3.3.

3.2.5 Threaded Connections

The following paragraphs discuss the threaded connections by which the wireline latch and impact limiter would be attached. These threaded and sealed connections would also serve as secondary containment, backing up the fill plugs. The attachments would have mating threads and sufficient strength to maintain seal integrity under hydrostatic loading plus loads from emplacement and stacking of packages in the borehole (see Figure 3-4).

Numerical stress analysis (Section 4.1) has generated important insights including

- Compressive stress is greatest, so that yielding will first occur, on the inner surface of the tubular section of every package concept analyzed. This mode of yielding is controlled by the ratio of tubular OD to wall thickness (D/t), which should have a value less than 12.42 (see Section 4.1.5). Buckling (possible at larger values of D/t) depends on localization of deformation and is significantly more difficult to predict than elasticity for FoS evaluation.
- Axial compression decreases the compressive hoop stress in the tubular section, and the magnitude is relatively small, so to a good approximation axial loading can be neglected in selecting tubular sections.
- Oilfield tubulars are available with dimensions and in materials that make it necessary to select medium-carbon high-strength steels to meet the maximum downhole pressure assumed for WPs.

Dimensions for small, medium and large WPs, based on the Tenaris-Hydril® line of high-strength steel tubing are presented in Table 3-2. The casing sizes shown are available in P110 and Q125 grades (110 and 125 ksi minimum yield strength) although some combinations may be more difficult to obtain, with minimum heat or lot size requirements. A schematic of the medium-size package concept, for Cs/Sr capsules in 3-packs, is presented in Figure 3-5.

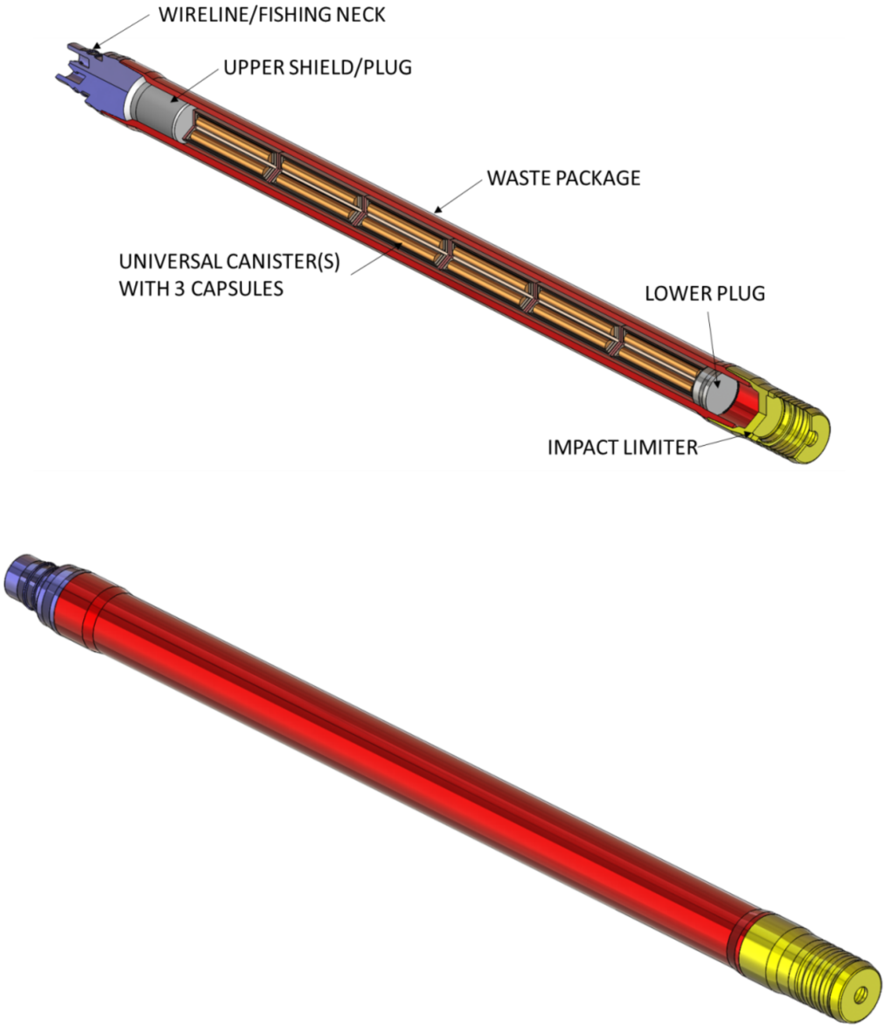


Figure 3-5. Schematic of medium-size internal semi-flush package for Cs/Sr capsules, with end fittings attached.

The casing sizes shown in Table 3-2 are also available in other grades (from Tenaris-Hydril®) that provide

- Higher strength with ductility for use in deeper wells ("DW" grade; 135 and 150 ksi)
- Sulfide stress corrosion resistance for sour gas applications ("SS" and "HS" grades)
- CO_2 corrosion resistance ("CS" and "CRA" grades; 1, 3, and 13% chromium)
- High collapse pressures ("HC" and "IC" grades; higher pressure ratings than API 5CT)
- Low-temperature and high-temperature performance ("LT" and "HT" grades)

The recommended choices for steel grades (Table 3-2) exploit oilfield experience inherent in the material specifications, the availability of possible alternative grades that address specific environmental challenges, and the commercial availability of fabrication technologies such as friction welding, for these same materials, that could be adapted to WPs. Final material selection for a DBD project would depend on site-specific information such as temperature, and the composition of formation fluid.

For maximum downhole pressure of 9,560 psi, and steels that retain 90% of yield strength at bottom-hole temperature the minimum external pressure rating to meet FoS = 2.0 would be 21,250 psi. This specification is met for the configurations in Table 3-2. For heat-generating waste at higher temperature, either a higher grade (e.g., Q125 instead of P110 for packages containing Cs/Sr capsules), greater wall thickness, or shallower target depth of disposal application would be needed. Pressure ratings for tubing and connections may include a small performance margin (e.g., allowed -12.5% variation of wall thickness in API ratings). Such small margins are not included in the calculations discussed here.

For internal semi-flush concepts (Figure 3-5) the connections would be built into external-upset tubing ends. Casing sections could be obtained from the manufacturer in specified lengths with completed forging, threading, final machining to accept upper and lower plugs, and final heat treatment. Because of the steel alloys used (American Society for Testing and Materials (ASTM) A519 4140 grade) all machining would likely need to be done before final heat treatment. The connections for which dimensions are given in Table 3-2 are available in various types. They would be used to attach the wireline latch and impact limiter for wireline emplacement, and would also serve as backup barriers as discussed above. In addition, for the internal semi-flush concepts a basket could be needed to hold waste canisters, and it may need to be inserted before modifying the tube ends or attaching plugs that reduce the inside diameter.

For the flask-type concept in the reference large size (Table 3-2), tubing would be joined with machined end fittings that include API numbered threads (e.g., NC-77). A method such as friction welding would be used, and heat treatment would be used as needed for stress relief and tempering to restore the nominal yield strength. With the tubing size and grade identified in Table 3-2, the large packages would be suited for non-heat generating waste. Large packages for service at temperatures greater than 170°C would require greater wall thickness, possibly using different materials. Among the design details that remain to be worked out and are not discussed above, two of the more important pertain to the design and closure of filling ports. For the internal semi-flush concepts, the concept drawings in Figure 3-5 show a gently tapered plug in a conical seat machined into the casing ID. This arrangement could detrimentally affect casing strength, although the plug itself could provide structural support if accurately seated.

The other detail is the design of final seals for fill plugs, which is potentially important because the packages cannot be heat treated (e.g., to 500°C) after filling with waste. If welding is used for final sealing, the internal semi-flush concepts would require welding against the ID of the casing, whereas for the flask-type a sealing weld would be made within a massive end plug. The former case may be more problematic because the cross-section is thinner. For both package types one solution could be to forgo the final sealing weld, and use a mechanical seal (e.g., threaded plug and metal-metal seal similar to premium casing threads) that is fully fabricated prior to heat treatment and waste loading.

3.3 Transfer Cask and Wellhead Equipment

This section describes the transfer cask and related equipment needed for package receipt, handling, emplacement, recovery, and other related operations for DBD. It begins with description of equipment and the sequence of operations, then discusses other operations such as package retrieval, and borehole equipment maintenance. The intent of this conceptual discussion is to show that emplacing highly radioactive WPs is feasible, recognizing that other solutions may be developed as design proceeds. Off-the-shelf components are identified, subject to further design analysis. For some equipment such as a transportation cask, and wireline logging tools, rental is identified as a feasible option.

This section describes equipment and operations that could be used for DBD, and normal operations. Off-normal events during surface DBD operations are not discussed.

3.3.1 Activity Sequence

3.3.1.1 Package Receipt and Movement into Transfer Cask

The disposal concept begins with receipt of single WPs in a transportation cask such as the NAC LWT® (NAC International; Figure 3-6). The package would be transferred into a custom-designed transfer cask because a double-ended, shielded cask is required for wireline emplacement, and no such cask has been found to exist in a useable size. Transfer of the WP from the transportation cask into the transfer cask would be performed in a horizontal orientation (Figure 3-7). In this conceptualization of the transfer system, both casks would be lifted and placed in horizontal cradles using rigging and cradle concepts routinely used for the LWT® cask. A transfer shield would assure acceptable dose rates during transfers, as discussed below. After moving the WP into the transfer cask, a side latch would be engaged to restrain the package and ensure that a single-point failure cannot result in dropping a WP before it is intended to be lowered into the borehole.

Figure 3-6. LWT® cask being lowered into a horizontal cradle (ORNL photo).

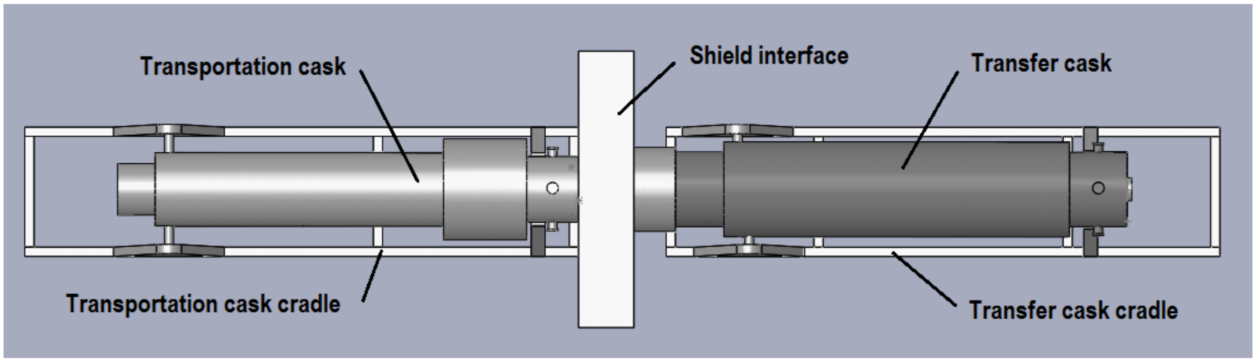


Figure 3-7. Casks in position for transfer of waste package.

3.3.1.2 Borehole Qualification

Prior to package emplacement, wireline logging would be performed to verify the condition of the borehole. The logging tool string would include a gauge ring and junk basket, and would be run prior to placing the transfer cask over the borehole. A valve on the borehole (located in the pit, discussed below) would be opened for this operation and closed again when completed.

3.3.1.3 Positioning of Transfer Cask in Borehole Shield

After the borehole condition is verified and the transfer cask closed with the WP inside, the cask would be lifted into a vertical orientation and placed into an insert hole in the wellhead carousel (Figure 3-8). The carousel would rotate in the pit shield plate, and it would initially be rotated into position over tooling in the pit for removing the lower shield plug from the transfer cask.

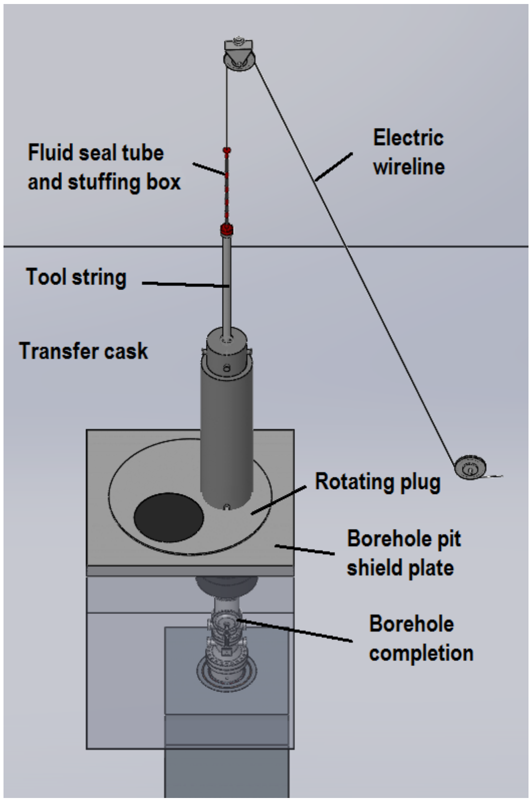


Figure 3-8. Transfer cask positioned over borehole.

3.3.1.4 Connection of Wireline and Removal of Lower Shield Plug

With the transfer cask latched into position in the carousel, the wireline would be connected to the top of the transfer cask. A small plug in the upper shield plug would be removed and a tool string containment tube attached (labeled as lubricator in Figure 3-9). A set of grease tubes or a stuffing box would be attached to the containment tube. With the package side latch still engaged, the wireline tool string would be attached to the top of the WP using the electromechanical release device. A pull test would verify that the connection is secure, but the wireline tension would remain slack. A mechanism within the pit would then disconnect the lower shield plug from the bottom of the transfer cask, and pull it out through the flange assembly.

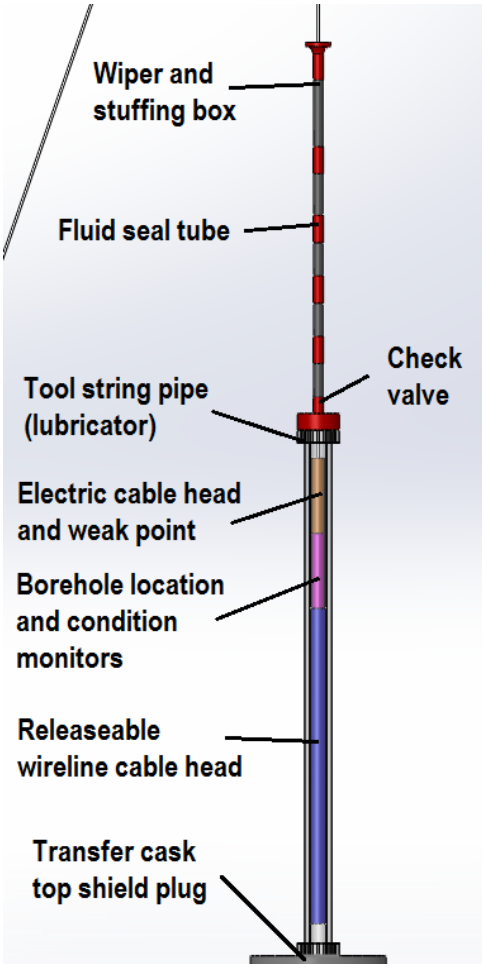


Figure 3-9. Tool string and wireline attached to top of transfer cask.

3.3.1.5 Connection of Transfer Cask to Wellhead Flange

The wellhead carousel would then be rotated to bring the cask into position over the borehole. Hydraulic kneeling jacks would then lower the cask onto the borehole, and a flange connection would be engaged remotely to couple the transfer cask to the borehole. The completed assembly, ready for package transfer to the borehole, is shown in Figure 3-10.

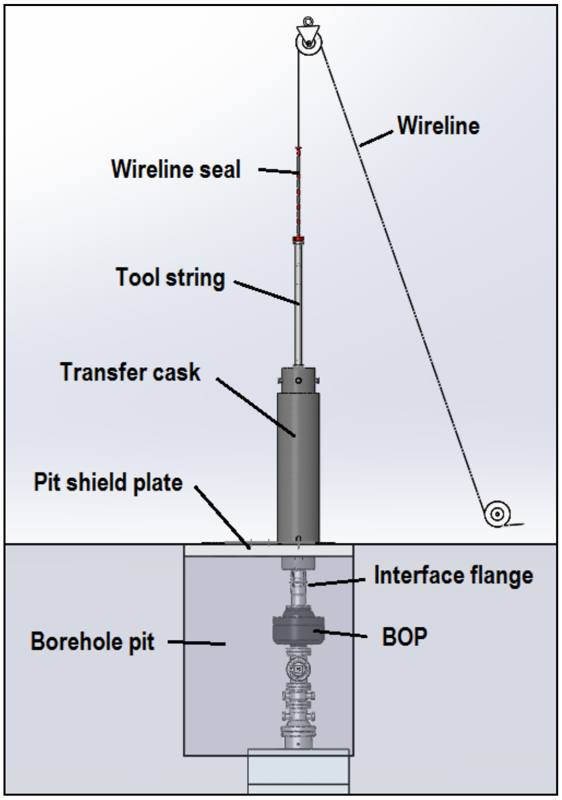


Figure 3-10. Cask over borehole, ready for package emplacement.

3.3.1.6 Waste Package Emplacement

With the WP still secured by the side latch, the borehole valve would be opened, wireline slack would be taken up, and the side latch holding the WP in place would be released thereby suspending the WP by the wireline over the open borehole. The WP would be lowered into position, as indicated by the amount of wireline played out, the locations of casing collars, and other instrumentation that may be included in the wireline tool string. With the package in position for emplacement, the electromechanical release would be actuated to release the package, and the wireline cable and tool string would be hoisted out of the borehole. With the tool string back inside the containment tube (lubricator), the borehole valve would be closed and any fluid in the transfer cask would be drained.

3.3.1.7 Sequence Completion and Prepare for Next Sequence

With the borehole valve closed and fluid drained, the containment tube would be disconnected from the top of the transfer cask, and the wireline tool string removed. The carousel would then be rotated back to position the transfer cask over tooling for re-insertion of the lower shield plug. Alternatively, the shield plug could be retrieved for re-installation by other means. The empty transfer cask would be lifted off the carousel and moved to a wash-down area. The cleaned cask would be inspected for damage, and prepared to receive another WP. The tool string on the end of the wireline would be similarly cleaned and inspected, and the electromechanical release rebuilt for its next use.

3.3.1.8 Accommodating Installation of Cement Plugs and Other Operations

As WPs are stacked upon each other in the borehole, the compressive load on the bottom packages will increase. At specified intervals, such as every 40 packages, a bridge plug would be set and cement poured to form a plug for supporting more packages.

The transfer and emplacement system must permit wireline logging, and insertion of coiled tubing and downhole assemblies such as bridge plugs. These activities can be accommodated by connecting a modified tool string containment tube (lubricator) or a coiled tubing injector directly to the borehole using the same type of Grayloc® flange connector that is used on the bottom of the transfer cask.

Ultimately a workover rig would be needed for borehole sealing, primarily to remove guidance tieback and upper crystalline basement liner (Figure 3-1). Package handling and transfer equipment would be designed for disassembly and removal when a rig is brought on site. A workover rig could also be needed to mitigate off-normal conditions.

3.3.1.9 Package Retrieval and Other Off-Normal Operations

Package retrieval from the borehole is a key requirement for DBD. The starting condition for this sequence would be a package at the bottom of the borehole and detached from the wireline. Package recovery would be performed using the emplacement wireline tooling fed through an empty transfer cask in the carousel, flanged onto the borehole. An overshot-style fishing tool would require opening the top of the transfer cask to its full ID, accomplished by removing the upper shield plug. Special tooling would replace the wireline tool containment tube. Once the package was raised to the surface and secured with the side latch, the borehole valve closed, and the lower shield plug replaced, the wireline fishing tool would be detached and the upper shield plug replaced (the upper shield plug on the package would protect personnel during this step). All package transfer operations would be designed to be performed in reverse, including insertion of the lower shield plug and transfer of a package back into the transportation cask. If a workover rig were needed for fishing stuck packages, this sequence would be adapted to a string of pipe or tubing, instead of wireline.

3.3.2 Package and Transportation Cask

For this conceptual design the NAC LWT® Type B transportation cask is steel-encased, lead-shielded, and commonly used for irradiated fuel and other materials. The cask body is approximately 200 inches long and 44 inches in diameter. The internal cavity is 178 inches long and 13.4 inches in diameter. Since the cavity diameter is slightly larger than the drift diameter of the guidance casing in the borehole, the cask can physically accept any of the WPs under consideration as long as the package length fits in the cavity. A cutaway of the LWT® cask with a package containing 18 Cs/Sr capsules (the same package geometry shown in Figure 3-5) is shown in Figure 3-11.

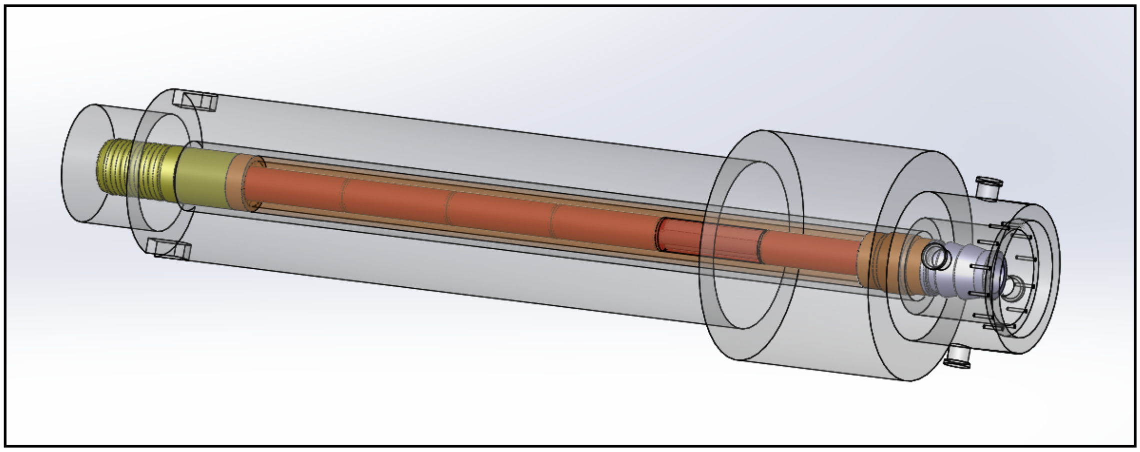


Figure 3-11. LWT® transportation cask with waste package.

