APPENDIX E

FCT DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/Revision No.	Deep Borehole Field Test Conceptual Design Report (Deliverable # M2FT-16SN080308081, FCRD-UFD-2016-000070 Revision 1)
Work Package Title and Number	FT-16SN08030808 Field Test Design - SNL
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Responsible Work Package Manager	Ernest L. Hardin (Name/Signature) [signature]
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Quality Rigor Level for Deliverable/Milestone[2]	☒ QRL-3	☐ QRL-2	☐ QRL-1 Nuclear Data	☐ Lab/Participant QA Program (no additional FCT QA requirements)

This deliverable was prepared in accordance with Sandia National Laboratories
(Participant/National Laboratory Name)

QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1-2000 ☐ Other

This Deliverable was subjected to:

☒ Technical Review	☐ Peer Review
Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
☒ Signature of TR Reviewer(s) below	☐ Signature of PR Reviewer(s) below

Name and Signature of Reviewers

Mark Rigali [signature]

NOTE 1: *Appendix E should be filled out and submitted with the deliverable. Or, if the PICS:NE system permits, completely enter all applicable information in the PICS:NE Deliverable Form. The requirement is to ensure that all applicable information is entered either in the PICS:NE system or by using the FCT Document Cover Sheet.*

NOTE 2: *In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity, along with the Document Cover Sheet, is sufficient to demonstrate achieving the milestone. If QRL 1, 2, or 3 is not assigned, then the Lab / Participant QA Program (no additional FCT QA requirements) box must be checked, and the work is understood to be performed and any deliverable developed in conformance with the respective National Laboratory / Participant, DOE or NNSA-approved QA Program.*

Deep Borehole Field Test Conceptual Design Report

Fuel Cycle Research & Development

Prepared for the
U.S. Department of Energy
Used Fuel Disposition Campaign

Sandia National Laboratories
Albuquerque, New Mexico
October, 2016
FCRD-UFD-2016-000070 Rev. 1

Revision History

FCRD-UFD-2015-000132 Rev. 0	Technical Review and Sandia programmatic review (Tracking Number 321249). For internal use only. Submitted to the Office of Used Nuclear Fuel Disposition for deliverable acceptance review.
FCRD-UFD-2015-000132 Rev. 1	Sandia formal review (SAND2015-8244R). This version also corrects typographical errors in Section 5.5.4 and Table 5-7, and makes small corrections to the off-normal cost data in Appendix C, which affect cost data in Tables 5-6, 5-7, and 6-1.
FCRD-UFD-2016-000070 Rev. 0	Technical Review and Sandia programmatic review (Tracking Number 475319), then approval by the Office of Used Nuclear Fuel Disposition (deliverable M2FT-16SN080308081). Additions and revisions compared to the FY15 *DBFT Specifications* deliverable include: 1) changes based on review of FCRD-URD-2015-000132 Rev. 1 by AREVA Federal Services,; 2) correction of minor errors in cost estimates; 3) concept enhancements for well pressure control during disposal operations; and 4) additional engineering analyses including surface equipment description, fluid dynamics analysis, risk experience data survey, waste package mechanical calculations, revised thermal-hydrology simulations, and analysis of disposal borehole completion options.
FCRD-UFD-2016-000070 Rev. 01	Re-checked and corrected results tabulated in Appendices A and B, and discussed in the text of Appendix A and Section 6, followed by final R&A at Sandia for Unclassified Unlimited Release.

Sandia National Laboratories

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Approved for Unclassified, Unlimited Release (SAND2016-10246 R).

Executive Summary

This report documents conceptual design development for the Deep Borehole Field Test (DBFT), including test packages (simulated waste packages, not containing waste) and a system for demonstrating emplacement and retrieval of those packages in the planned Field Test Borehole (FTB). For the DBFT to have demonstration value, it must be based on conceptualization of a deep borehole disposal (DBD) system. This document therefore identifies key options for a DBD system, describes an updated reference DBD concept, and derives a recommended concept for the DBFT demonstration.

The objective of the DBFT is to confirm the safety and feasibility of the DBD concept for long-term isolation of radioactive waste. The conceptual design described in this report will demonstrate equipment and operations for safe waste handling and downhole emplacement of test packages, while contributing to an evaluation of the overall safety and practicality of the DBD concept. The DBFT also includes drilling and downhole characterization investigations that are described elsewhere (see Section 1). Importantly, no radioactive waste will be used in the DBFT, nor will the DBFT site be used for disposal of any type of waste. The foremost performance objective for conduct of the DBFT is to demonstrate safe operations in all aspects of the test.