The cask body consists of a 0.75-inch stainless steel inner shell, a 5.75-inch lead gamma shield, a 1.2-inch stainless steel outer shell, and a neutron shield tank. The inner and outer shells are welded to a 4-inch thick stainless steel bottom end forging. The cask bottom consists of a 3-inch thick, 20.75-inch diameter lead disk enclosed by a 3.5-inch stainless steel plate and bottom end forging. The cask lid is 11.3-inch thick stainless steel with a stepped design, secured to a 14.25-inch thick ring forging with twelve 1-inch bolts. The neutron shield tank consists of a 0.24-inch stainless steel shell with 0.50-inch end plates. The neutron shield region is 164 inches long and 5 inches thick, and consists of an ethylene glycol/water solution that is 1% boron by weight.

The LWT® cask has a maximum design heat rejection rate of 2.5 kW. The maximum weight of the loaded cask is 52,000 lb and the maximum weight of the contents and basket is 4,000 lb. This is more than adequate for a package containing Cs/Sr capsules, with a total weight of roughly 2,200 lb, plus a spacer. (The weight of a medium-sized package containing 18 Cs/Sr capsules is somewhat uncertain because of the unknown weight of universal canisters containing capsule 3-packs.)

The LWT® cask is shipped in a horizontal configuration, resting on a trailer-mounted cradle and enclosed in an International Standards Organization container structure that can be dismantled for removal of the cask. Impact limiters fabricated of a honeycomb material are attached to each end. At a DBD site after the impact limiters are removed, a crane would lift the cask as shown in Figure 3-6. Similar cradles (Figure 3-12) would support the LWT® cask and the transfer cask during transfer of packages and during cask maintenance operations.

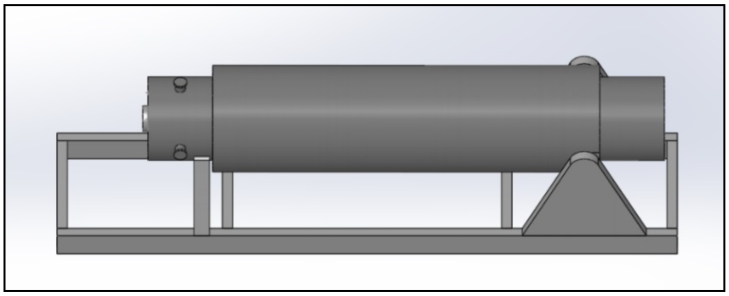


Figure 3-12. Cradle used for both LWT® cask and the transfer cask.

3.3.3 Transfer Cask

A sketch showing the main features of the transfer cask is shown in Figure 3-11. Externally, the cask would be similar to the LWT® cask; with the same array of pintles and pockets for cask handling and support in the horizontal cradle. The transfer cask would not use impact limiters. The lower end of the cask (to the left in Figure 3-12) would be shaped to fit into the carousel over the borehole, and the upper end would have a reduced diameter above the elevation at which radioactive material would be present.

The central feature of the transfer cask would be the internal cavity. The diameter of the cavity would be 12.5 inches, approximately the same as the casing drift diameter. The internal length of the cavity with shield plugs in place would be 176 inches, similar to the length of the LWT® cask cavity (length can easily be adjusted as required during the design process). An outline of a WP 174 inches long is shown in Figure 3-13. The central cavity could be formed using a section of standard 14-inch, Schedule 80 steel pipe, which has the desired inner diameter, and flanges at either end.

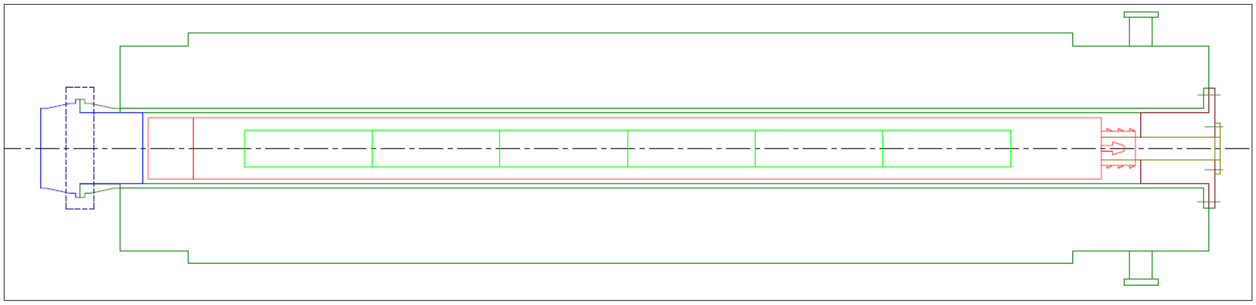


Figure 3-13. Key elements of the transfer cask.

A shielding analysis for Cs/Sr waste forms in a cask similar to the LWT® transportation cask was performed by Oak Ridge National Laboratory (ORNL). For steel, a body (wall) thickness of 14 inches was found to reduce the dose at the cask surface to less than 2.5 mrem/h, giving a cask OD of 40.5 inches. Fabrication methods for the shield could include machining the entire cask out of a solid steel casting, or smaller cylinders could be added over a central pipe.

A flange at the bottom of the cask would interface with a flange on top of the wellhead. As described here the wellhead flange would be located under the pit shield plate and carousel. A common type of flange, using a side clamp rather than bolt ring, is produced by Grayloc® (now a division of Ocean Engineering). Grayloc® produces a remotely operated clamp mechanism as an off-the-shelf component (a 6-inch flange and remote clamp is shown in Figure 3-14). A Grayloc X14GR125® flange hub would be welded to the base of the transfer cask, and another to the spool piece at the top of the wellhead. A Grayloc X14® remotely operated clamp would be mounted on the hub at the base of the transfer cask. The lower shield plug would then be formed from a blind hub in the reverse orientation, with a 12.5-inch diameter solid section placed into the cask cavity and secured by the clamp (as seen to the left on Figure 3-11).

Figure 3-14. Remotely-actuated Grayloc® flange connection system (ORNL photo).

The upper shield plug, seen to the right in Figure 3-13, would provide radiation shielding while allowing manipulations such as pulling the WP from the transportation cask into the transfer cask and attachment of the wireline tool string to the top of the WP. It would consist of a 12.5-inch OD plug attached to the top of the cask with a standard 150 lb flange bolt arrangement, and an inner 4-inch OD plug that forms part of the package grappling mechanisms. Use of the upper shield plug is described later in this section.

The estimated transfer cask weight with both plugs in place but no WP is 64,000 lb.

The WP would be supported in the cask at all times such that a single failure of any component could not result in dropping a package. During final positioning over the borehole (with the lower plug removed), only the wireline tool string would support the package. To prevent single mode failure at this step, a side latch mechanism would be included in the cask. This mechanism could be as simple as pins passing through the cask body that fit into pockets in the WP, which are sealed against fluid leakage by tube fittings fixed to the outer surface of the cask.

3.3.4 Transportation/Transfer Cask Interfacing Equipment

Waste packages would be pulled from the transportation cask into the transfer cask in a horizontal orientation, with both casks resting on horizontal cradles that are aligned with the transfer shield assembly between them. The cradles would be moveable for access to the transfer shield; options include rails, or handling pockets to allow the use of a large forklift truck.

The transfer shield between casks would consist of a rectangular, sliding shield interface structure (Figure 3-7). This structure would have an outer enclosure made of steel plate, with internal shielding of steel or a material such as concrete. The thickness of the moveable slab would be determined by shielding requirements and the thickness of plugs used in each cask.

Operations at the first position of the transfer shield are depicted in Figure 3-15. The LWT® cask would be positioned against the shield, with the sliding shield in position to receive the end plug. The bolts would be removed, and a positioning disk would be attached (to prevent the end plug from being cocked and jammed). The end plug would be pulled into a cavity in the shield. With the transfer cask open on the other side of the shield, the shield would be slid to the second (central) position.

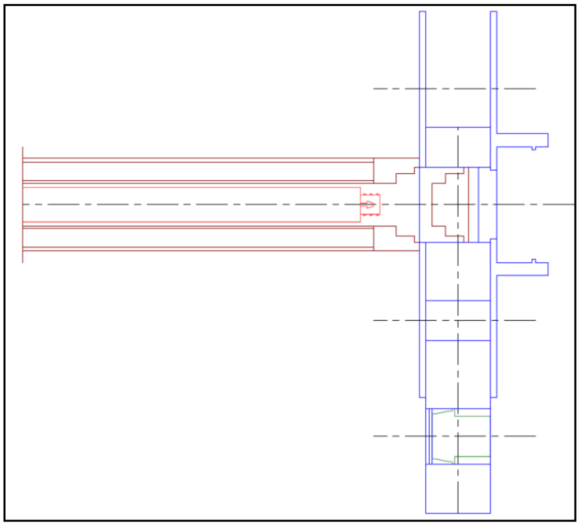


Figure 3-15. Transfer shield in first position for removal of LWT® cask end shield plug.

The second position for the transfer shield would open a clear path for package transfer (Figure 3-16). Because the transfer cask is not shielded over the bottom flange ring, the transfer shield interface structure includes a shield ring around the flange. A grapple assembly on an extension rod would be inserted through the far end of the transfer cask and engaged to the upper end of the WP. The package would then be pulled into the transfer cask (using some type of mechanical assist). The extension rod and grapple would be withdrawn and a flange screwed on in its place to the top of the cask upper shield plug.

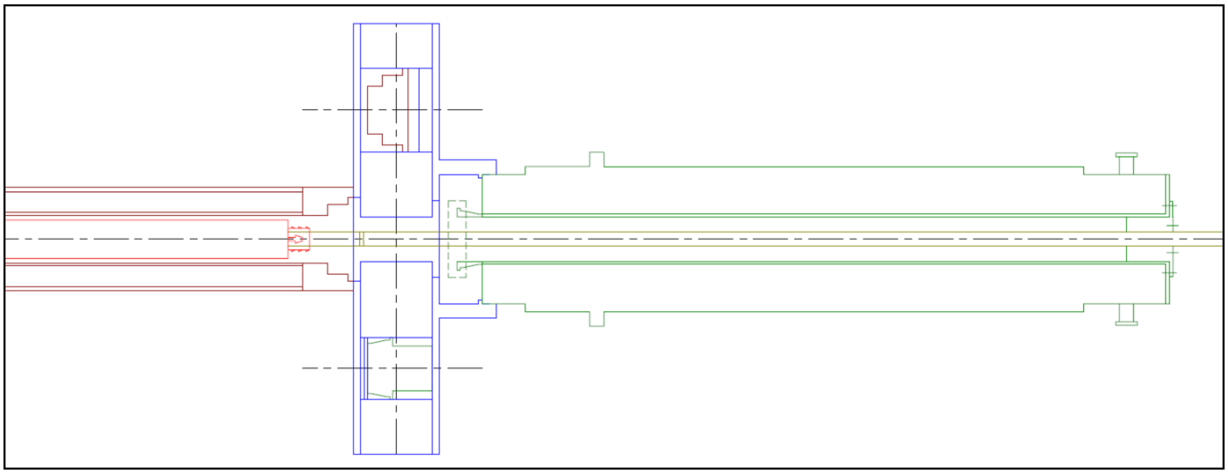


Figure 3-16. Transfer shield in second position for package transfer.

The transfer shield would then be slid to its third position (Figure 3-17). The lower shield plug for the transfer cask is pre-positioned in the shield, and would now be inserted, and the remote clamp can be actuated, completing shielding for the cask. The LWT® cask would then be moved away.

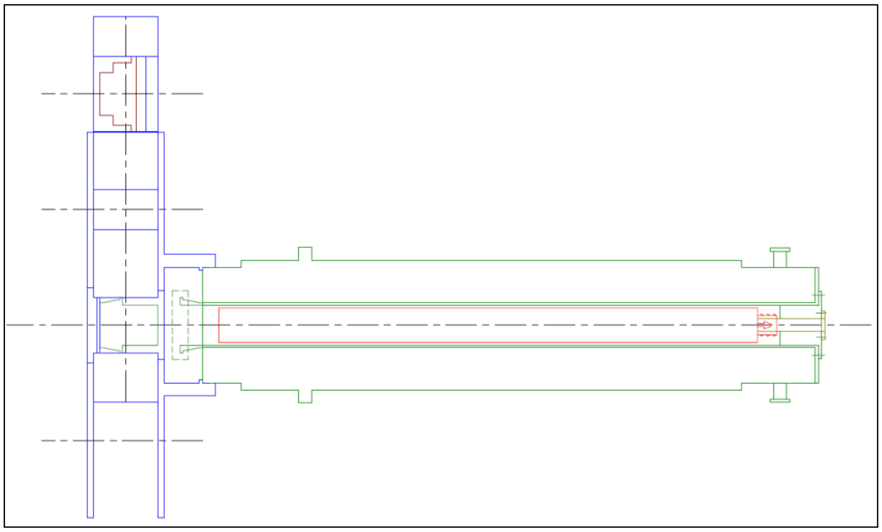


Figure 3-17. Transfer shield in third position for placement for closure of transfer cask.

After the transfer operation is complete, the WP would be restrained in the cask cavity with sufficient but not excessive clearances. The side latch mechanism (not shown in the figures) would be engaged, and the transfer cask lifted to a vertical orientation and placed in the wellhead carousel.

After removal of the package, the LWT® cask would be surveyed for radioactive contamination, cleaned, and inspected. The end plug would be re-inserted and bolted in place. The LWT® cask would then be returned to its trailer and shipped back to the WP loading facility. The shield interface structure would be similarly surveyed, inspected, and prepared for its next operating sequence.

3.3.5 Borehole Surface Installation and Equipment

If a BOP is required during emplacement operations, a single annular-type BOP is assumed for this concept description. This type of device can close on an open hole, a wireline, or a WP with minimal likelihood for damage. A potential wellhead configuration is shown in Figure 3-18.

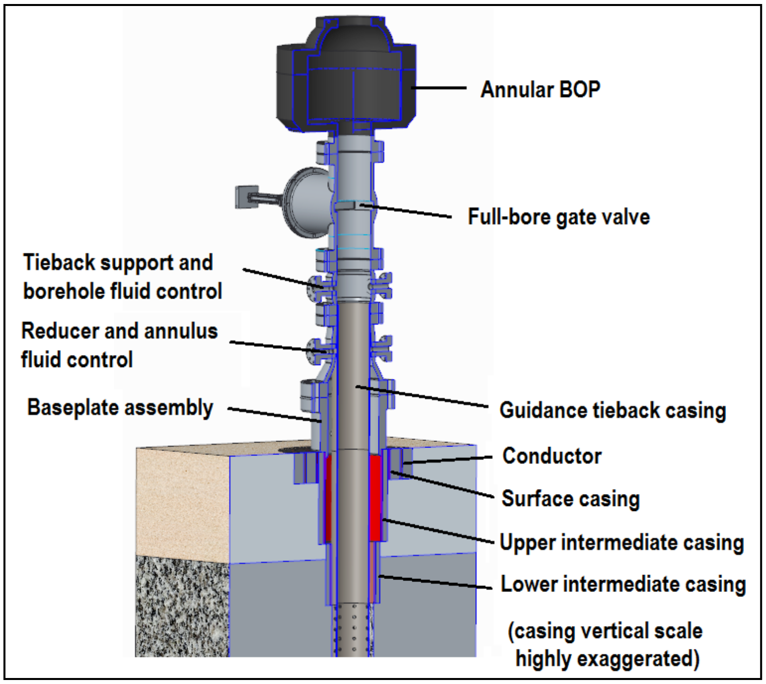


Figure 3-18. Wellhead configuration showing fluid control taps, closure valve, and annular BOP.

The intermediate casing, surface casing, and conductor pipe (Figure 3-1) would be fully cemented up to the surface (in this context, "surface" is the floor of the pit), leaving the 13-3/8 inch guidance tieback casing hung from the top of the 24-inch intermediate casing. A base plate would be set on the intermediate casing, and a reducing section with fluid taps would extend from an API flange on the 24-inch base to a 13-5/8 inch flange. A spool piece with fluid taps would be bolted above this flange, and the 13-3/8 inch guidance tieback casing welded into the flange section of the spool piece. This would provide the means to suspend the 3 km of tieback casing in the borehole. Fluid taps in both the central hole and the annulus region would allow monitoring and control of fluid pressure and level in each; and they would allow conventional or reverse circulation in the upper 3 km of the borehole. These would connect to fluid drain and makeup systems, a surge tank, and a lined surface pond.

A shutoff valve would be located above the fluid control/tieback hanger spool piece. For example, a Cameron-Newco® cast steel bolted-bonnet fully-opening gate valve (series 600 or 900) could be used, with a pneumatic actuator and manual override. This valve would be closed whenever emplacement or retrieval operations were not underway, ensuring the section above the valve would be dry. A small drain valve would be included above the large shutoff valve so any fluid that remains in the transfer cask can be captured prior to disconnecting the transfer cask from the wellhead flange.

The annular BOP is represented by a Cameron T-90® device with replaceable packing, sized for 13-3/8 inch casing and fitted with an API 13-5/8 in. bolted flange. It would bolt to the top of the valve (Figure 3-18). A short spool consisting of another API 13-5/8 inch flange at the bottom and an appropriately sized Grayloc® hub above would allow coupling to another Grayloc® hub at the bottom of the transfer cask.

3.3.6 Borehole Shield and Connection System

The equipment described above would be located in a pit, sized to provide space for equipment operation and maintenance. The pit would be covered with a fixed pit shield plate (Figure 3-8 and Figure 3-10), and a rotating wellhead carousel. The carousel would provide for

- Precise alignment of the transfer cask (combined with the capability to slide the pit shield plate as discussed below).
- Placement of the transfer cask over a lower plug removal system, or over the borehole.
- A range of observation and maintenance activities all while maintaining radiation doses to operators at acceptably low levels.

The proposed carousel would be based on a translating/rotating system that has been used in other operations at ORNL (Figure 3-19). In the present application, the carousel would serve to support and align the transfer cask, and as a maintenance shield (Figure 3-20). The pit shield plate would be 12 inches thick, with rectangular dimensions of approximately 14 ft by 13 ft. It would be supported on two steel beams along the long sides, with the capability to slide along the beams for a short distance (a few inches) for alignment purposes. The carousel would be approximately 10 ft in diameter, with sufficient thickness for shielding and to support the transfer cask. A central pillar anchored to the pit basement would support the center of the carousel from below; the pillar would be provided with the means to accommodate the slight translation of pit shield plate and carousel.

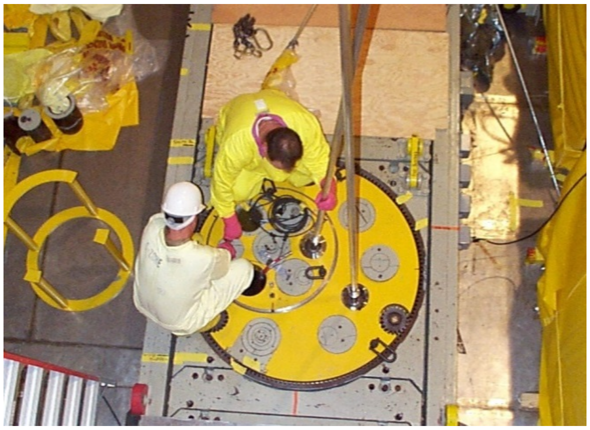


Figure 3-19. Example of a rotating-plug maintenance shield used at ORNL.

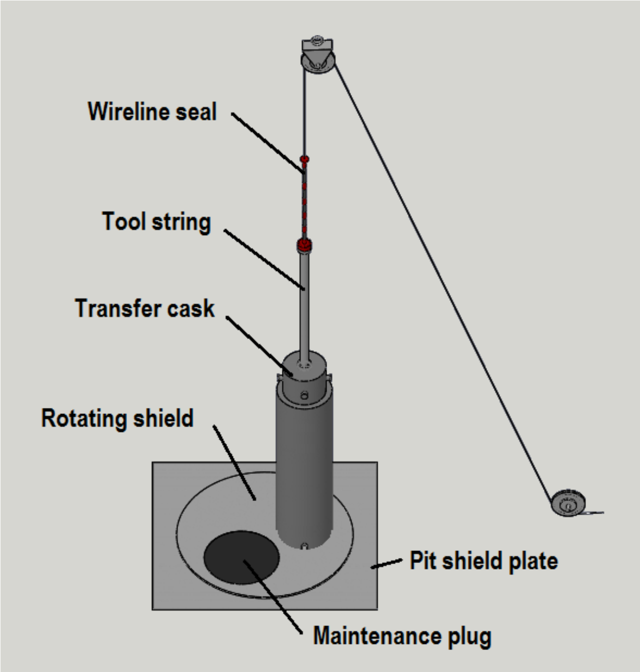


Figure 3-20. Transfer cask over the wellhead carousel and pit shield plate.

There are two key operating positions shown in Figure 3-8, Figure 3-10, and Figure 3-20. The position right of center is the borehole location, with the lower Grayloc® hub fitting (i.e., flange) that couples to the transfer cask. The transfer cask itself would be set into a stepped circular opening in the carousel, sized such that an external chamfer on the transfer cask would be set halfway into the carousel plate.

The other operating position (30° to the left of center) is the position for removal of the cask lower shield plug. This is the first position the cask is placed in; a remotely operated lift would raise a mechanism up to the lower transfer cask shield plug, and the remote clamp would be released to allow lowering of the plug. The operation would be reversible, allowing replacement of the plug as necessary.

The transfer cask would be elevated slightly in the carousel by hydraulic kneeling jacks, so that the cask clears the wellhead flange when the carousel is rotated into position over the borehole. With the cask in position the jacks would lower the cask onto the wellhead flange hub, and the remotely operated Grayloc® clamp would be actuated, coupling the transfer cask to the borehole.

Figure 3-20 also shows a large diameter maintenance plug that could be rotated over either the borehole or the shield plug removal mechanism, facilitating access for maintenance or replacement of components by hoisting, rather than removing the carousel. The maintenance plug would also be large enough to allow, by its removal, personnel access into the pit.

The carousel and the pit shield plate would also be provided with work positions as seen in the example (Figure 3-19). These would accept long-handled tools through a shielded ball arrangement, and allow for inspection and response in cases where problems are encountered with a radioactive WP present. Tooling is available for visual inspection (shielded windows, cameras, periscopes), lighting, radiation survey, and common tools such as wrenches (including remotely operated tools) and lifting tools. Ultimately, however, the carousel plate or the pit shield plate could be lifted off to obtain clear access or to allow access by a workover rig.

An elevation view of the pit is shown in Figure 3-21. The pit design would include details of the plug removal tool positions, floor and platform elevations, a sump, secondary structural supports as needed, and work platforms. The distance between the wellhead flange hub to the pit floor would be about 12.5 ft (assuming the annular BOP is included). The lower end of the transfer cask would extend about 6 inches below the carousel. Each of the two Grayloc® hubs would be about 7 inches high, and 7 inches would be allowed for the top spool and API flange. Thus, the overall depth of the pit, from the bottom of the carousel plate to the top of the pit floor, would be about 15 ft. The pit would also be ventilated for safe access by personnel.

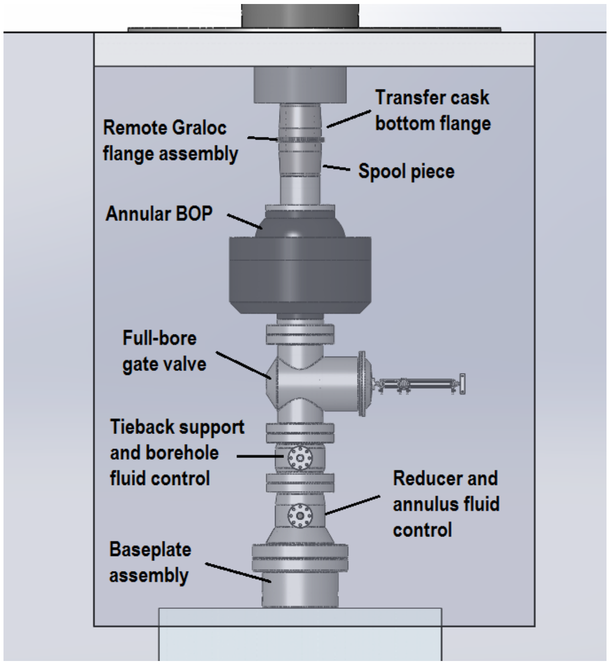


Figure 3-21. Overall pit arrangement.

3.3.7 Wireline Cable and Tool String

The wireline system would consist of the wireline cable, wireline winch, a cable head designed for electric wireline, and a tool string that includes an electromechanical release and logging tools that aid in locating the string and monitoring downhole conditions. The wireline emplacement option as well as the associated cable and downhole tools are described in Section 3.4. This section describes how the wireline would be sealed against the transfer cask during emplacement operations.

Common technology to establish a fluid seal on a moving wireline involves tightly-fitting grease tubes and stuffing boxes. With stranded cable, stuffing boxes primarily establish a seal against static wireline; thus both a grease tube and a stuffing box are depicted here. NOV Elmar provides the Enviro grease injection control head system, consisting of the Enviro combination stuffing box and line wiper, and the flow tube. It is designed for a working pressure up to 10,000 psi (far above the anticipated fluid conditions under normal operating conditions). Elmar provides off-the-shelf tubes up to 0.537-inch ID, and recommends a clearance of 0.003 to 0.008 in (for 0.535-inch OD Tuffline®, this would indicate a 0.541- to 0.551-inch ID flow tube is desired).

Figure 3-22 depicts the tool string, grease tube, and stuffing box interfacing between the transfer cask and the wireline support. The tool string is assumed to consist of a 6 ft long electronic release device at the bottom, a 1.5 ft long electric wireline cable head at the top, and other tools with an overall length of 1.5 ft in the center of the string. The tool string is maintained inside a containment tube (lubricator) modeled as a 10 ft section of 4-inch Schedule 40 pipe. Flanges are provided on both ends; one bolts onto the top of the large shield plug in the transfer cask; the other is used to attach the fluid control system. The latter is shown as a 6 ft length of greased flow tube and a 2 ft long stuffing box assembly. A ball check valve is often used at the bottom of the flow tube; this closes should the wireline break and come out of the tube.

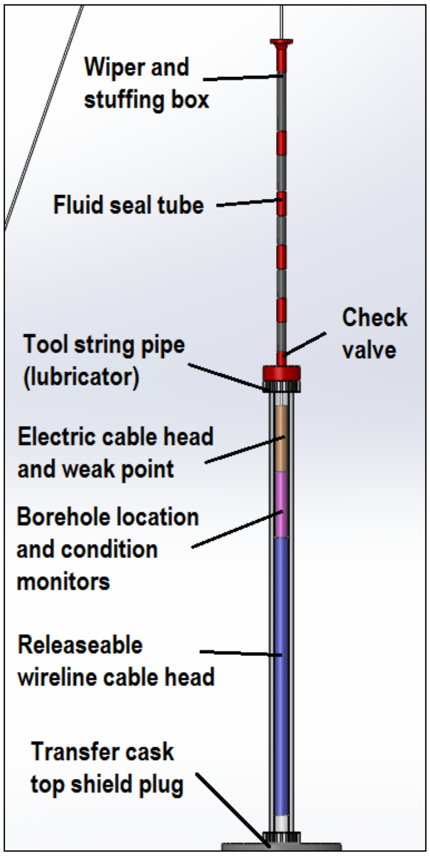


Figure 3-22. Wireline cable head, tools and remote disconnect.

3.4 Waste Emplacement

Several options for emplacing WPs in a disposal borehole have been proposed: drill string, wireline, conveyance casing, coiled tubing, and drop-in. The wireline emplacement option has been selected as the preferred option for the conceptual design and is described in more detail below. In the wireline emplacement option, a single package is emplaced in the borehole in a single operation using wireline.

Packages for wireline emplacement would have specialized subs threaded on the top and bottom. A latch that mates with an electrically actuated wireline release tool would be attached to the top, and an impact limiter would be attached at the bottom. Mechanical loads on these connections would generally be smaller than for drill-string operations. However, the packages and the subs must sustain compressive loads from a stack of up to 40 packages during emplacement, and must sustain loads from fishing if they become stuck.

After the drill rig is moved off of the borehole and before wireline emplacement can begin, the following would be installed: surface pad, wellhead shield, wireline winch, headframe, ancillary surface equipment, and a control room. After waste emplacement, a completion/sealing workover rig will be used for final sealing and plugging.

3.4.1 Surface Supports

A steel-reinforced concrete pad or footings sufficient to support equipment operations would be constructed around the wellhead at grade level, to support the borehole pit shield, package transfers between casks, the headframe described below, and other items.

3.4.2 Wireline Winch

A standard truck- or skid-mounted wireline unit with at least 20,000 ft of modern wireline such as Schlumberger Tuffline® would be used. This wireline has seven electrical conductors, and uses double-armor made from corrosion resistant steel, encapsulated with a high-temperature synthetic polymer. The armor is torque-balanced so that “seasoning” is not required. It has a working load limit of 18,000 lb (depending on which version of the product is used). According to a Schlumberger description, the Tuffline® wireline does not require a dual-capstan device if tension at the surface is less than 12,000 lb. Buoyant weight is typical for wireline products (350 lb per 1,000 ft), so with a package and wireline tool string, the tension at total depth would be less than 12,000 lb.

3.4.3 Ancillary Surface Equipment

During emplacement operations, cement plugs would be set using a coiled tubing rig, with separate borehole fluid and cement handling systems. Bridge plugs (for controlling cement) could be set using either the coiled tubing or the wireline. A crane would be used to remove impact limiters from the transportation cask (if a transfer cask is not used), hoist the transportation and transfer casks into position for transfer, hoist the transfer cask onto the wellhead, and support the coiled-tubing injector. Other equipment would be organized on the surface, including generators, and handling equipment for emplacement fluid and cement.

3.4.4 Handling and Emplacement Steps

Before the transfer cask is placed over the borehole, a caliper log would be run to the next waste emplacement position, to ensure safe condition of the borehole. A crane would lift the transportation cask, and then the transfer cask, placing them on cradles for transfer of the package (Section 3.3.4). With the shielding replaced, the crane would then lift the transfer cask by the upper end, and lower it onto the wellhead flange where it would be bolted or pinned in place.

Packages would be lowered one at time and stacked on the bottom. With a package lowered into emplacement position, an electrically actuated release mechanism would disengage the wireline cable and tool section. After stacking up to 40 packages, a bridge plug and cement plug would be set prior to support the next stack of packages. A stepwise description of emplacement steps that was used for hazard analysis was presented by Sandia National Laboratories (SNL 2015).

Status of the emplacement operation would be provided by the tools making up the wireline tool string. Tools such as the casing collar locator and natural gamma log would provide location information. A downhole tension sender would verify correct operation during lowering, and verify package release.

After waste emplacement a workover rig would be mobilized to remove the guidance casing tieback and the intermediate casing (as discussed above) from the seal zone. The same rig would be used for seals emplacement and plugging of the disposal borehole.

3.4.5 Wireline Emplacement Rate-of-Progress

The descent rate for lowering packages would be comparable to lowering bridge plugs on wireline (6,000 ft/hr or 1.7 ft/sec; Arnold et al. 2011). The rate of package emplacement would be controlled by the maximum sink rate, which in turn depends on: 1) radial clearance; 2) emplacement fluid density and viscosity; and 3) package buoyant weight. Terminal sinking velocity for single packages is estimated to be in the range of approximately 5 to 15 ft/sec. If a descent rate of 2.0 ft/sec is achieved, and the wireline cable can be respooled at twice this rate, the round-trip time for wireline emplacement would be approximately 6 hr. This includes a slower descent rate of 0.5 ft/sec for the first 1 km (3,280 ft) to control load transients (the wireline is stiffer with less length deployed in the borehole) which have the greatest potential to break the wireline with a package attached.

3.4.6 Wireline Cable Release Mechanisms

Two models of electromechanical wireline cable release mechanisms were considered. These are typically used to allow release of the wireline cable in the event a tool string becomes stuck. For this application the release mechanism would be used at the bottom of the tool string, for release of the WP and recovery of the tool string, and could therefore require modification. Schlumberger provides the SureLoc 12000® electronically controlled cable release device; it can sustain a 12,000 lb load, service temperatures up to 260°C, and external pressure up to 30,000 psi. Halliburton provides a releasable wireline cable head (RWCH®) with overall length of 6.3 ft and OD of 3.63 inches. The Halliburton disconnect is rated for temperature up to 176°C and external pressure of 20,000 psi. It normally couples to a conventional 2.31-inch fishing neck. Modification of the release mechanism could be needed so that: 1) the latch and not the tool is fixed to each package and left in the borehole; 2) the package can be re-latched downhole for retrieval; and 3) the mechanism can be configured to either release only when not under full load (as a safety feature), or to release under full load (to initiate a free drop test).

A headframe would support an upper wireline sheave above the borehole, and a lower sheave near ground level The upper sheave would be about 3 m above the containment tube and grease tube assembly (Section 3.3.1). The upper sheave would thus be approximately 15 m above grade. A surface-mounted dual capstan could be used to control wireline tension, but would not be required for the Tuffline® cable in normal operation.

3.4.7 Borehole Qualification for Wireline Emplacement

Once borehole and surface facility construction are complete in preparation for waste emplacement, borehole qualification would proceed. Qualification would consist of monitoring the borehole fluid level and acoustic emissions, and surveying the casing or wireline condition, over a period of a few weeks or months. The objective would be to increase confidence in borehole and casing stability over the projected duration of waste emplacement.

Immediately prior to emplacing each WP, an acoustic caliper log and radiation detector, and a gauge ring with junk basket would be run. The acoustic caliper produces a detailed image of the inner surface and the geometry of the casing; it can be run at normal logging speed and it operates in large-diameter casing. The radiation detector would identify waste leakage into the borehole fluid. The gauge ring would be sized slightly larger than the WPs, and any particles that it strained from the mud or dislodged from the casing (i.e., junk) would be collected in the basket for inspection.

3.4.8 Waste Emplacement Steps

The steps for emplacing a WP in the EZ of the borehole in this conceptual design are summarized below. These steps would start after the WP has already been transferred from the transportation cask to the transfer cask (Section 3.3.4) and the side latch has been engaged. Many of the following listed steps would be performed remotely.

- Open the wellhead valve (or BOP).
- Verify the condition of the borehole by running a gauge ring with junk basket, and other logs as discussed above.
- Close the wellhead valve.
- Pull the transfer cask out of the transfer shield pocket.
- Rotate the transfer cask to a vertical orientation using a portable crane.
- Place the wellhead carousel in the first position, the one that is used for removing the transfer cask shield plug (Figure 3-20).
- Lower and secure the transfer cask into the opening of the wellhead carousel.
- Remove a small plug in the top shield of the transfer cask.
- Attach a tool string containment tube to the top of the transfer cask.
- Attach the wireline latch to the top of the WP.
- Verify the wireline latch is secure by performing a pull test, leaving slack in the line.
- Remove the lower transfer cask shield plug by remote operation.
- Rotate the carousel to the second operating position, over the borehole.
- Take up the slack in the wireline and release the side latch.
- Open the wellhead valve.
- Lower the WP to the downhole emplacement position, verifying its position using geophysical logs. The descent rate would be 0.5 ft/sec for the first kilometer, then 2 ft/sec thereafter.
- Set the package on the bottom, or on the previous package emplaced.
- Disconnect the wireline tool string from the WP by activating the electromechanical release.
- Hoist and re-spool the wireline and tool string. The ascent rate of the wireline would be 4 ft/sec.
- Close the wellhead valve.
- Drain any fluid in the transfer cask.

- Rotate the carousel back to the first position and reinsert the lower shield plug in the transfer cask.
- Disconnect the tool string containment tube from the transfer cask.
- Move the transfer cask to a wash-down area for cleaning, inspection, and preparation for receipt of another WP.
- Clean and inspect the tool string and its components, and prepare the tool string and its components for the next use.
- Repeat steps 1 through 25 to emplace additional packages.
- At specified intervals (up to every 40 packages or more frequently) set a drillable bridge plug, preferably on coiled tubing using pressure, and install a cement plug following the recommend cementing option (Section 3.1).

3.5 Normal and Off-Normal Emplacement Operations

The wireline emplacement steps presented in Section 3.4 are based on normal operations, i.e., no off-normal events occur before the disposal borehole is loaded, sealed, and plugged. Anticipated normal conditions during emplacement operations are described in Section 2.2. The outcome for normal conditions is that all WPs are emplaced as intended in the EZ of the disposal borehole without any WPs being breached prior to closure or becoming stuck in the borehole.

However, as with any engineered system, equipment failures and human errors could occur resulting in off-normal outcomes. Five general off-normal outcomes from emplacement operations have been developed:

A. **Waste package becomes stuck and breached above the EZ**. If the WP can be removed, then the borehole would be decontaminated, sealed, and plugged afterward. If the WP cannot be removed, the borehole would be decontaminated to the extent possible, sealed, plugged, and monitored with the stuck package left in place. (Efforts to free a stuck package would be intensive to avoid this undesirable outcome.)

B. **One or more waste packages are breached in the EZ**. The packages would be left in place and the borehole decontaminated, sealed, and plugged. Further waste emplacement operations would be terminated in the borehole.

C. **Waste package is dropped and comes to rest intact (unbreached) within the EZ**. Junk such as wireline tools or cable may also be dropped on the package. The borehole would remain available for emplacing additional WPs, after “fishing” as necessary and installation of a cement plug above the dropped WP.

D. **Intact (unbreached) waste package becomes stuck in the EZ**. The stuck package would be left in place and the borehole sealed, and plugged. Further waste emplacement operations would be terminated in the borehole because of the potential for additional packages to become stuck.

E. **Intact (unbreached) waste package becomes stuck above the EZ**. If the WP cannot be removed, the borehole would be sealed, plugged, and monitored with the stuck package left in place. (Efforts to free a stuck package would be intensive to avoid this undesirable outcome.)

Another possible off-normal occurrence is dropping the WP in air, not in the borehole, possibly during a transfer or transportation cask lift. Such a drop could result in WP breach or an intact WP being out of position above the ground surface. Note that the terminal sinking velocity in the borehole would be reached with a moderate drop in air of only 1 to 2 ft. This occurrence was not considered in the emplacement mode selection study because it does not discriminate between the two emplacement options considered. However, the possibility of drops during handling and transfers at the surface would be thoroughly evaluated in the development of a DBD system.

Some of the basic events that were identified as primary events in the wireline fault tree that result in one of the five possible outcomes, include

- Human error
- Overtension of the wireline due to winding the wrong way against the stops
- Breakage of the wireline due to accumulated damage
- A WP getting stuck on debris such as residual cement from setting plugs
- A WP getting stuck because of casing collapse
- Misassembly of the cable head

Other off-normal events that could occur during emplacement include seismic events, receipt of an incorrect WP, failure of the transfer system at the surface, boiling of emplacement fluid, and errors in the installation of cement plugs. This latter list of events was not considered in Appendix C because it would not discriminate between the two emplacement options considered. The events described above serve as examples of off-normal events, and do not represent an exhaustive list of all off-normal events that would need to be considered if a DBD site is designed, built, and licensed.

The probability of occurrence of many off-normal events, or the severity of the consequences, can be reduced significantly by the use of functional safety controls, appropriate routine inspection and maintenance, and a robust quality assurance/quality control program. A functional safety system would consist of sensors and programmable logic, to implement interlocks that mitigate human errors and equipment malfunctions. For example, the safety system would not allow the wellhead valve to be opened unless the wireline were connected and tensioned and the side latch engaged. Such a system could reduce the probability of dropping a WP into the borehole. Routine inspection and maintenance of the wireline and other critical components could reduce the probability of wireline failure, thus reducing the probability of dropping a WP into the borehole. A robust quality assurance/quality control program would decrease the probability of human error when the package release mechanism is assembled, which occurs every time a package is emplaced.

4 SUPPORTING ENGINEERING ANALYSES

This section presents the engineering analyses that were conducted to support the reference design for DBD and the conceptual design for the DBFT engineering demonstration presented in the previous sections. Section 4.1 presents a stress analysis that is used to develop some of the assumptions made in Section 2.4 and to support WP design (Section 3.2). Sections 4.2 and 4.3 present thermal analyses that are used to support the WP design assumption that the WP temperature will not exceed 250°C (Section 2.4). Section 4.4 presents shielding calculations that support transfer cask design (Section 3.3.3).

4.1 Package Stress Analysis

Stress analyses were performed for four WP options. This section presents finite-element stress and thermal analyses of selected package concepts, performed using SolidWorks Simulation® software. Analyses are conducted at ambient temperature unless specified otherwise. Package FoS values are reported for yield strength that is reduced by an estimated 10% at 170°C compared to normal yield strength (20°C).

The dimensions of each of the four WP options are shown in Table 4-1. The maximum external diameter includes any secondary gripping features for design options 1 and 3 and the external upset for threads for options 2 and 4. The minimum inner diameter captures the reduction in the opening due to the sealing plugs for each of the design options.

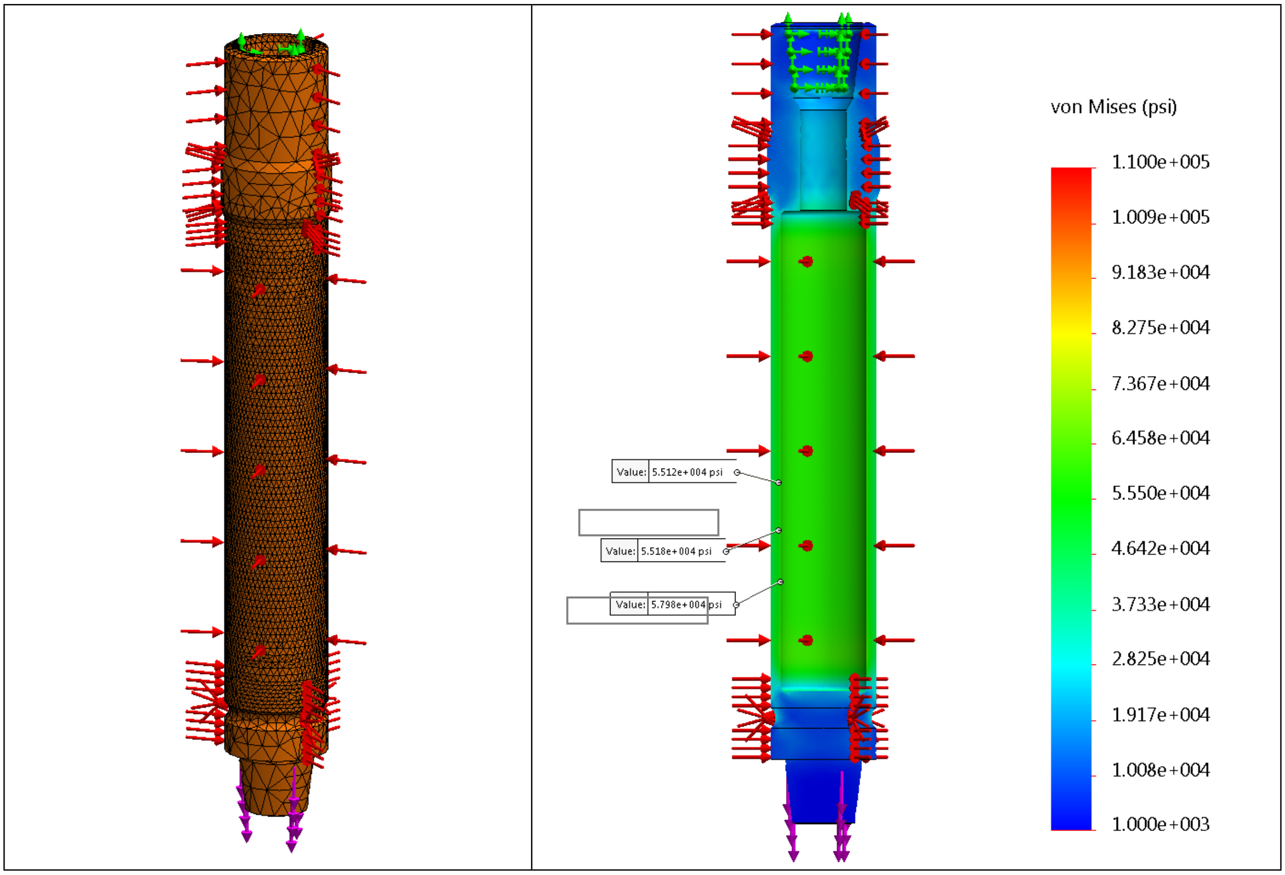
Table 4-1. Waste package dimensions for stress analysis

Package Design Concept Option	Nominal OD (in)	Nominal ID (in)	Max OD (in)	Min ID (in)	Weight (lb) [A]
1	10.75	8.75	11.50	6.00	2415
2	10.75	8.75	11.46	8.75	2200
3	5.00	4.00	5.40	2.8	510
4	5.00	4.00	5.36	4.0	500
[A] Listed weight provides 197 in (5 m) internal cavity length, without waste.					

Note that the following calculations used a downhole hydrostatic pressure of 9,600 psi, compared to the value of 9,560 psi described in Section 3.2. and discussed in Section 2.6 (the results presented here are not significantly affected by the difference).