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 1-1). 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 U.S., including deep borehole disposal of commercial spent nuclear fuel. R&D programs for deep borehole disposal have been ongoing for several years in the U.S. and the U.K. These studies have shown that the DBD concept could be safe, cost effective, and technically feasible.

The DBFT engineering demonstration will emphasize developmental aspects unique to possible future DBD. It will include fabrication and testing of test packages (simulated WPs not containing radioactive waste), development of handling and emplacement equipment, and downhole emplacement/retrieval of test packages. Instrumentation will monitor downhole conditions encountered by test packages, such as temperature and accelerations. Packaging and handling technologies used for the DBFT will be similar to current practices for nuclear materials, but will meet downhole environment specifications. Emplacement and retrieval of test packages in the FTB will be novel, with some precedents in the oil and gas industry, but with new equipment and reliability objectives.

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 (preliminary and final design for the DBFT engineering demonstration). Requirements and assumptions are developed for both the DBD reference concept and the DBFT. Some remaining design questions are identified, with recommendations for further design development and engineering analysis.

The following paragraphs summarize the conceptual design for DBD and how key aspects will be demonstrated in the DBFT. The conceptual design is supported by engineering analysis of several types: numerical stress analysis, finite element heat transfer modeling, thermal-

hydrologic simulation, fluid dynamics simulation and analysis, fragility analysis for dropped package assemblies, impact limiter performance, and radiological shielding.

Waste Forms and Packaging Options

Waste forms to be disposed of in deep boreholes are identified for the purpose of designing the DBFT engineering demonstration. Waste forms to be considered for the DBFT include granular high-level waste (HLW) materials, and HLW in sealed capsules. Two basic waste packaging concepts are presented: 1) flask-type packages for bulk waste (such as granular calcine waste), and 2) internal semi-flush packages for pre-canistered waste (such as the Hanford Cs/Sr capsules). Suitable materials, connection types, and fabrication services are available in vendor offerings to the oil and gas industry. Simple packaging concepts of each type were developed, and numerical stress analysis was performed for the projected downhole environment to verify adequate margins of safety against containment failures.

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 factor of safety = 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).

FTB Construction Options

Borehole drilling and construction for the DBFT 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. Options for borehole drilling and construction methods include: directional drilling, diameter/casing plan, and surface equipment such as blowout preventers.

For a disposal borehole, options for completing the EZ vary with respect to how cement would be emplaced to anchor guidance casing, which determines the extent to which the casing has been perforated when packages are being emplaced. Casing perforations are important because they allow flow between the casing bore and the annulus, which could impact the sinking velocity of WPs that are accidently dropped, and thus the potential for waste package breach and release of radioactivity during emplacement operations. The impact of different perforation schemes on test package sinking velocity will be evaluated in the DBFT demonstration.

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 for the DBFT engineering demonstration, 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.

Probabilistic risk assessment (i.e., a cost-risk study) was used to compare the wireline and drill-string methods. The likelihood for any off-normal event that could cause a WP to breach in the borehole releasing radioactivity, was estimated to be less than 0.002% per borehole with 400 WPs, for wireline emplacement. This kind of reliability is possible with use of an impact limiter on every WP to mitigate consequences if a package is accidentally dropped. The probability of package breach for drill-string emplacement (i.e., using a drill rig and lowering strings of packages on drill pipe) was found to be approximately 400 times greater because of the risk from dropping much heavier assemblies of packages and pipe.

The probabilistic risk assessment analyzed only off-normal events that could occur in the borehole during emplacement operations. Another class of off-normal events that was not considered because it does not readily discriminate between emplacement options, is dropping WPs (or casks containing packages) in air at the surface. Evaluation of hazards from such events may be undertaken during design for the DBFT engineering demonstration.

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 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 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.

DBFT Engineering Demonstration

Two or more test packages will be fabricated and leak tested. One or more of these will be subjected to drop testing and external pressure testing, with additional leak testing to verify condition, before deployment in the DBFT demonstration. Impact limiters and electromechanical wireline latch fittings will be developed and used on all test packages.

In addition, a test instrumentation package will be developed with a closure that can be opened and resealed in the field, for deploying an instrument module (6-axis motion, pressure, temperature). The instrument module will be used to investigate the dynamics of motion for a package that has been dropped; the results will support future WP design and safety assessments.