4.1.1 Stress Analysis for Packaging Concept Option 1

A stress analysis of the design was performed using SolidWorks Simulation. An external pressure of 9,600 psi was applied over the exterior surfaces. An axial tension force of 154,000 lb (representing buoyant weight of a string of 40 packages) was applied through the threaded connection. The results of the stress analysis are shown in Figure 4-1. As expected, the highest von Mises stresses (a measure of the maximum multi-axial stress state for comparison to yield strength under uniaxial tension) are in the tubular section of the package. The external loads result in a von Mises stress of around 58 ksi at the inner wall of the package.



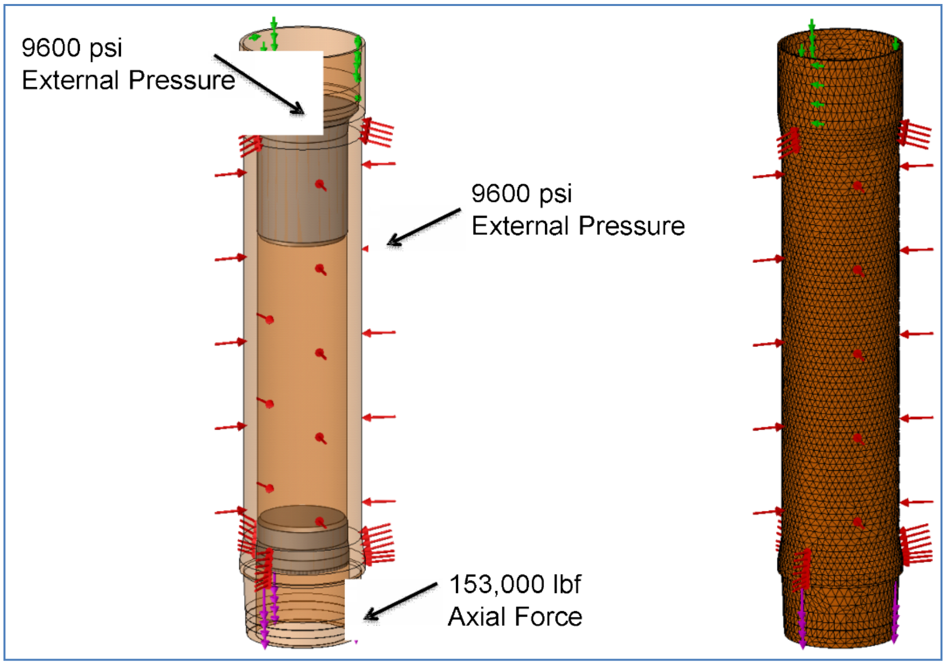
Note: Package aspect ratio shortened for illustration.

Figure 4-1. Option 1 stress analysis with 9,560 psi external pressure and 154,000 lb tension.

With a standard high-collapse grade casing of P110 with a material yield strength of 110 ksi (Section 2.6) reduced to 95.7 ksi at downhole temperature, the FoS is around 1.65, which is less than value of 2.0 discussed in Section 2.3. An alternative material choice would be a Q125 grade casing or equivalent which would provide a FoS of approximately 2.0.

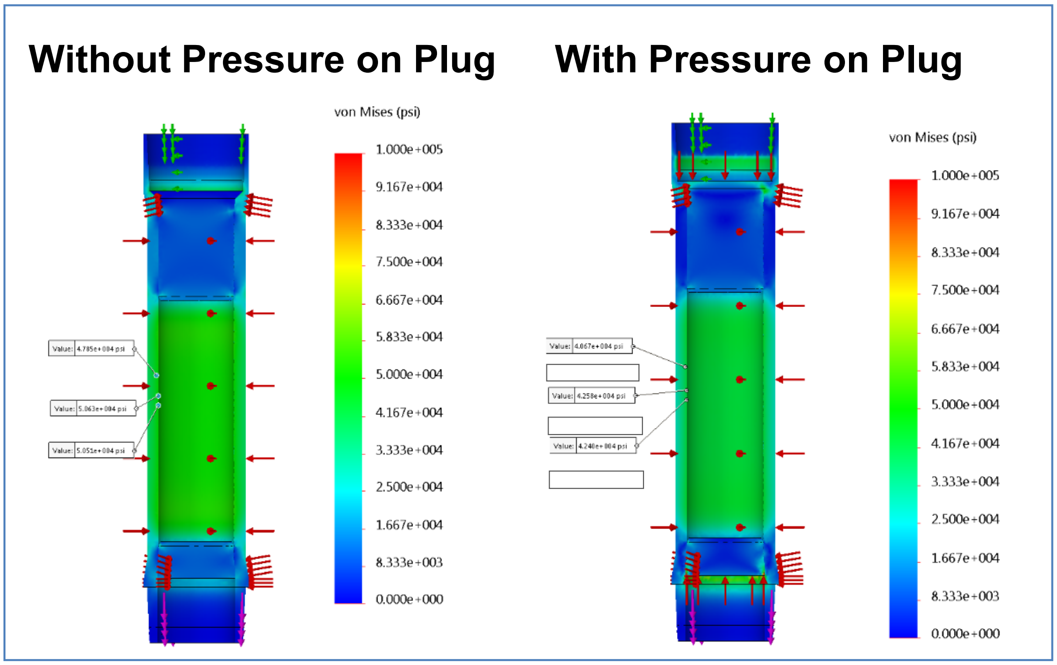
4.1.2 Stress Analysis for Packaging Concept Option 2

Two configurations were analyzed: 1) threaded connections between packages leak, so that borehole pressure reaches the internal plugs (Figure 4-2 and Figure 4-3); and 2) threaded connections between packages do not leak. The contact between the plugs and the overpack body is treated as a bonded line contact at a sealing weld. The rest of the contact between the plug and body is treated as a non-penetrating interface between bodies. The hydrostatic and axial tension force conditions were the same as used for analysis of Option 1. If external pressure reaches the plugs, the maximum von Mises stress at the inner surface of the tubing is approximately 40 ksi (Figure 4-3). If the connection does not leak, the maximum stress is approximately 46 ksi (FoS = 2.1 for nominal yield strength of 110 ksi, reduced at temperature). This reduction in overall stress occurs because the compressive axial load imparted by the external pressure acting directly on the plugs reduces the net stress on the overpack.



Note: Package aspect ratio shortened for illustration.

Figure 4-2. Option 2 simulation loads and mesh.

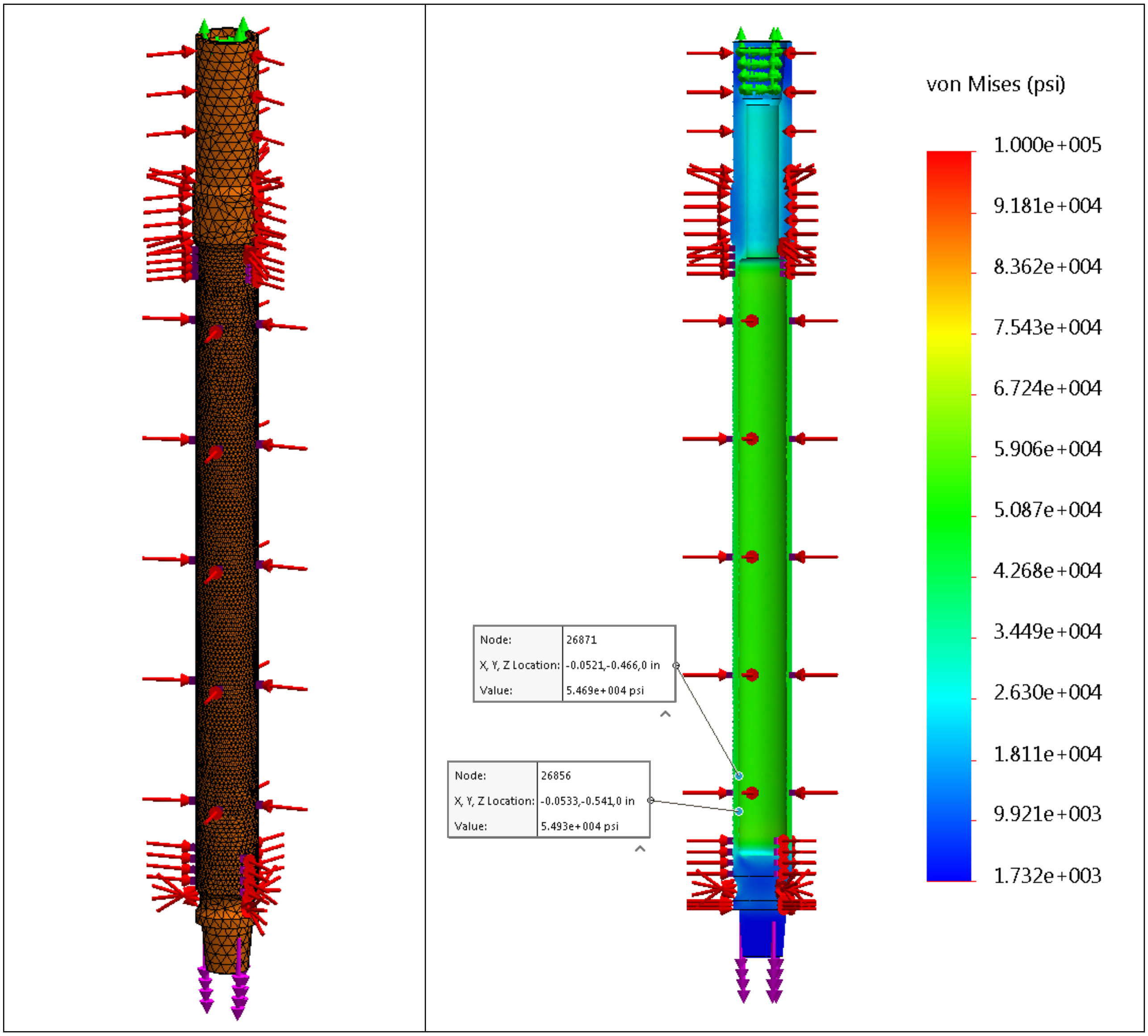


Note: Package aspect ratio shortened for illustration.

Figure 4-3. Option 2 stress analysis.

4.1.3 Stress Analysis for Packaging Concept Option 3

A 9,600 psi external pressure was applied over the entire overpack, and an axial tensile load of 27,600 lb simulating a string of small diameter packages on the bottom in the EZ. The stress analysis results are consistent with analytical calculations for external pressure and axial loading (Figure 4-4). For the combined loading, the maximum von Mises stress at the inner surface of the casing is approximately 55 ksi (FoS = 2.0 for nominal yield strength of 125 ksi, reduced at downhole temperature).



Node: 26871
X, Y, Z Location: -0.0521,-0.466,0 in
Value: 5.469e+004 psi

Node: 26856
X, Y, Z Location: -0.0533,-0.541,0 in
Value: 5.493e+004 psi

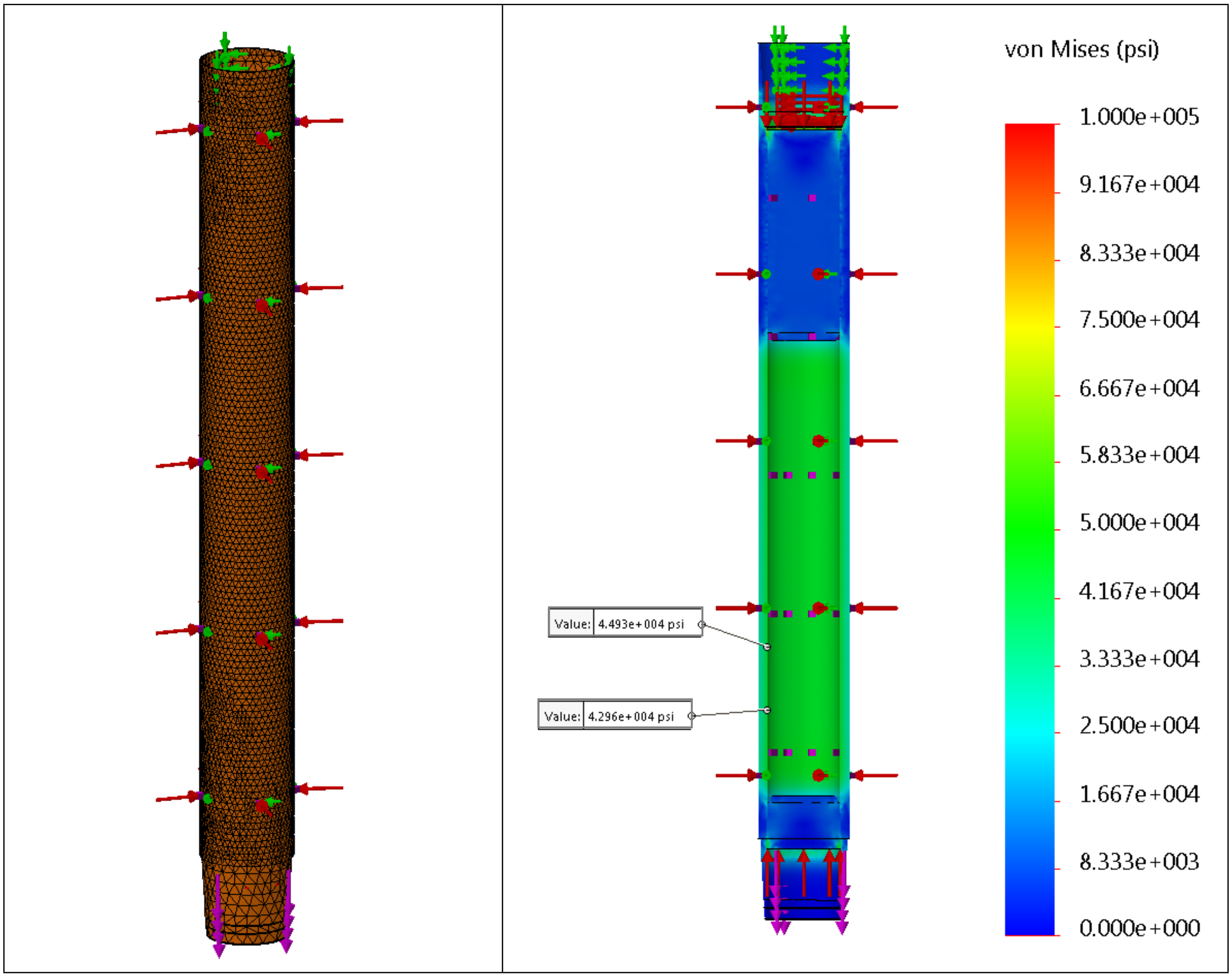
Note: Package aspect ratio shortened for illustration.

Figure 4-4. Option 3 stress analysis.

4.1.4 Stress Analysis for Packaging Concept Option 4

The loading conditions for the analysis are the same as in the previous option. A 9,600 psi external pressure is applied over the entire overpack. Axial tensile load of 27,600 lb is applied at the joint. For stress analysis, the borehole pressure is assumed to reach the inner plugs which leads to greater maximum stress in the body tube.

The stress analysis results are consistent with the analytical calculations for external pressure and axial loading (Figure 4-5). For the combined loading, the maximum von Mises stress at the inner wall of the tubing is approximately 45 ksi (FoS = 2.4 for nominal yield strength of 125 ksi, reduced at temperature).



Note: Package aspect ratio shortened for illustration.

Figure 4-5. Option 4 stress analysis.

4.1.5 Package Mechanical Response Analyses

4.1.5.1 Energy Needed for Package Breach

According to Section 2 of API Bulletin 5C3 (API 1994) the yield strength collapse pressure (P_{yp}) for a pipe with yield strength (Y_p) under external pressure is given by Eq. 4-1. This criterion is based on the Lamé thick-wall elastic solution and actually predicts the onset of yielding at the inner surface (Staelens et al. 2012). It is applicable to the tubular portion of the packaging and is valid when the OD divided by wall thicknesses (D/t) is less than 12.42.

$$P_{yp} = 2Y_p \left[\frac{\left(\frac{D}{t}\right) - 1}{\left(\frac{D}{t}\right)^2} \right] \qquad (4\text{-}1)$$

If the pipe is also subjected to tensile axial stress, then the yield strength is modified (Y_{pax}) to account for axial stress (S_A):

$$Y_{pax} = Y_p\left\{\left[1 - \frac{3}{4}\left(\frac{S_A + P_{ax}}{Y_p}\right)^2\right]^{1/2} - \frac{1}{2}\left(\frac{S_A + P_{ax}}{Y_p}\right)\right\} \tag{4-2}$$

where P_{ax} is the axial stress contributed by external pressure, and S_A is the additional axial tensile stress. This relationship can be used as a check on the stress magnitudes (and factors of safety) calculated by the finite element method.

Axial tension has a detrimental effect on collapse pressure while axial compression has a beneficial effect on the collapse-pressure rating. The benefit of compressive axial load on collapse pressure rating is typically ignored to maintain a conservative rating (Bourgoyne et al. 1986).

4.1.5.2 Effect of Bending or Borehole Curvature

Borehole curvature could, in principle, produce additional stress in the package wall due to bending. Bending was analyzed previously for strings of packages threaded together, for drill-string emplacement (SNL 2015). For wireline emplacement of single packages, 18.5-ft packages would not make bending contact with 13-3/8 inch guidance casing, if dogleg severity is limited to 3°/100 ft. If the package axis is parallel to the casing axis at its midpoint, then the deviation over half the package length (1/2 × 18.5 ft) × tan(1/2 × 18.5 ft × 3°/100 ft) is 0.55 inches, or less than the diametral clearance between the package and the casing (nominally 1-3/8 inches). Therefore, even for the maximum package length (18.5 ft) bending due to allowable borehole curvature is not geometrically plausible. Addition of a wireline tool string to the package would increase the effective diametral clearance if the tool string has smaller diameter.

4.1.5.3 Loading Due to Impact

This calculation provides an estimate of the effect of falling packages striking a stationary package at the bottom of the borehole, or the impact on the lowest package in a string falling on the bottom. It is a simple fragility analysis, intended to characterize the difference in potential damage resulting from a single package drop, compared to a string of packages.

Assume that the speed of the packages is known and the kinetic energy of the falling packages is converted to strain energy in the stationary package.

The kinetic energy of the moving/falling packages is given by

$$KE = \frac{1}{2}mv^2 \tag{4-3}$$

where m is the mass of the packages and v is the speed at impact.

The maximum strain energy due to a change in length of the package is given by

$$U = \frac{E \cdot A \cdot \delta_{\max}^2}{2L} \tag{4-4}$$

where E is the modulus of elasticity, A is the area of the package body, L is the pre-impact nominal length, and δ_{max} is the change in length due to the impact load.

The static deflection in the stationary package due to the weight of the falling packages is given by

$$\delta_{static} = \frac{W \cdot L}{A \cdot E} \tag{4-5}$$

Assume all kinetic energy is absorbed as strain energy. This is a conservative estimate in that in reality, a portion of the impact will be converted to plastic deformation and heat.

Solving these equations for δ_{max} gives the following expression for the maximum deflection in the package.

$$\delta_{\max} = \sqrt{\frac{m \cdot v^2 \cdot L}{A \cdot E}} \tag{4-6}$$

The corresponding maximum stress is given by

$$\sigma_{\max} = \sqrt{\frac{m \cdot v^2 \cdot E}{A \cdot L}} \,. \tag{4-7}$$

For packages each weighing 4,620 lb (2,100 kg mass) falling at 8 ft/sec (2.5 m/sec), the force imparted on the impacted stationary package vs. the number of packages is shown in Figure 4-6. This would suggest that approximately 20 packages moving at 2.5 m/sec impacting a stationary package would generate a maximum axial stress of around 105 ksi. For a 10.75-inch OD × 8.75-inch ID large size reference package, the corresponding impulsive axial force is shown in Figure 4-6.

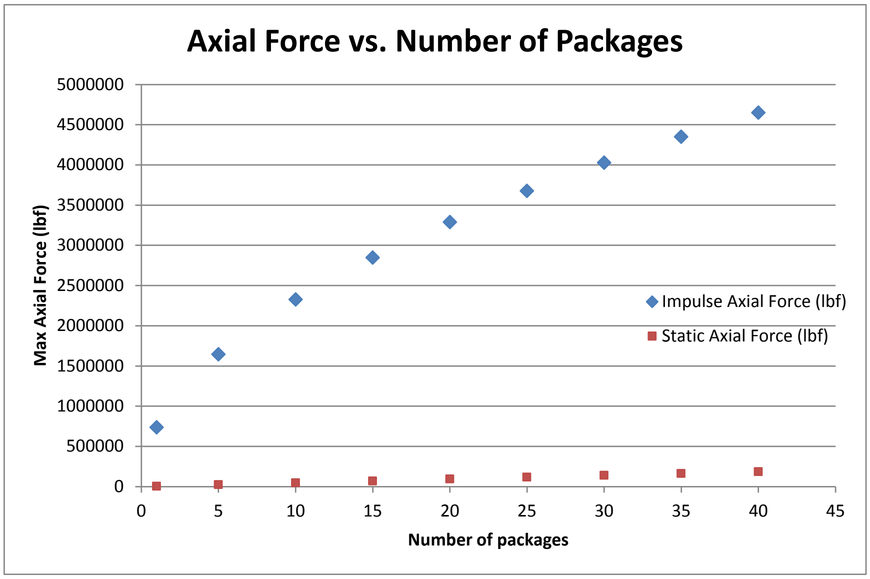


Figure 4-6. Static and impulsive axial force due to falling waste packages (reference package).

A similar estimate of impulse forces was made for small (slim) packages containing eight Cs/Sr capsules arrayed end-to-end (Table 2-1 and Table 3-2). Assuming each such overpack and its contents weigh 880 lb, with sinking velocity as noted above, the impulsive forces imparted to an impacted package are shown in Figure 4-7.

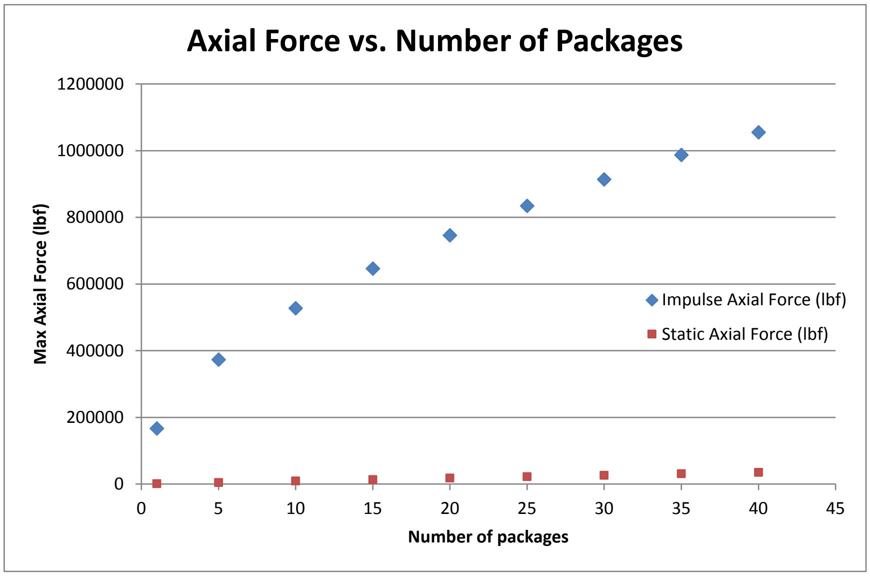


Figure 4-7. Static and impulsive axial force due to falling waste packages (small package).

Using these impulse force estimates as external loads, several quasi-static finite element simulations were conducted to determine the additional stresses using the flask-type package concept. The properties of steel were assumed for the package, with linear elastic behavior. The additional axial load is combined with the external pressure from the weight of the emplacement fluid as shown in Figure 4-8. The additional load is assumed to be applied eccentrically over a 40° sector on the face of the box end of the package. The material yield strength was set to 110 ksi for the analysis.

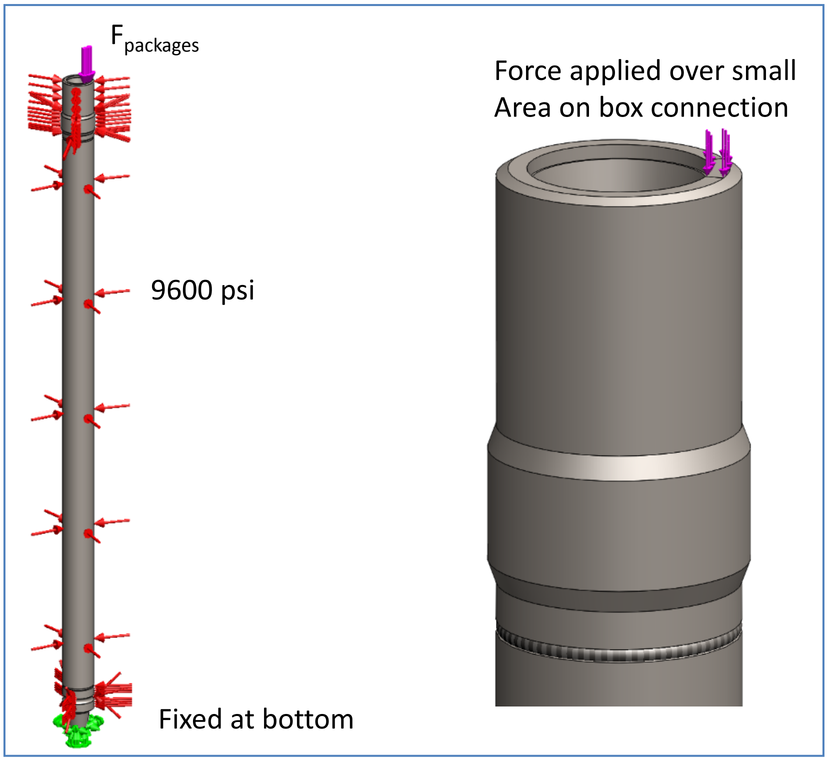


Figure 4-8. Waste package loading conditions.

Stress contours due to impact force levels for both for the reference and small (slim) package are shown in Figure 4-9 and Figure 4-10, respectively. For a single package, there will likely be localized yielding in the contact region. Beyond the contact region, there are stress concentrations in the joint between the box and the tubular package body. Stresses in the tubular section remain uniform and are approximately 55 ksi due to a combination of axial load, external pressure, and bending due to the eccentric load.

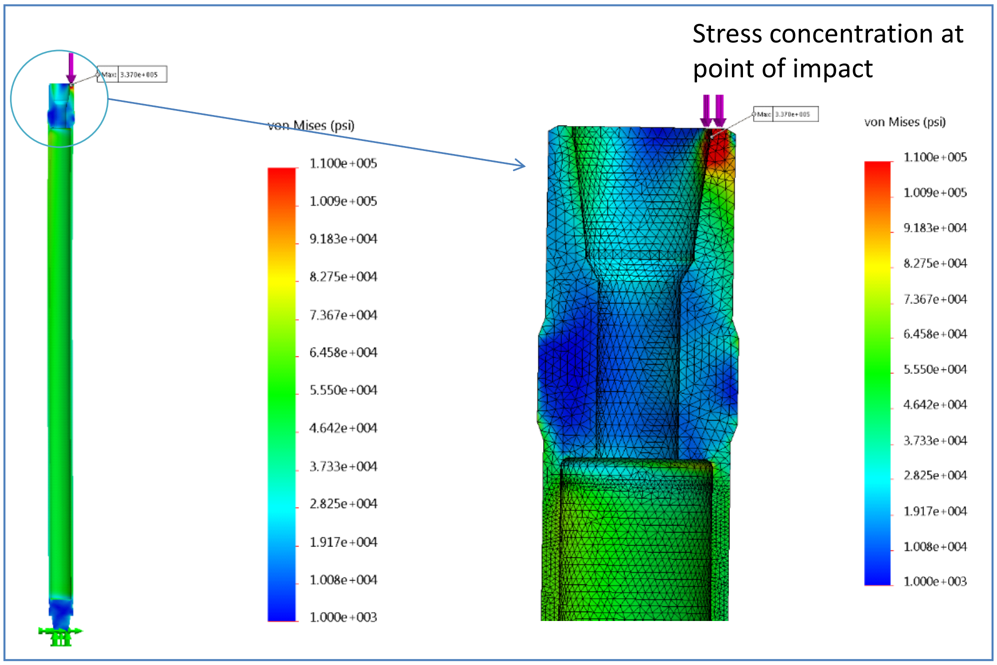


Figure 4-9. Calculated stress from impact of a single reference-sized WP falling at terminal velocity.

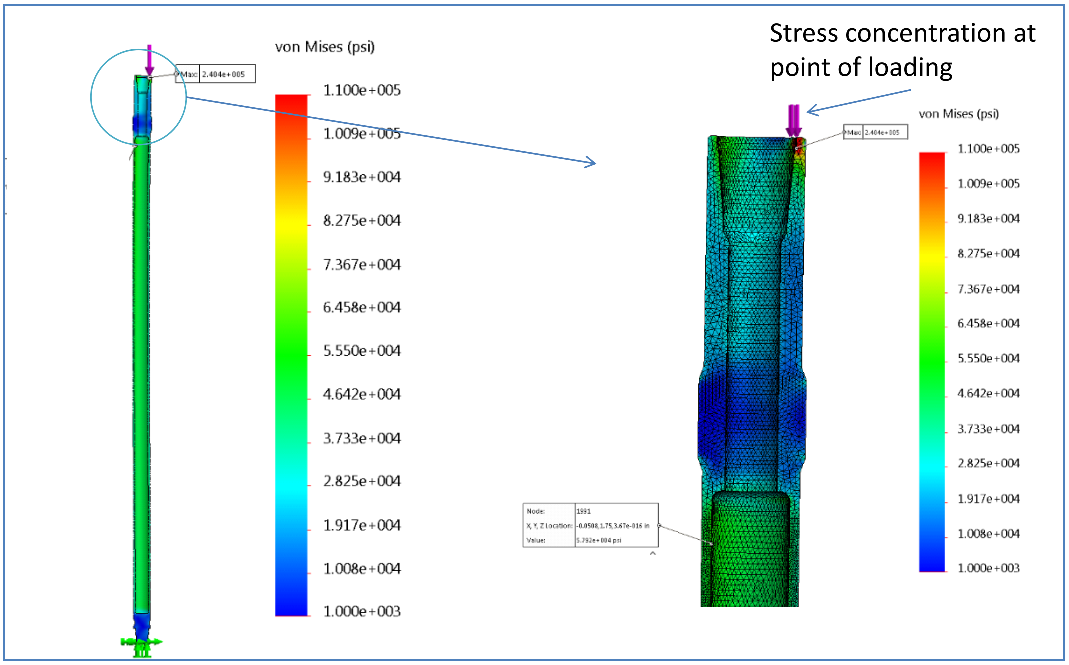


Figure 4-10. Calculated stress from impact of a single small size (slim) WP falling at terminal velocity.

The conclusion from this study is that the impact from dropping any assembly heavier than a single package would likely lead to yielding and significantly increased likelihood of package breach. Use of impact limiters would help to ensure that no breach could occur from dropping a single package.

4.1.6 Fluid-Filled Waste Package

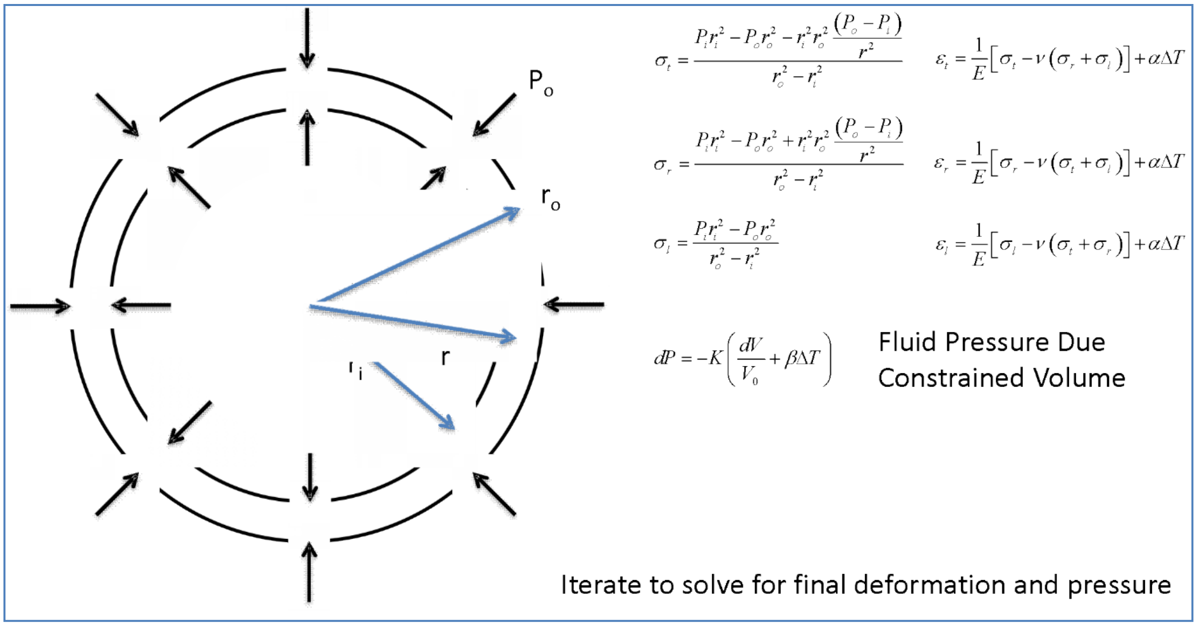
The FoS requirement along with the high differential pressure between the inside and outside of the package result in a thick-wall design which reduces the available waste disposal volume. One possible way to limit wall thickness while maintaining the desired FoS is to balance the internal and external pressure. Contraction of the internal volume due to external pressurization, and expansion of an internal, compressible fluid (water) are considered in the analysis.

An analytical model of a simplified package was constructed to estimate the impact of having a fluid-filled volume. The internal pressure is initially at 1 atm when filled and sealed at the surface. As the package is lowered into the borehole, temperature and external pressure both increase. The interior volume change, and the net volumetric thermal strain, create a pressure change proportional to the bulk modulus of the filling fluid.

Key assumptions in the analysis are as follows:

- Internal volume is completely full of de-gassed fluid (water)
- Adiabatic process (no heat produced from external pressure)
- Bulk modulus of fluid (K) is constant over the temperature range (20 to 170°C)
- Use a constant value of the volumetric coefficient of thermal expansion (β) for fluid
- Constant external pressure (9,600 psi)

Figure 4-11 shows the Hooke's law relationships for a cylindrical pressure vessel. The stress relationships are used to solve for the resulting strain in the package. The change in strain is then used to estimate the change in volume of the vessel. The pressure in the interior of the package is found by iterating until the internal pressure balances the external pressure based on the change in strain.



Note: Symbols use nomenclature of Bourgoyne et al. (1986).

Figure 4-11. Internal fluid pressure illustration.

The basic calculation sequence is as follows:

1. Apply external pressure to package
2. Calculate the change in internal volume due to the external pressure
3. Calculate the change in internal fluid pressure due to volume change and temperature change
4. Calculate net change in strain due to external and internal pressure
5. Iterate until the internal pressure converges.

For example, if the package is filled with water and then pressurized externally to 9,600 psi, with no change in temperature, the internal pressure would be approximately 1,000 psi (Figure 4-12). The converged solution for pressure and temperature changes is shown in Figure 4-13.

For a relatively incompressible fluid like water, external pressure acting on a steel package could create an internal pressure of approximately 1,000 psi. Adding thermal expansion, this pressure is much greater (Figure 4-13) and could provide additional margin of safety (assuming corrosion and other interactions between the filling fluid, packaging, and waste forms are limited).

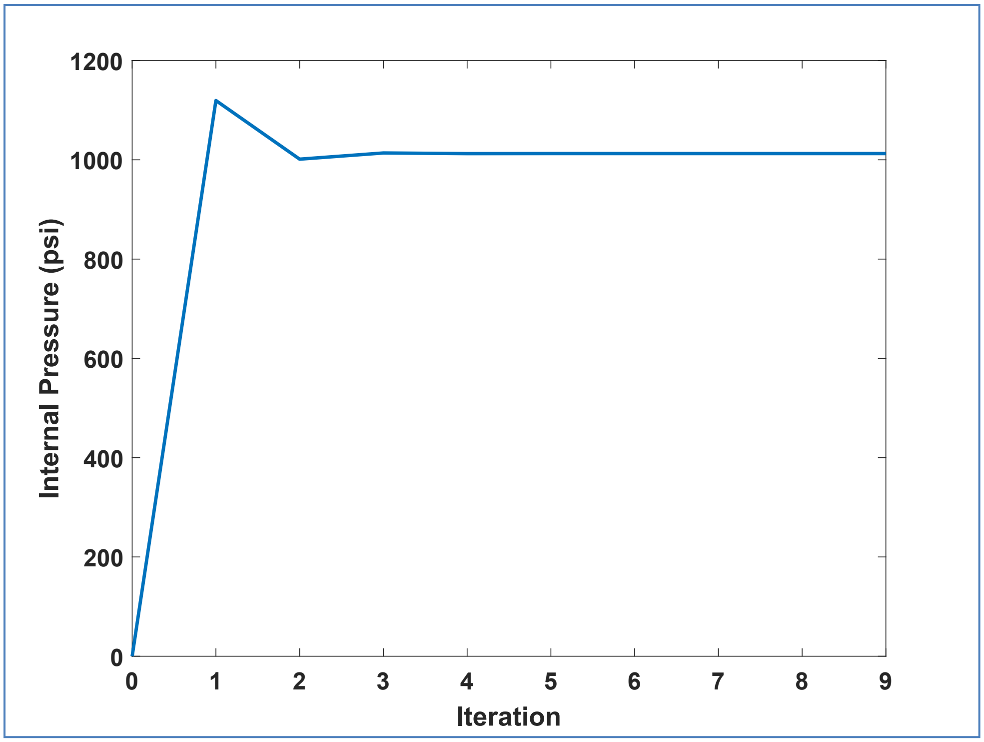


Figure 4-12. Internal fluid pressure iteration for ΔT = 0.

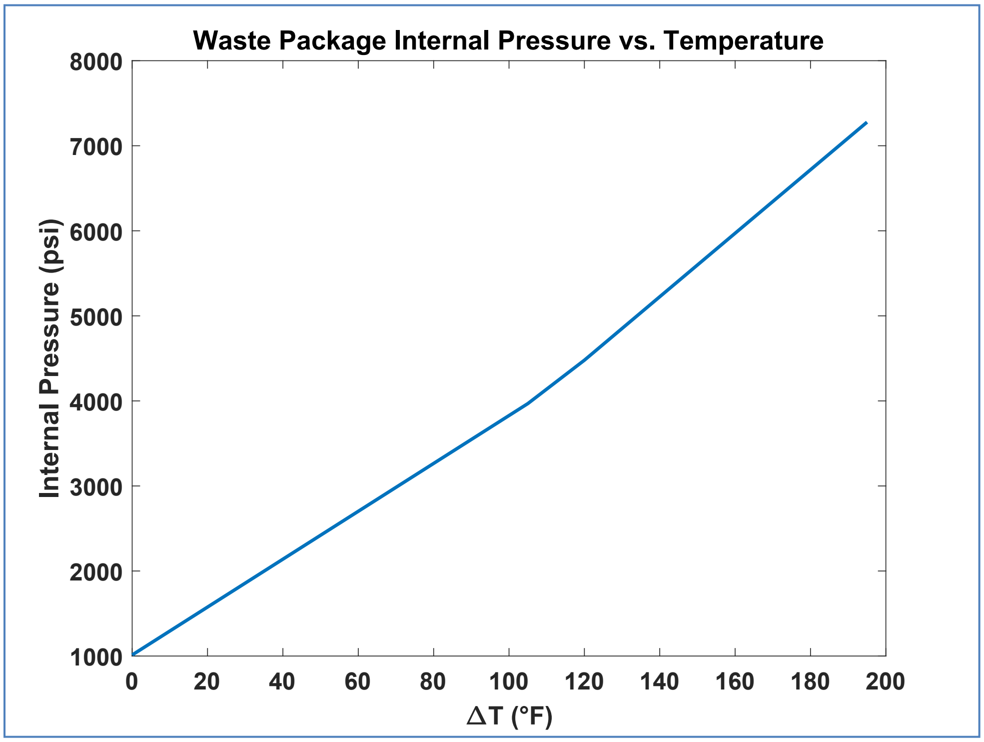


Figure 4-13. Internal fluid pressure vs. temperature and 9,600 psi external pressure.

4.2 Internal Package Heat Transfer

A detailed thermal analysis including internal package temperatures was conducted to investigate the temperature response of packages containing heat-generating waste. The main concern is peak temperature of waste packaging, and resulting strength reduction, during emplacement and plugging/sealing operations, prior to permanent closure.

The package size selected for analysis is the medium size (Table 2-1) internal semi-flush design (Section 2.6) configured to contain Cs/Sr capsules in bundles of three ("3-packs") arranged in thin-walled "universal canisters" stacked six high (18 capsules per package). This configuration would be an efficient way to handle the capsules from the point of origin (Price et al. 2015) and could accommodate the universal canisters (Figure 4-14 and Figure 4-15). All 1,936 capsules could be packaged in about 108 packages and emplaced in a 12-1/4 inch borehole within a depth interval of less than 600 m. Dimensions of the WP containing the universal canister are given in Table 4-2. In this table, the maximum OD is the diameter of the external upset for threads.

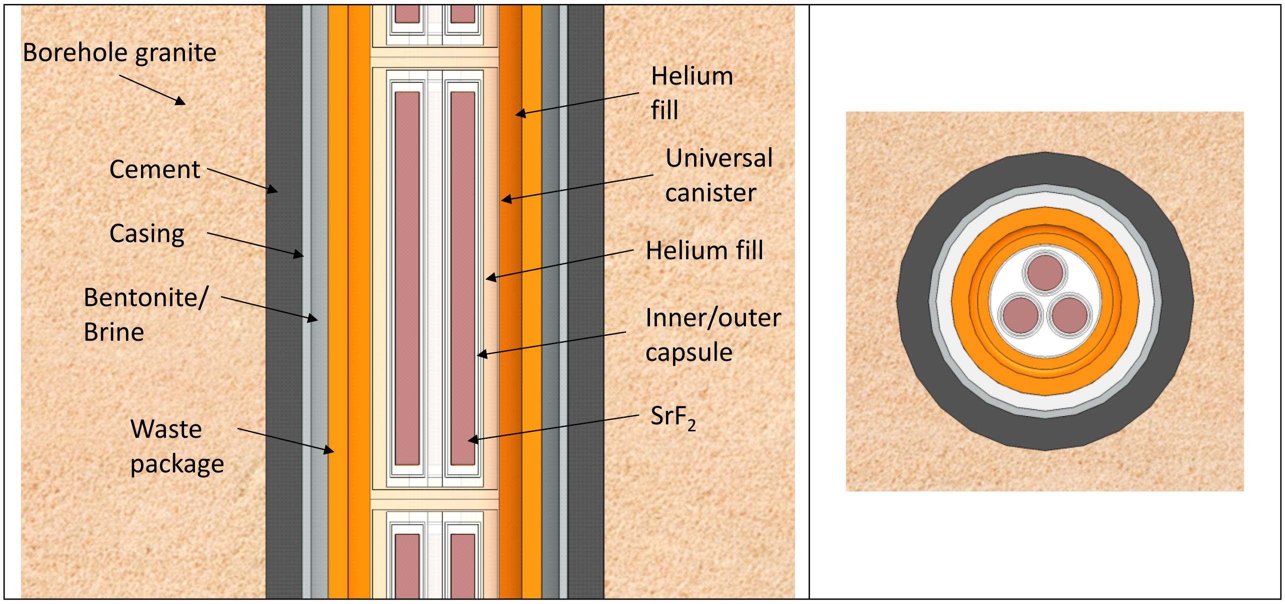


Figure 4-14. Waste package configuration within borehole, for finite element thermal model.

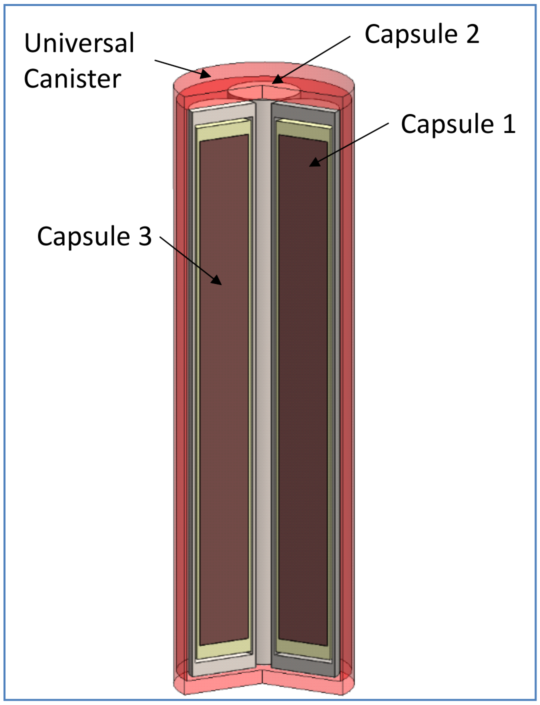


Figure 4-15. Universal canister with three capsules.