All features of the transfer cask and associated equipment will be demonstrated. This includes the transfer equipment described above, also cradles, shield plates, a shielded wellhead pit, and minor components such as trunnions, rigging, shield plugs, kneeling jacks, etc. These components will be defined during the DBFT engineering design process.

All features of the wireline system and associated equipment for package emplacement and retrieval will be demonstrated. This includes commercially available components such as the wireline cable and winch, cable head, wireline logging tools, sheaves, etc. The electromechanical mechanism for releasing packages downhole may be modified from commercial equipment.

The equipment used in the DBFT can be simplified, as appropriate to focus resources on those aspects that are most developmental and risk significant. For example, among the risk insights presented in Appendix A, wireline overtension is particularly risk-significant for wireline emplacement. An important objective for the DBFT field demonstration is to test the function of impact limiters on each test package (a free drop test). Impact limiters must prevent test package breach on impact, and also not hang up on the casing or become jammed in the casing after crushing.

Before the engineering demonstration at the DBFT field site is conducted, an integrated test of the engineered components will be performed. The purpose is to identify and resolve any equipment operability or interface issues at a location with access to shop facilities. Test packages and components of the transfer/emplacement system, including a mockup borehole, crane, and wireline setup will be used. The integrated test will also be an opportunity to check the condition of rented equipment such as the wireline cable, winch, and downhole tools.

The DBFT engineering demonstration will be supported by an engineering services contractor, for which procurement is planned in FY16/17. The contractor will develop preliminary and final designs, conduct design reviews, prepare fabrication specification packages, and oversee fabrication and testing. The contractor will develop an integrated testing facility, then integrate with the FTB management contractor to perform the DBFT engineering demonstration in the field. The DBFT is funded and managed by the U.S. Department of Energy (DOE), Office of Used Nuclear Fuel Disposition.

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Acronyms and Abbreviations

ALARA	As low as reasonably achievable
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BOP	Blowout preventer
CB	Characterization Borehole
CFD	Computational fluid dynamics
CFR	Code of Federal Regulations
DBD	Deep borehole disposal
DBFT	Deep Borehole Field Test
DOE	U.S. Department of Energy
EZ	Emplacement zone
FEPs	Features, events and processes
FoS	Factor of safety
FT	Fault tree
FTB	Field Test Borehole
HEP	Human error probabilities
HEPA	High efficiency particulate arrestance
HMIs	Human-machine interactions
HRA	Human reliability analysis
ID	Inner diameter
ISMS	Integrated Safety Management System
ITF	Integrated Test Facility
HLW	High-level waste
LLW	Low-level waste
LWT	Legal-weight truck (transportation cask designation)
MUA	Multi-attribute utility analysis
NAC	NAC International
NEPA	National Environmental Policy Act
OD	Outer diameter
ORNL	Oak Ridge National Laboratory
PRA	Probabilistic risk analysis
PSF	Performance shaping factors
PWR	Pressurized water reactors
QA	Quality Assurance
QC	Quality Control
R&D	Research and Development
ROM	Rough order of magnitude
RSS	Rotary steering system
SFT	Spent Fuel Test

SPAR-H	Standardized plant analysis risk model human reliability analysis method
SNL	Sandia National Laboratories
TBD	To be determined
TD	Total depth
UK	United Kingdom
USS	U.S. Steel Corporation
WCS	Waste Control Specialists
WM	Waste management
WP	Waste package

Acknowledgments

Author	Contributed to Report Sections
Abiodun Adeniyi/ORNL	Section 3
Andrew Clark/SNL	Appendices A and B
John Cochran/SNL	Section 2 and Appendix C
John Finger/SNL Consultant	Appendix C
Ernest Hardin/SNL Project Lead	All sections and appendices
Teklu Hadgu/SNL	Section 5
Karen Jenni/Insight Decisions, LLC	Appendices A and B
Paul Nogradi/ORNL	Sections 3 and 4
Fred Peretz/ORNL	Sections 3 and 4
Laura Price/SNL	Sections 2, 3, 4, 5 and 6
Georgeta Radulescu/ORNL	Section 5
Dave Sevougian/SNL	Appendix B
Emily Stein/SNL	Section 5
Jiann Su/SNL	Sections 2 and 5
Venugopal Varma/ORNL	Sections 3 and 4