Table 4-2. Waste package dimensions for thermal analyses

Nominal OD (in)	Nominal ID (in)	Max OD (in)	Min ID (in)	Weight (lb)[A]
7.625	6.625	8.01	6.625	460
[A] **Listed weight provides 135-inch internal cavity length, without waste which could add an additional 792 lb (at 44 lb per capsule with basket).**				

Note that DBD of Cs/Sr capsules is not actually planned, and that the calculation described here addresses thermal feasibility only.

SolidWorks Flow Simulation CFD® (Computational Fluid Dynamics) software was used to model the thermal behavior of the capsules and canisters within the package, using solid bodies to represent actual components. This simulation software handles heat conduction in fluid, solid, and porous media with conjugate heat transfer between solids. Arrangement of the package within the borehole is shown in Figure 4-14.

4.2.1 Materials

Material properties used in the analysis are shown in Table 4-3. Borehole and casing dimensions were consistent with Table 2-1, based on Arnold et al. (2014). Bentonite was used as a surrogate for any solid material, including cement, that completely fills all voids in the EZ.

Table 4-3. Material properties.

Material	Thermal Conductivity (W/m-K)	Heat Capacity (J/kg-K)	Density (kg/m^3)
SrF_2 salt waste	3.7	425	2,940
Inner capsule layer	16.3	550	7,900
Outer capsule layer	16.3	550	7,900
Universal canister	16.3	550	7,900
Overpack envelope	17	500	7,850
Emplacement fluid (brine)	0.58	4,192	1,100
Cement	1.7	900	2700
Bentonite layer	1.7	800	2,700
Granite host rock	2.5	880	2,700

4.2.2 Initial and Boundary Conditions

The boundary of the computation domain is maintained at 135°C to represent the downhole conditions. The computational domain extends 25 m radially away from the borehole. For the brine-filled borehole, free convection is not considered. The WP is assumed to be isolated and located at hottest location in the disposal zone.

4.2.3 Model Setup

Waste packages are modeled as individual volumetric heat sources. For this analysis only strontium capsules were used because they are generally hotter than cesium capsules. Rather than use the average heat output of the strontium capsules, the simulated package was loaded with the six hottest SrF_2 three-packs (Table 4-4) that were selected using a blending algorithm that levelized 3-pack thermal output over all 601 SrF_2 capsules. Heat outputs are for 2050. The distribution of the heat sources is shown below in Figure 4-16. The heat output decays with time using the decay constant of ^{90}Sr (and decay energy including daughters).

Table 4-4. SrF_2 Blended hottest 3-pack configurations (heat output in year 2050).

	Thermal Power Output			
3-Pack ID	Capsule 1 (W)	Capsule 2 (W)	Capsule 3 (W)	3-Pack Total (W)
1	181.03	51.24	7.95	240.21
2	166.90	51.33	9.77	228.00
3	162.77	51.43	10.34	224.53
4	162.62	51.82	12.75	227.19
5	156.63	52.19	12.82	221.64
6	153.12	52.23	13.36	218.71

Within the package, universal canisters each containing three capsules were arranged end-to-end (Figure 4-16). The hottest 3-packs were placed towards the middle of the package with relatively cooler ones closer to the ends. The model mesh is shown in Figure 4-17. A higher grid refinement level was used in the borehole and the package, decreasing away from the borehole.

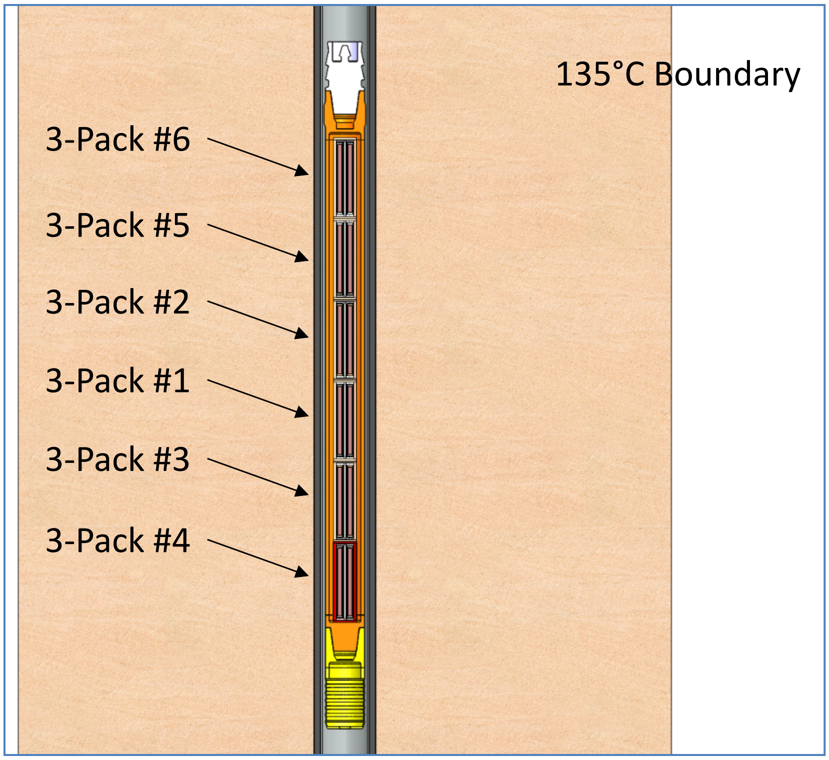


Figure 4-16. Capsule and 3-pack configuration within the waste package.

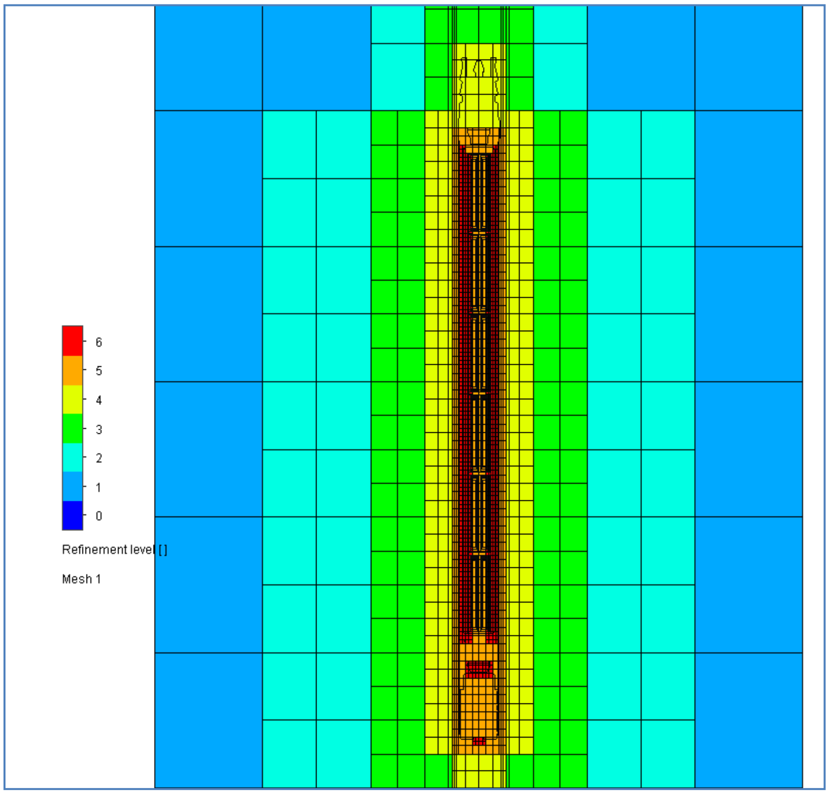


Figure 4-17. Model grid for 3-dimensional thermal simulation of SrF_2 capsule disposal.

Heat transfer in the simulations was limited to thermal conduction in solids, in helium that fills void volume within the universal canister, and in emplacement brine. Temperatures at the edge of the waste form (Capsule ID), the inside surface of the universal canister (Universal Canister ID), and the inside surface of the package (Waste Package ID), where compressive stress is greatest, were used as convergence goals for the simulations.

Simulations were conducted for a brine-filled and a bentonite-sealed borehole. Steady-state (constant heating rate) and transient (exponentially decaying) analyses were conducted for each case. For the transient analyses, the heat output decayed exponentially according to the Sr decay constant. All elements in the simulation were initialized at the *in situ* temperature and the heat output was turned on at time $t = 0$. The physical time simulated was 1,000 years starting in 2050.

4.2.4 Results

Both steady-state and transient calculations were performed. Results for both sets of calculations are presented below.

4.2.4.1 Steady-State Conditions

Under steady-state conditions, the peak WP temperatures are highest in the capsules and decrease away from the center of the WP. The difference in maximum temperatures between the brine-filled borehole and the bentonite-sealed borehole is approximately 10°C at the WP inner wall. This temperature difference is due to the low thermal conductivity of the brine compared to the bentonite/cement.

Figure 4-18 shows the simulation results for the brine-filled borehole. Temperature gradients in the WP are due to the asymmetry both axially and radially. The inner wall of the WP, which sees the highest stress, has a maximum temperature of approximately 220°C.

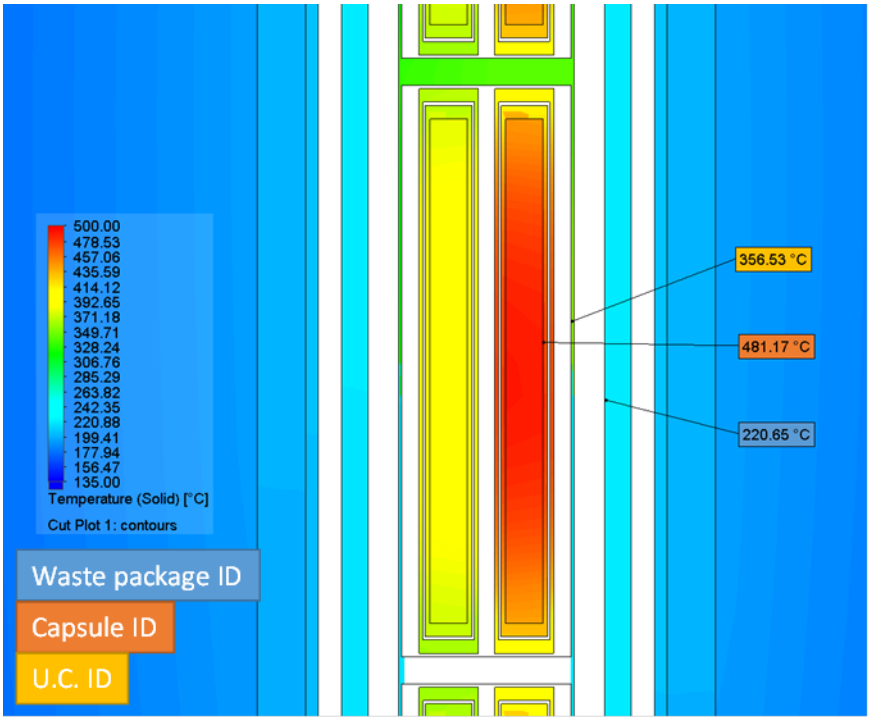


Figure 4-18. Steady-state waste package temperature distribution (brine in casing).

Figure 4-19 shows the simulation results for the bentonite-sealed borehole. The simulation results indicate that there is fluid circulation within the WP and the universal canister due to temperature gradients. The maximum temperature on the WP inner wall is approximately 210°C. The temperature rise in the region surrounding the borehole is more prominent as well.

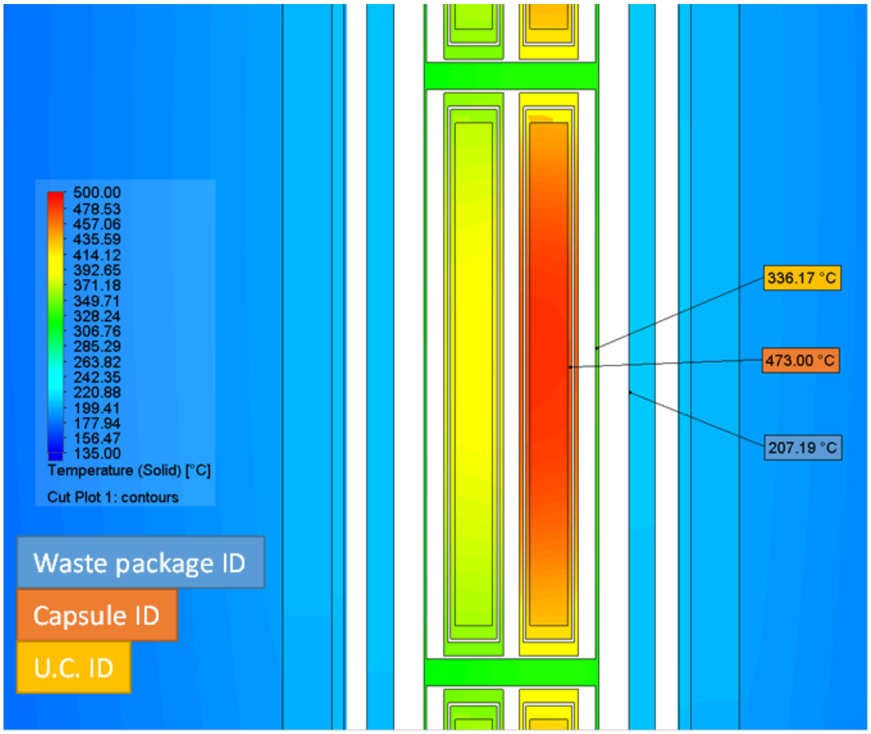


Figure 4-19. Steady-state waste package temperature distribution (sealed in bentonite).

The maximum temperatures in the WP and related components are shown in Table 4-5. These temperature values are based on ambient conditions of 135°C.

Table 4-5. Maximum steady-state-temperatures in waste package

Calculation Location	Max. Temp. (C) Brine-filled (no convection)	Max. Temp. (C) Bentonite-sealed
Waste Package ID	221	208
Capsule ID	481	473
Universal Canister ID	356	336

4.2.4.2 Transient Conditions

For the domain as modeled, the temperature rises until temperatures plateau in the WP at approximately 0.3 years (110 days) as shown in Figure 4-20. Peak temperatures in the universal canister ID are reached at around 0.6 years. Waste package ID peak temperatures are reached at approximately 0.9 years. The peak temperature values are consistent with those predicted in the steady-state simulations. Temperature briefly stabilizes at or near the peak, then begins to decay after approximately 1 year. After approximately 350 years, the WP and internal contents are within 0.1°C of the surrounding temperatures.

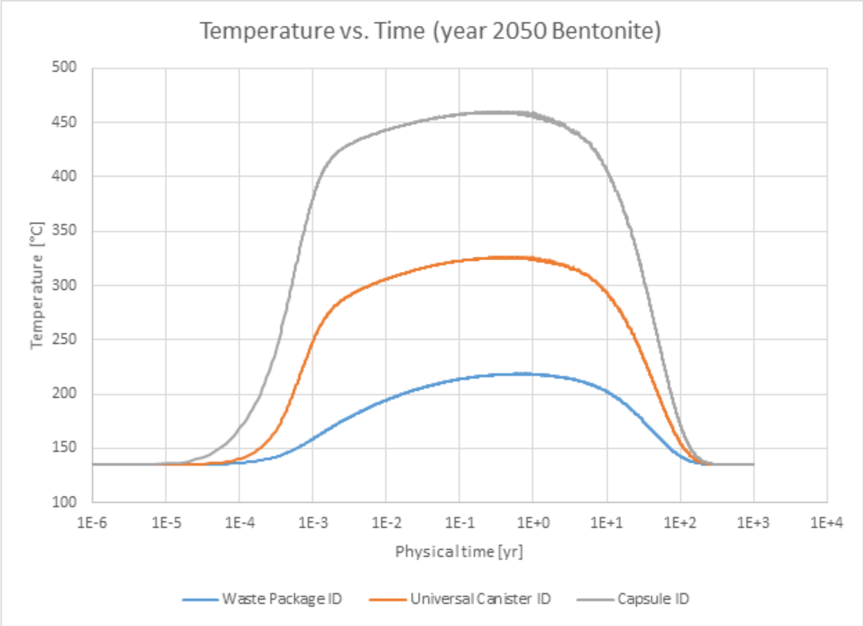


Figure 4-20. Transient temperature response of WP sealed in bentonite (log time).

A linear time scale plot of the temperature rise is shown in Figure 4-21. The rise time (90% of maximum temperature) for the WP and its contents is approximately 0.011 yr (4 days).

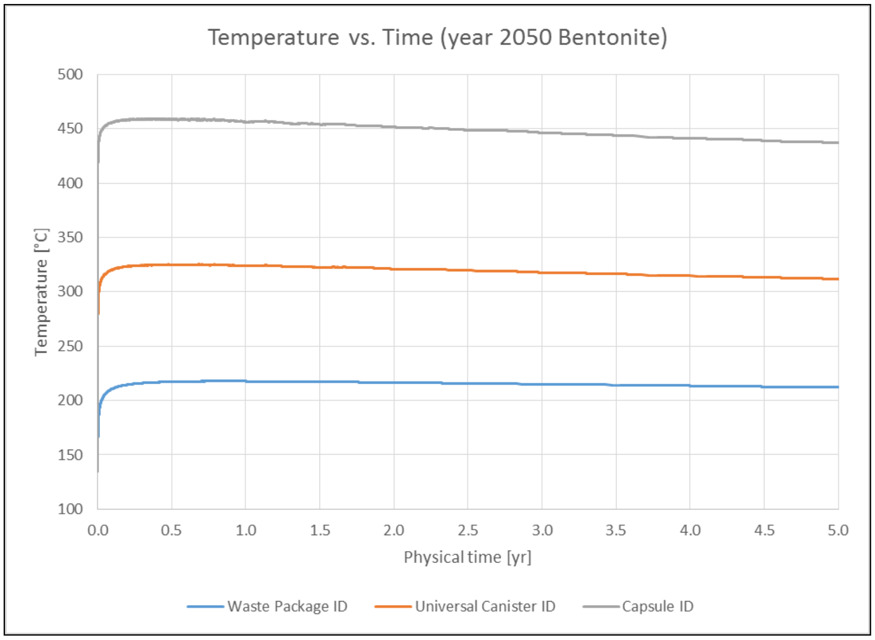


Figure 4-21. Transient temperature response of WP sealed in bentonite (linear time).

A simulation was also conducted assuming a brine-filled borehole. The results are shown in Figure 4-22 and Figure 4-23. The results show a similar behavior between the solid and brine-filled borehole. The rise time for the temperatures in the WP is approximately 0.0084 yr (3.0 days). The temperature continues to rise until approximately 0.32 yr (118 days) when it reaches a maximum value. From there, the temperature begins to drop and is within 0.1°C of the surroundings after approximately 350 years.

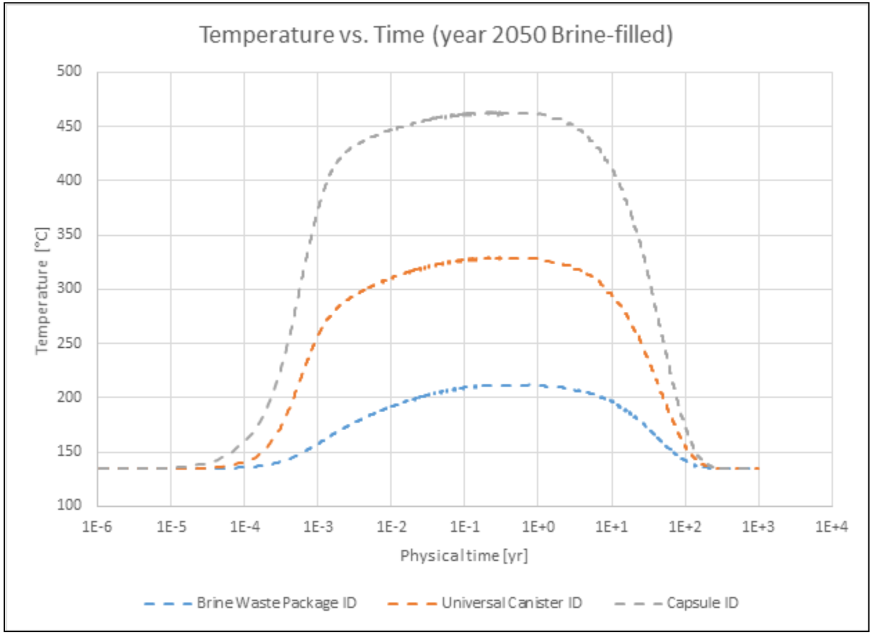


Figure 4-22. Transient temperature response of waste package in brine (log time scale).

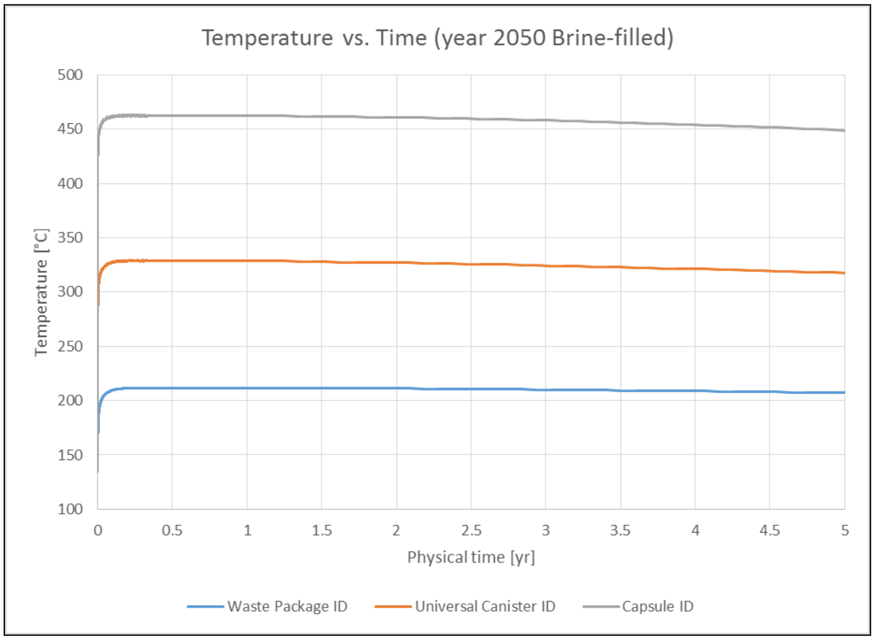


Figure 4-23. Transient temperature response of WP in brine (linear time scale).

4.3 Coupled Heat and Fluid Flow from Deep Borehole Disposal of Cs/Sr Capsules

Deep borehole disposal of Cs/Sr capsules would involve drilling a 5-km deep borehole, at least 3 kilometers of which would penetrate crystalline basement. The disposal zone would lie at the base of the borehole, where the low permeability of the surrounding rock and the great depth would hydraulically isolate the waste from the biosphere.

There are a total of 1,335 CsCl capsules and 601 SrF_2 capsules stored at the Hanford Site (SNL 2014), all of which could be disposed of in a single borehole. The current reference case calls for packing 18 capsules into each WP in an arrangement of triplets stacked six high. A total of 108 WPs would be needed, each one approximately 3.76 m in length. Even with the hardware at the ends of each package, and the cement plugs in the EZ, the entire EZ could be less than 600 m in length.

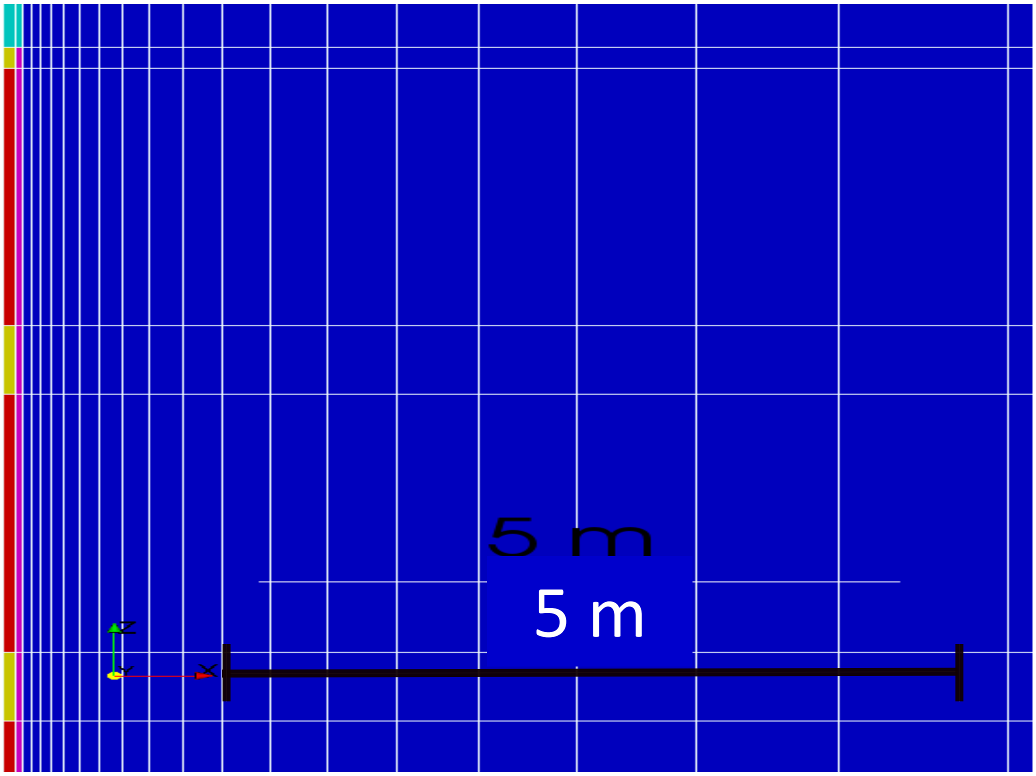
For this analysis emplacement is assumed to occur in 2050 at which time the entire heat output of all 1,935 capsules will be 114 kW (calculated from 2007 values in Arnold et al. 2014). Thermal loading is of interest for two main reasons: 1) temperature at the WP wall in excess of 250°C could lead to significantly less efficient package designs because of degraded strength properties requiring greater wall thickness; and 2) groundwater heated by the WPs would rise some distance through the borehole annulus, cement plugs, and the disturbed rock zone (DRZ) surrounding the borehole, potentially transporting radionuclides into the seal zone.

The models described below simulate the evolution of temperature, and vertical fluid flux in the borehole and the host rock, for a DBD system containing the entire inventory of CsCl and SrF_2 capsules emplaced in 2050. A range of heat output conditions is also used to represent the effects from additional decay storage.

4.3.1 Numerical Model

Simulations of coupled heat and fluid flow in a fluid saturated system were completed with PFLOTRAN, an open-source massively parallel flow and transport simulator (Hammond et al. 2011). Eight cases are presented, varying WP heat source strength among four options, and the material filling the borehole annulus between two options.

The model domain is axisymmetric with a radius of approximately 1 km, and a height of 3 km, extending from 6 to 3 km below the ground surface. The bottom of the borehole is at 5 km. Elevation is referenced from the base of the domain (z = 0 m) which is 1,000 m below the bottom of the borehole. The 544.08-m tall EZ (Figure 4-24) extends upward from the bottom of the borehole (starting at z = 1,000 m). It contains 108 WPs, each 3.76 m long and separated from neighbors by 1.0-m of associated hardware. Three cement plugs, each 10 m long, are located above the 40th, 80th, and 108th WPs. A bentonite seal extends from the top of the uppermost cement plug (z = 1544.08 m) to the top of the model domain (z = 3,000 m). A narrow DRZ surrounds the entire length of the borehole (z = 1,000 to 3,000 m). Waste package and borehole dimensions (Table 4-6) are taken from Arnold et al. (2014).



Note: Red = waste package; yellow = impact limiter/fishing neck; pink = annulus filled with either cement or brine; green = cement plug; and dark blue = granite. The DRZ is indistinguishable by color; it occupies the first three cell widths to the right of the annulus.

Figure 4-24. Portion of the model domain showing materials in the disposal zone.

Table 4-6. Waste package and borehole dimensions

Model Region	Diameter (m)	Height (m)
Waste Package[1]	0.191	3.76
Impact Limiter	0.191	0.7
Fishing Neck	0.191	0.3
Cement Plug	0.311	10.0
Borehole[1]	0.311	*NA*
Disturbed Rock Zone (DRZ)[2]	0.747	*NA*

Notes:

1. See Table 2-1 of this report, and Arnold et al. (2014)
2. Radial extent of the DRZ is 1.4 times the radius of the borehole.

Undisturbed crystalline rock comprises the bulk of the model domain; its properties are representative for granite (Table 4-7). Darcy permeability of 10^{-18} m^2 is assigned on the basis of values for sparsely fractured granite measured at Forsmark, Sweden (Follin et al. 2014) and elsewhere (Stober and Bucher 2007). Heat capacity (880 J/kg-K) and thermal conductivity (2.5 W/m-K) are chosen appropriate for granite at depth (i.e., at temperatures of 100°C and warmer; Vosteen and Schellschmidt 2003).

Table 4-7. Material properties

Material	Permeability (m^2)	Porosity	Thermal Conductivity (W/m-K)	Heat Capacity (J/kg-K)	Density (kg/m^3)
Waste Package [1]	1.00E-22	0.01	17	500	7850
Impact Limiter/Fishing Neck [2]	1.00E-22	0.01	43	480	7850
Drilling Fluid [3]	1.00E-12	0.99	0.58	4192	1100
Cement [4]	1.00E-16	0.15	1.7	900	2700
Bentonite Seal [4]	1.00E-19	0.20	1.7	800	2700
Undisturbed Granite [5]	1.00E-18	0.01	2.5	880	2700
Disturbed Rock Zone [6]	1.00E-16	0.01	2.5	880	2700

Notes:

1. Waste package is modeled as stainless steel.
2. Impact limiter and fishing neck are modeled as carbon steel.
3. Drilling fluid is modeled as a dense brine with permeability chosen to create a tractable problem.
4. Jove Colon et al. (2014).
5. Granite permeability is appropriate for sparsely fractured granite (Follin et al. 2014; Stober and Bucher 2007).
6. Disturbed rock zone permeability is approximately equal to the highest measured values at the Korean (Cho et al. 2013) and Canadian (Martino and Chandler 2004) underground research laboratories.

Materials in the disposal zone include: 1) individual WPs and intervening impact limiters and fishing necks; 2) cement plugs; 3) either cement or drilling fluid (i.e., dense brine) within the annulus of the borehole; and 4) the DRZ. Waste packages are modeled as stainless steel, impact limiters and fishing necks as carbon steel. The DRZ has the same thermal properties as undisturbed granite, and a permeability two orders of magnitude greater (10^{-16} m^2) consistent with values measured in underground research facilities in crystalline rock (Cho et al. 2013; Martino and Chandler 2004). Above the EZ the DRZ continues to the top of the model domain, and borehole properties represent a bentonite seal (Jove Colon et al. 2014).

The detailed representation of materials in and around the borehole is an improvement over previous simulations which used a coarser grid that represented the WP, borehole annulus, seals, and the DRZ as a single composite material (Arnold et al. 2014).

All eight cases have identical initial and boundary conditions. Initial conditions were established through the use of a 1-dimensional model domain consisting solely of undisturbed granite, and extending from z = 0 m to z = 6,000 m (land surface) to simulate the hydrostatic pressure and geothermal temperature gradients resulting from a fixed surface pressure of 101.325 kPa, a fixed surface temperature of 10°C, and a basal heat flux of 60 mW/m^2. The steady-state pressure and temperature values resulting from the 1-dimensional simulation were used as initial conditions for the axisymmetric domain. Pressure and temperature at the top and radial boundaries of the axisymmetric domain were held at initial values. At the bottom boundary, zero fluid flux and a constant heat flux of 60 mW/m^2 were maintained.

Waste packages were modeled as individual volumetric heat sources. Four heat source strengths were used. For three of them the heat source strength was based on three values of the average initial line load over the entire length of the EZ ("line load" simulations). The values used were 275, 300, and 325 W/m. These line loads resulted in initial heat output for every WP of 1,309, 1,428, and 1,547 W, respectively. For the fourth case, disposal of the true inventory of CsCl and SrF_2 capsules in the year 2050 was simulated (2050 simulation cases). The deepest 74 WPs were assumed to contain the entire inventory of CsCl capsules; each of these was assigned an initial heat output equal to 18 times the average heat output over all CsCl capsules in 2050 (totaling 978 W/WP). The uppermost 34 WPs were assumed to contain the entire inventory of SrF_2 capsules; the uppermost 33 of these were assigned an initial heat output equal to 18 times the average heat output over all SrF_2 capsules in 2050 (1,229 W/WP). The deepest SrF_2 WP was assigned initial heat output equal to 18 specific SrF_2 capsules selected to include the hottest six, the coolest six, and six with intermediate heat output (1,354 W total in 2050).

For all of the line load simulations, and the SrF_2 WPs in the 2050 simulations, the decay function for ^{90}Sr was used (and its daughter ^{90}Y). For CsCl WPs in the 2050 simulations, the decay function for ^{137}Cs was used (and its daughter ^{137m}Ba). Heat output was truncated to 0 W at 2000 years.

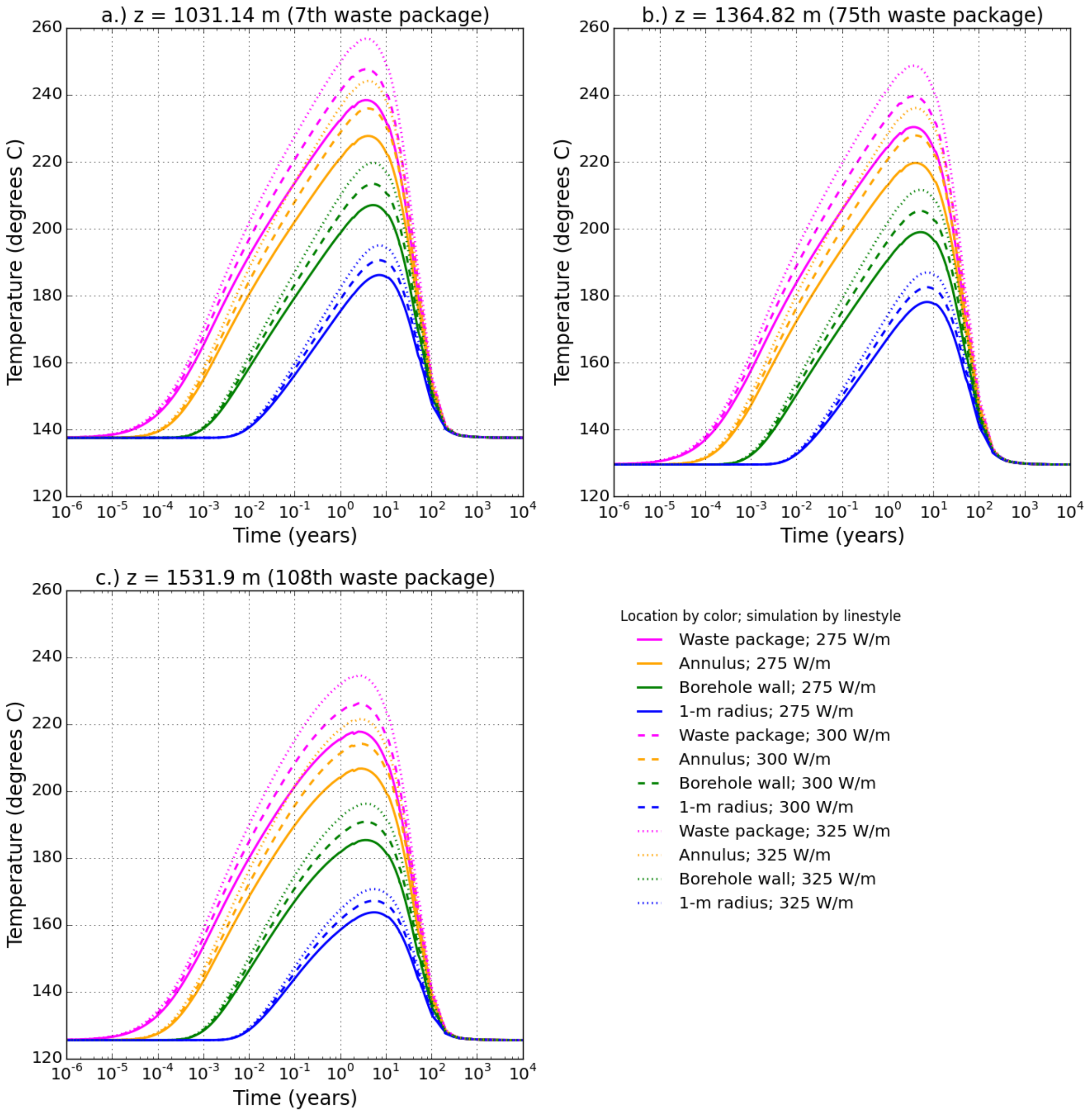
4.3.2 Simulation Results

Each of the line load cases and the 2050 case were simulated twice, once with cement in the borehole annulus and once with brine, generating eight cases. The following discussion summarizes histories of temperature and fluid flux, calculated for various locations.

4.3.2.1 Temperature

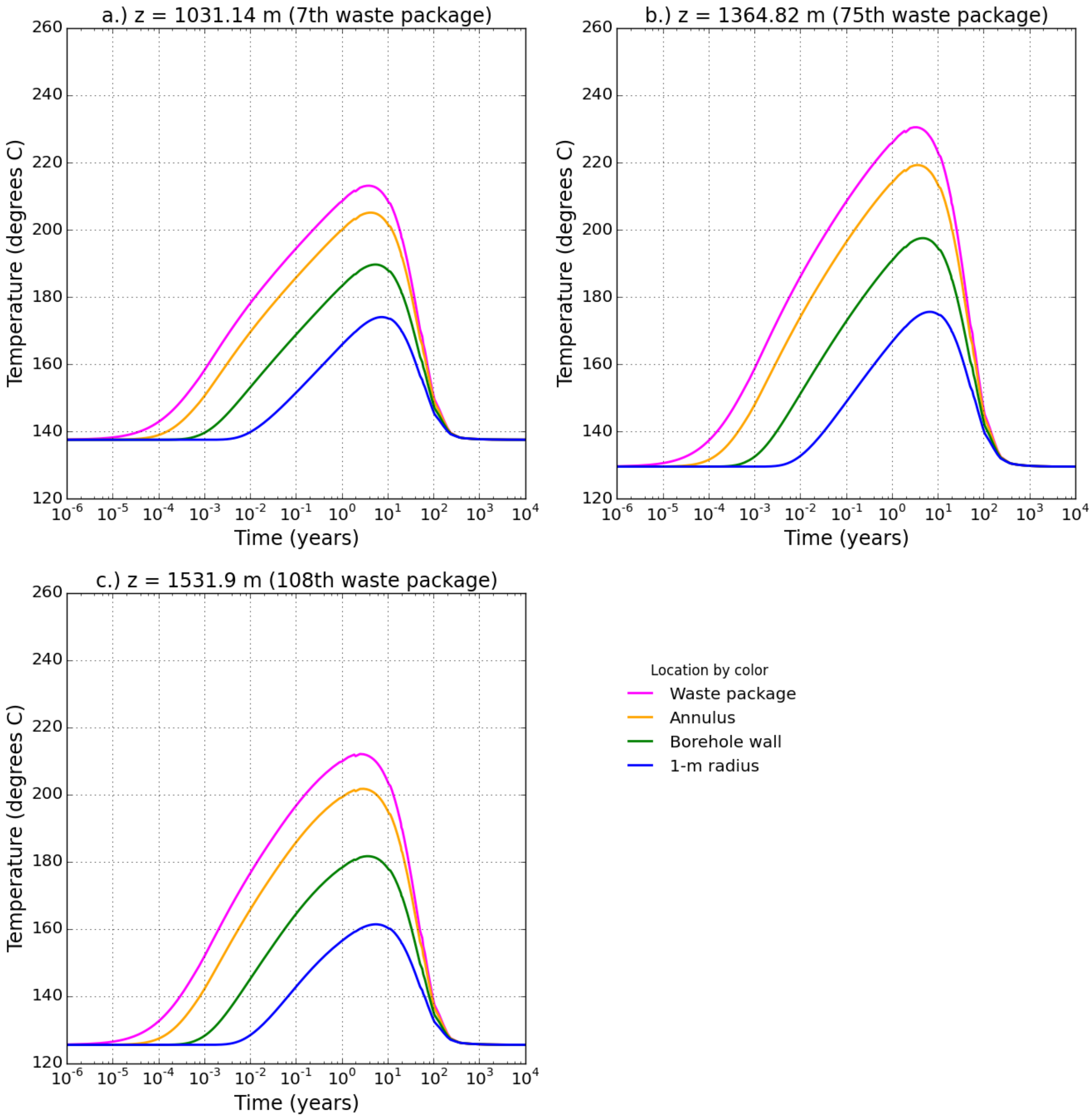
Waste package temperature is bounded by the reported temperature of the WP, and of the borehole annulus (Figure 4-25 through Figure 4-28). In an integrated finite difference formulation, temperature and flux data are calculated for nodes located at centroids of the grid blocks (and not at interfaces such as the WP surface). Temperatures at four elevations are reported:

- At the WP with the greatest temperature rise (z = 1031.48 m, the 7th WP)
- At the deepest SrF_2 WP (z = 1364.82 m, the 75th WP)
- At the uppermost WP (z = 1531.9 m, the 108th WP)
- Within the bentonite seal just above the top cement plug (z = 1546.58 m)



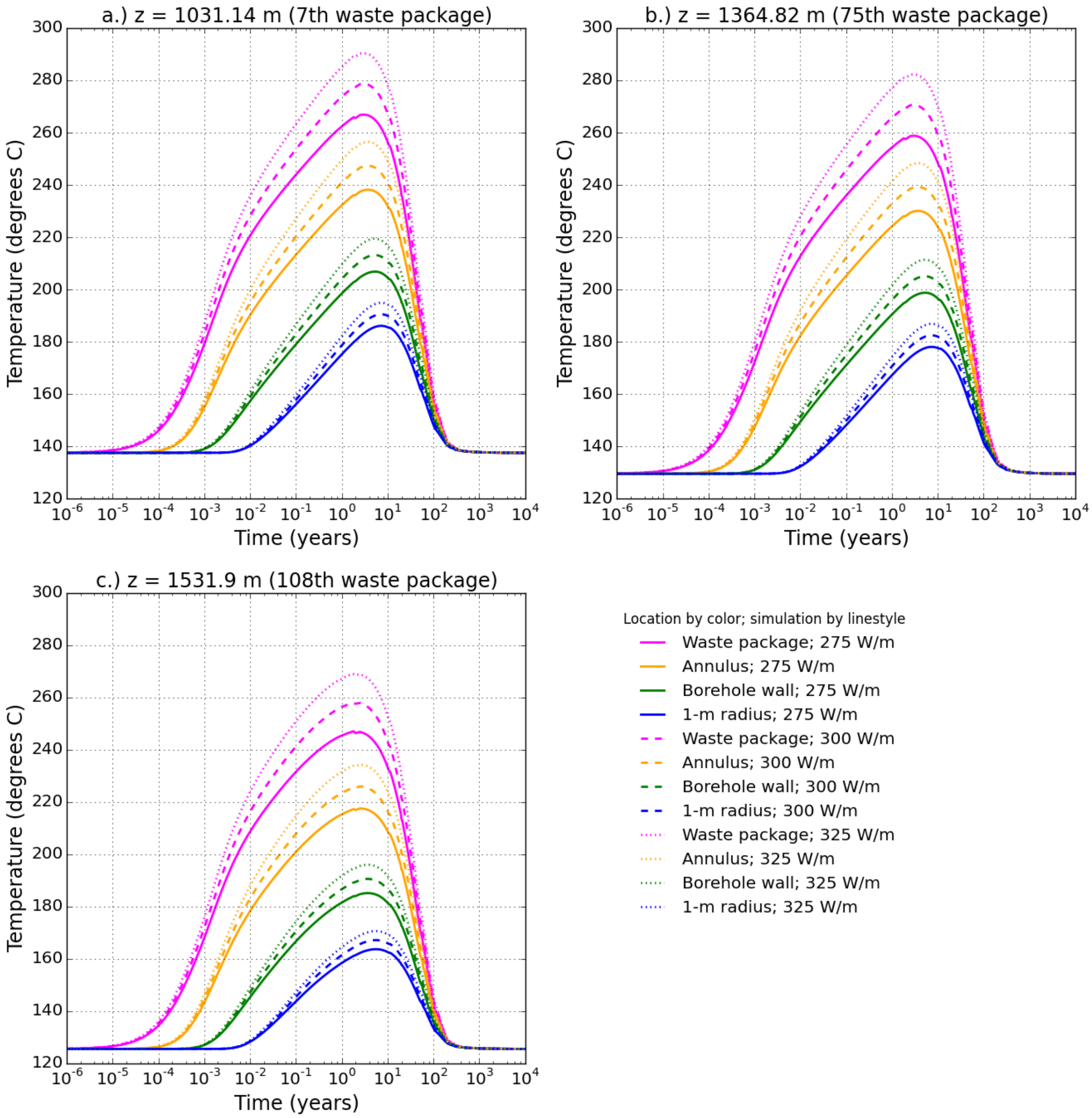
Note: the 7th package is 7th from the base of the EZ, the 75th is the deepest SrF_2 package, and the 108th is the uppermost package.