Reviewer/Consultant	Contribution Area
AREVA (Sven Bader, Technical Lead)	Review of SNL (2015) Report
Geoff Freeze/SNL	Requirements Development
Michael Gross/SNL Consultant	Reviewer
Katrina Groth/SNL	Risk Analysis Review
Steve Knudsen/SNL	Concept Development – Drilling Engineering
Kris Kuhlman/SNL	Requirements and Concept Development
Bob MacKinnon/SNL	Requirements Development
Alice Muna/SNL	Risk Analysis Review
Mark Rigali/SNL	Reviewer
Dave Rosewater/SNL	Risk Analysis Review
Dave Sassani/SNL	Requirements Development
Steve Pye/SNL Consultant	Concept Development – Drilling Engineering
Tim Wheeler/SNL	Risk Analysis Review

Thanks are due also to the administrative and management support staff at SNL including Laura Connolly, Lori Harkins, and Libby Sanzero.

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1. Introduction

1.1 Purpose and Scope for This Report

This report documents conceptual design development for the Deep Borehole Field Test (DBFT), including test packages (simulated waste packages, not containing waste) and the system for demonstrating emplacement and retrieval of those packages in the planned Field Test Borehole (FTB). For the DBFT to have demonstration value, it must be based on conceptualization of a deep borehole disposal (DBD) system for specific waste forms. This document therefore identifies key design options for a DBD system, describes a reference DBD concept, and justifies selection of design features for the DBFT.

A valid conceptual design such as that presented here is one that is shown by limited analysis to be technically feasible and likely to meet requirements. Conceptual design development is part of a process that proceeds in three stages: 1) *conceptual* design including feasibility studies; 2) *preliminary* design that includes technical and cost information necessary for final design; and 3) *final* design sufficient for fabrication or construction. The DBFT engineering demonstration will follow such an evolution. Whereas design evolution typically begins with bench-scale and pilot-scale investigations proceeding to conceptual, preliminary, and final designs, the DBFT can proceed directly to design because of extensive previous published work on waste packaging and handling, industrial deep-hole drilling and construction, and downhole operations. Hence, this report will allow commencement of preliminary and final design, leading to fabrication and testing, and demonstration of waste emplacement in a deep borehole.

The design concepts described in this report are workable solutions based on expert judgment, and are intended to guide the follow-on design activities. The reference DBD concept and the analysis of waste packaging and emplacement options are used to develop requirements and assumptions for the DBFT and to recommend DBFT specifications. Some remaining design questions are identified, with recommendations for further design development and engineering analysis, anticipating future design activities.

Note that cost and schedule for implementing the DBFT engineering demonstration are not included here, but are left to be developed in conjunction with activities to procure engineering support services.

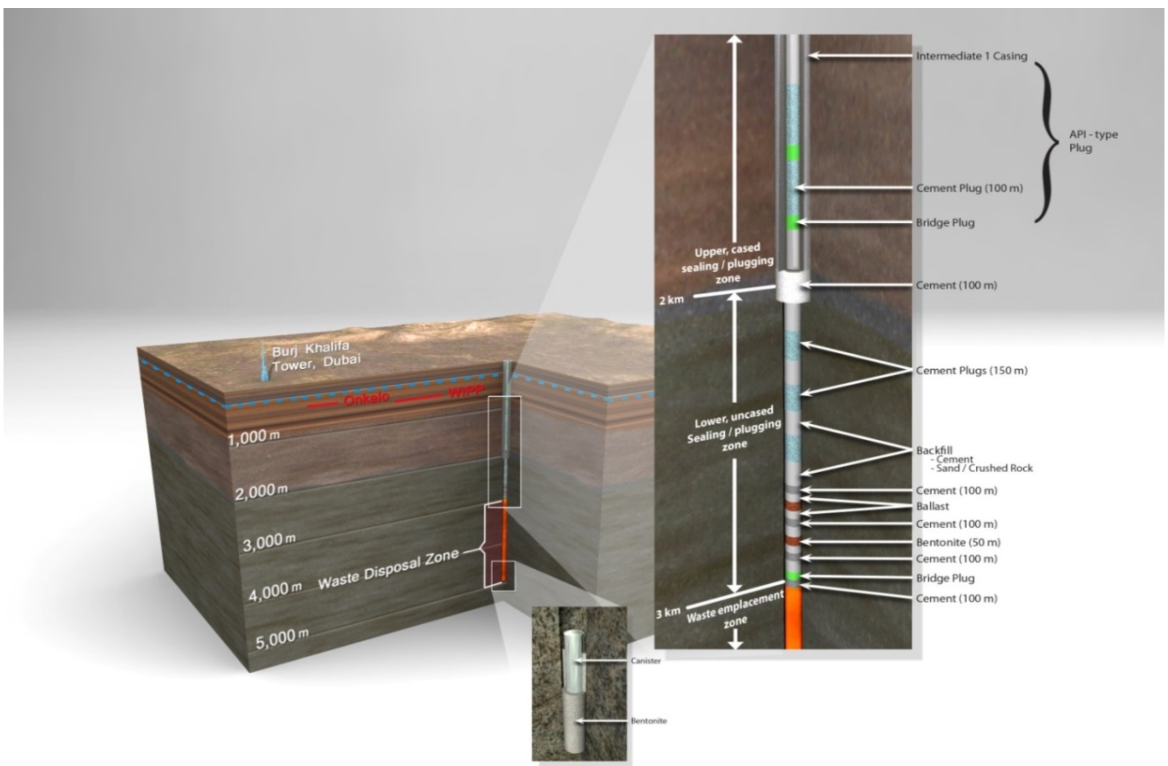
1.2 Overview of Deep Borehole Disposal Concept