Figure 4-25. Temperature histories for the line load simulations with cement in the borehole annulus, for 3 elevations, 4 locations, and 3 power levels as indicated.



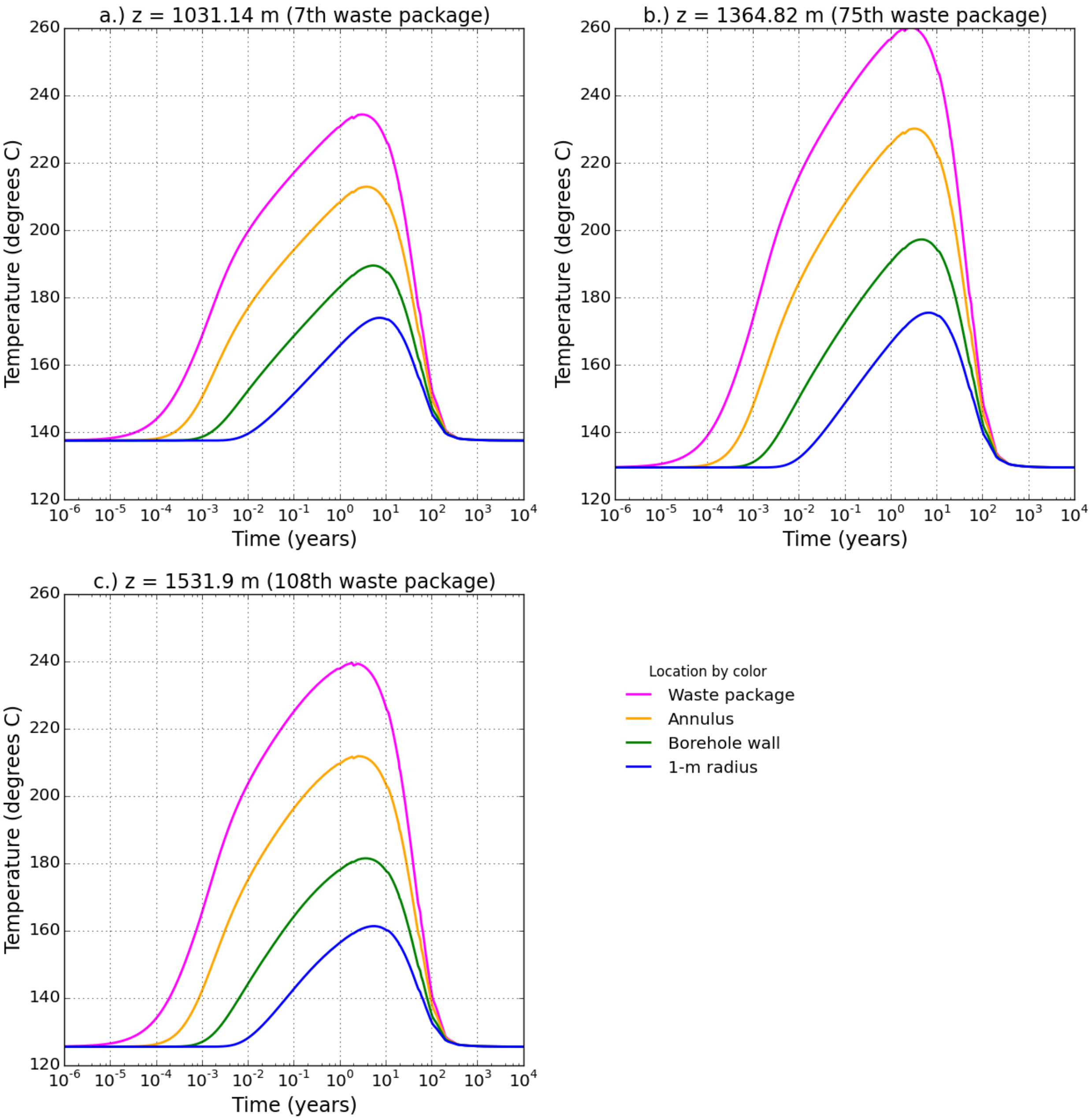
Note: the 7th package is 7th from the base of the EZ, the 75th is the deepest SrF$_2$ package, and the 108th is the uppermost package.

Figure 4-26. Temperature histories for the 2050 simulations with cement in the borehole annulus, for 3 elevations and 4 locations as indicated.



Note: the 7th package is 7th from the base of the EZ, the 75th is the deepest SrF$_2$ package, and the 108th is the uppermost package.

Figure 4-27. Temperature histories for the line load simulations with brine in the borehole annulus, for 3 elevations, 4 locations, and 3 power levels as indicated.



Note: the 7th package is 7th from the base of the EZ, the 75th is the deepest SrF_2 package, and the 108th is the uppermost package.

Figure 4-28. Temperature histories for the 2050 simulations with brine in the borehole annulus, for 3 elevations and 4 locations as indicated.

Temperature histories are plotted for the first three of these elevations (Figure 4-25 through Figure 4-28) at four locations:

- Within the WP
- Within the annulus
- Within the first cell of the DRZ (labeled “borehole wall”)

- Within the undisturbed granite at 1-m radius

Temperature at the fourth elevation above is not plotted because the perturbation to ambient temperature is less than 3°C at all locations.

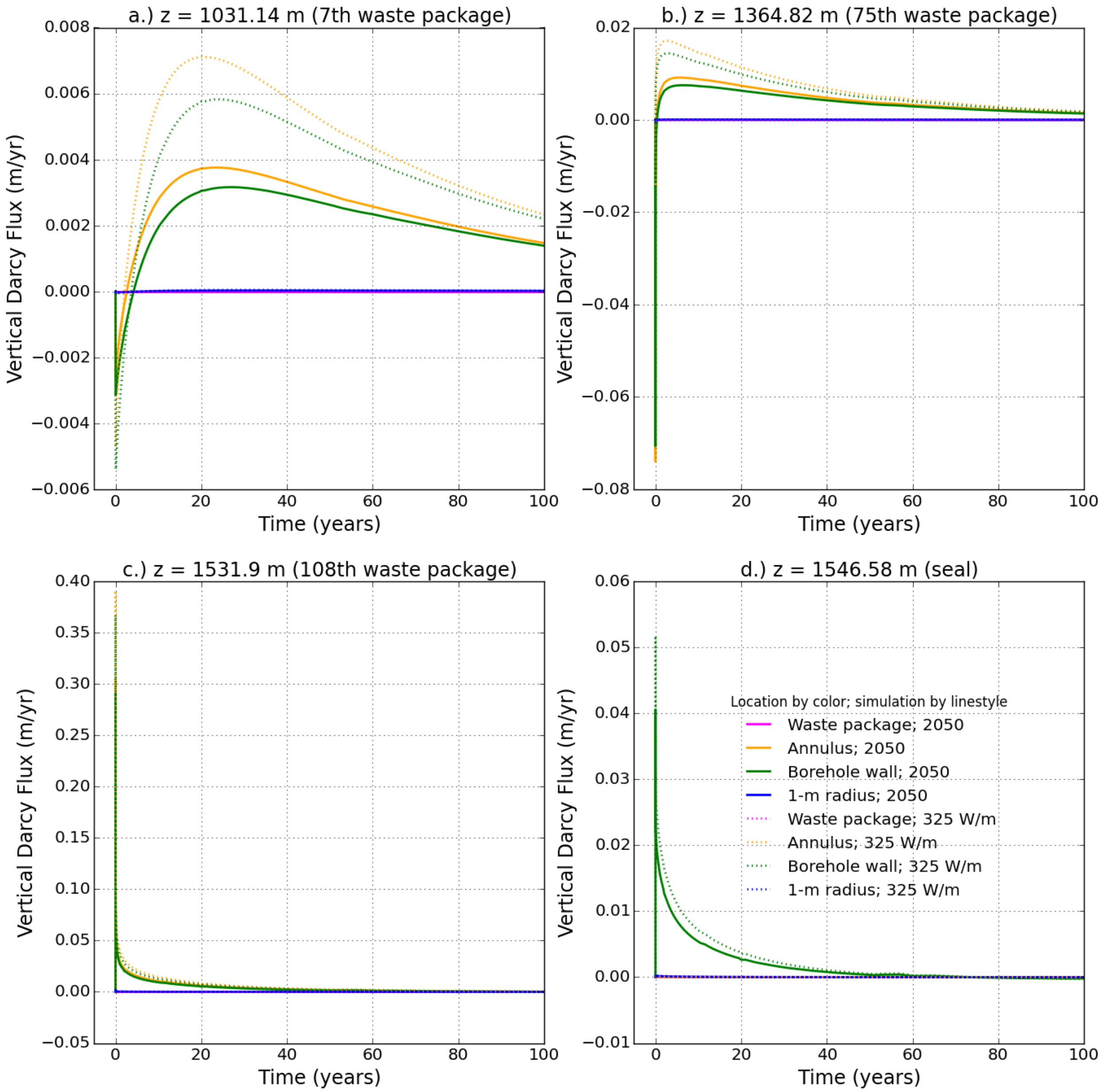
For the line load simulations, temperature rise is proportional to line load strength (Figure 4-25 and Figure 4-27). For example in the cement simulations (Figure 4-25) at the 7th WP (largest temperature rise) the temperature increased 120°C from 137°C to a maximum of 257°C at 4 years with an initial line load of 325 W/m. Temperature at the same location increased 101°C to a maximum of 238°C with an initial line load of 275 W/m.

Calculated temperature rise is greater with brine in the borehole annulus than cement (Figure 4-27 and Figure 4-28). Higher temperatures occur because brine has lower thermal conductivity, even though the simulations produce fluid fluxes in the near field that are orders of magnitude greater than in cement (Figure 4-25 and Figure 4-26). The calculated liquid flux is small and does not transport enough heat to significantly change temperatures. In the line load brine simulations, at the 7th WP, temperature increased 153°C to a maximum of 290°C at 3 years with an initial line load of 325 W/m; and increased 130°C to a maximum of 267°C with an initial line load of 275 W/m.

The 2050 simulations resulted in lower temperatures than the line load simulations everywhere except at the elevation of the 75th package, because WP heat sources in the 2050 simulations were less than the 275 W/m initial line load everywhere except at that package (where heat output was similar to the 275 W/m line load) (Figure 4-25 and Figure 4-27). In the 2050 simulations the largest temperature rise was calculated at the elevation of the 75th package. In the cement simulation, temperature increased 101°C from 129°C to a maximum of 230°C at 3.5 years. In the brine simulation, temperature increased 131°C to a maximum of 260°C at 2.5 years.

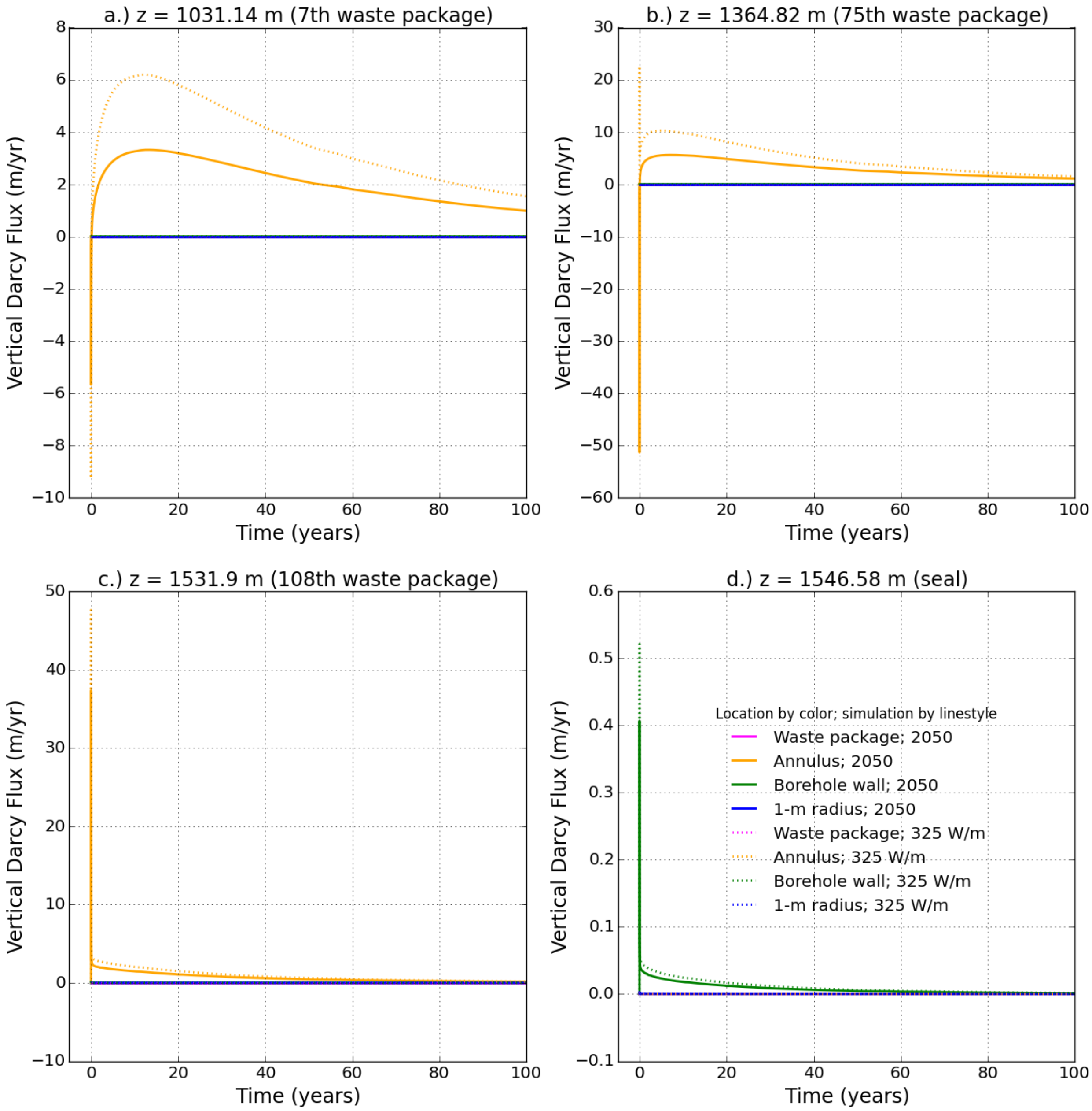
4.3.2.2 Fluid Flux

If WP heat sources generate sufficient upward fluid flux, the borehole seal and the DRZ represent potential pathways for radionuclide release to the biosphere. Vertical fluid flux (reported as Darcy flux, q, in $m^3/m^2/y$) versus time is plotted for the 325 W/m line load simulations and the 2050 simulations in Figure 4-29 (cement in annulus) and Figure 4-30 (brine in annulus). Early fluxes of very short duration occur as a result of fluid expansion when the WP heat sources are turned on at the start of the simulations. In reality such expansion fluxes would occur not in the sealed system modeled here, but in an open borehole during emplacement operations, and in conjunction with fluxes created simply by displacement of water as WPs are emplaced. Later vertical fluxes due to buoyancy of the hot fluid, which generally peak at the same time as temperatures, are those relevant to possible radionuclide release. The largest flux values predicted above the disposal zone occur in the DRZ and are on the order of 0.01 m/yr. Given a DRZ effective porosity (ϕ) of 0.01, the Darcy velocity in the DRZ is on the order of 1 m/yr, sustained for fewer than 40 years. These results indicate that after an initial thermal pulse in which slight upward flow is produced by fluid thermal expansion and buoyant convection, there is no upward flow with the potential to advectively transport released radionuclides to the biosphere.



Note: the 7th package is 7th from the base of the EZ, the 75th is the deepest SrF_2 package, and the 108th is the uppermost package. Note difference in vertical scales.

Figure 4-29. Vertical fluid flux versus time with cement in the borehole annulus, for 4 elevations, 4 locations, and 2 thermal loading conditions as indicated.



Note: the 7th package is 7th from the base of the EZ, the 75th is the deepest SrF_2 package, and the 108th is the uppermost package. Note difference in vertical scales.

Figure 4-30. Vertical fluid flux versus time with brine in the borehole annulus, for 4 elevations (including the base of the seal zone), 4 locations, and 2 thermal loading conditions as indicated.

4.3.2.3 Discussion

In these simulations the initial line load of 275 W/m and annulus filling of cement maintained the estimated WP peak temperature a few degrees below 250°C (approximating the package wall temperature by that calculated at the grid node within the package). Increasing the heat source to 325 W/m or decreasing the thermal conductivity of the material in the annulus (brine simulations) increased the calculated WP temperatures. In 2050, the heat output of an individual

WP (assuming 18 capsules per WP) will depend on the individual capsules within the WP, and has the potential to be greater than that corresponding to a 275 W/m line load. To keep package wall temperatures below an imposed temperature limit (such as 250°C), possible adjustments can be made to: 1) WP loading and waste decay storage; 2) thermal properties of materials filling the borehole and the annulus; and 3) disposal depth (background temperature).

Given the values used for permeability and porosity of the seal zone and the DRZ, and the small buoyancy forces created by heating in the EZ, neither the seal zone nor the DRZ will be paths for significant flow (and by inference, potential radionuclide releases) to the biosphere.

4.4 Impact Limiters

A linear energy-balance calculation is used to compute the force characteristics of an impact limiter, to arrest a sinking package at terminal velocity. Impact limiters can be constructed with effective crush strength ranging from approximately 1 to 100 MPa, through use of energy absorbing material (e.g., Hexcel 2015a,b) or tubular crush boxes (Figure 4-31) (Noss et al. 2000).

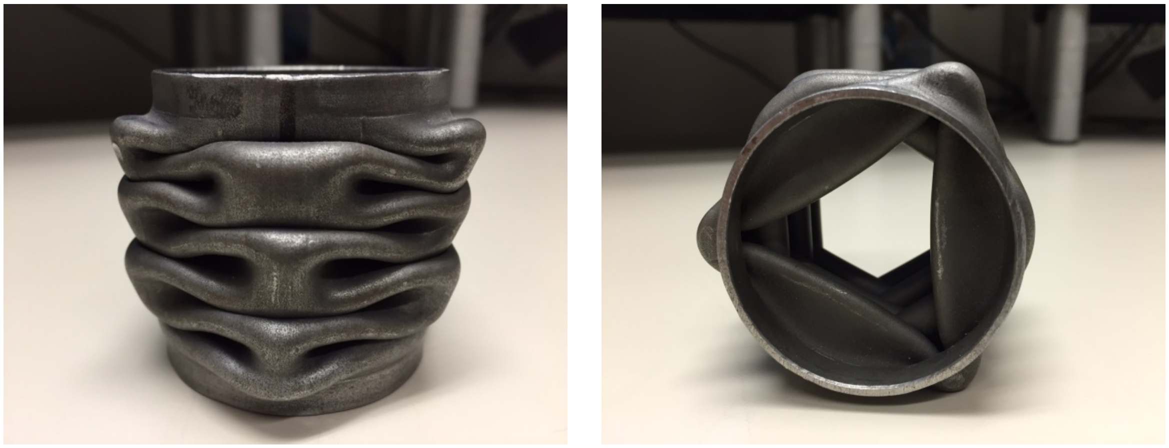


Figure 4-31. Tubular crush box impact limiter, after crushing (provided by Brad Day, SNL).

The following derivation describes the behavior of impact limiters that could be attached to every package, to mitigate the consequences of accidentally dropping a package vertically, either in the fluid-filled borehole or in air during surface operations (e.g., dropping a transfer cask containing a package). The terminal velocity of single packages in a fluid-filled borehole is assumed to be 8 ft/sec (2.5 m/sec).

4.4.1 Derivation

D = Impact limiter diameter
M = Package mass (single package, or multiple packages threaded together possibly including drill pipe)
V = Velocity (initial, maximum velocity for deceleration problem)
fcr = Average crushing strength in pressure units
s = Crushing stroke
g = Acceleration of gravity
a = Average rate of deceleration

The kinetic energy of the falling package is equal to the work done by the crushing force:

$$\frac{1}{2}MV^2 = \frac{\pi D^2}{4} f_{cr} s \tag{4-25}$$

so that

$$s = \frac{2MV^2}{\pi D^2 f_{cr}} \tag{4-26}$$

and deceleration rate is

$$a = \frac{V^s}{2s} = \frac{\pi D^2 f_{cr}}{4M} \tag{4-27}$$

4.4.2 Result

Using the softest crush strength noted above (1 MPa), and assuming that the impact limiter would have 80% of the cross-sectional area of the package (e.g., allowing for a taper), and assuming that the crushed length would be 50% of the initial length, then a minimum limiter length of approximately 28 cm would be needed, the deceleration rate would be approximately 2.3 g, and the crushing force would be approximately 47 kN. This is much less than the weight of a stack of 40 packages, so impact limiters designed to this description would crush one-by-one during waste emplacement.

An alternative approach could allow a greater deceleration rate because of the robust construction of the packages. For example, for an impact limiter with length of 10 cm and stroke length of 5 cm, the constant deceleration rate would be about 6.4 g. This deceleration rate is likely to be well within the capability of packages that are robust enough to withstand bottom-hole pressure, and which resemble high-pressure gas cylinders.

To address uncertainty as to package weight and sinking velocity, and to control crushing during package stacking, a composite or progressive impact limiter could provide variable crushing strength that increases with stroke. Requirements identified for impact limiters include not mushrooming so that they become stuck in the casing, and progressive response so that crushing under the weight of a stack of packages occurs in a controlled manner (Section 2.3).

5 CONCLUSIONS

The United States Department of Energy is investigating the use of a universal canister to store, transport, and dispose of radioactive waste (such as high level waste). The universal canister would be designed such that it would not have to be reopened to treat or repackage the waste contained in it. Therefore, the universal canister would have to be designed to meet requirements for possible disposal options for the waste contained in it. This report focuses on the conceptual design for disposal of radioactive waste in deep boreholes so that the universal canister can be compatible with deep borehole disposal.

The conceptual design for disposal of radioactive waste in deep boreholes is based on expected preclosure and postclosure conditions associated with disposal, on the requirements that can be identified at this preliminary stage, and on reasonable assumptions that are made to further the design process. The conceptual design includes technically feasible proposals for borehole drilling and construction, waste packages, surface handling equipment, and waste emplacement; these are all consistent with identified requirements and stated assumptions. Furthermore, these elements of are supported by engineering analysis of waste package stress, heat transfer in the borehole, and waste package fragility. The conceptual design of deep borehole disposal helps to specify requirements for the conceptual design of the universal canister.

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