The general disposal concept consists of drilling a borehole (or array of boreholes) 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 (Figure 1-1). These depths are several times deeper than for typical mined repositories (e.g., Onkalo and the Waste Isolation Pilot Plant), resulting in greater natural isolation from the surface or near-surface environment. The emplacement zone (EZ) in a single borehole could contain up to about 400 WPs, each with length of approximately 15 to 18 ft (comprising 2 km total). The borehole seal system could consist of alternating layers of compacted bentonite clay, cement, and cement/crushed rock backfill.

A number of disposal options for radioactive waste were investigated in the 1980’s in the U.S., including deep borehole disposal of commercial spent nuclear fuel (Woodward–Clyde 1983). That study was the first to propose a means for emplacing strings of WPs, threaded together, using a drill rig (drill-string emplacement). Other evaluations of DBD were also conducted

(O'Brien et al, 1979; Juhlin and Sandstedt 1989; SKB 1992; Heiken et al. 1996; NIREX 2004; Anderson 2004; Gibb et al. 2008). R&D programs for deep borehole disposal have been ongoing for several years in the U.S. and the U.K. (Sapiie and Driscoll 2009; Beswick et al. 2014). Technical leadership for the DBFT is provided by Sandia National Laboratories for the U.S. DOE, and builds on Sandia's DBD R&D activities which were started in 2009 (Brady et al. 2009). These studies have shown that the DBD concept could be safe, cost effective, and technically feasible.

It is important to note that there are hundreds of deep-injection wells for wastewater and liquid hazardous waste in the U.S., licensed under regulations from the U.S. Environmental Protection Agency (EPA 2001). Approximately 500 to 600 wells have been put into service with depths from 3,000 to 12,000 ft. Injection intervals are typically separated from underground sources of groundwater by multiple low-permeability confining units. Injection wells have double casings, double-cemented, to isolate the waste path from overlying units. Final sealing and plugging of these wells follows established procedures for oil-and-gas wells.



Note: The dashed blue line indicates typical lower extent of useable fresh groundwater resources.

Figure 1-1. Generalized concept for DBD of radioactive waste showing emplacement zone and seal zone above.

1.3 General Description of Deep Borehole Field Test (DBFT)

The objective of the DBFT is to confirm the safety and feasibility of the DBD concept for long-term isolation of radioactive waste. The DBFT has four primary goals: 1) demonstrate the feasibility of constructing and characterizing deep boreholes, 2) demonstrate equipment and operations for safe waste handling and emplacement downhole, 3) study geologic controls on waste form stability and isolation, and 4) evaluate overall safety and practicality of the DBD concept (DOE 2012). The design concept, operations, and engineering demonstration described in this report (Figure 1-2) will accomplish the second goal while contributing to the fourth. Additional investigations that are part of the DBFT are described elsewhere (SNL 2014, 2015; Kuhlman et al. 2015). Importantly, no radioactive waste will be used in the DBFT, nor will the DBFT site be used for disposal of any type of waste.

It is anticipated that the DBFT will also support the goals and objectives listed above, by:

- Fostering collaboration among industrial, academic, national laboratory, and international participants. The DBFT will involve a diverse range of technical fields.
- Informing nuclear waste regulators and policymakers. The DBFT program can provide technical rationale for new regulations that control DBD.
- Demonstrating the resource commitments that would be needed to field a DBD program.

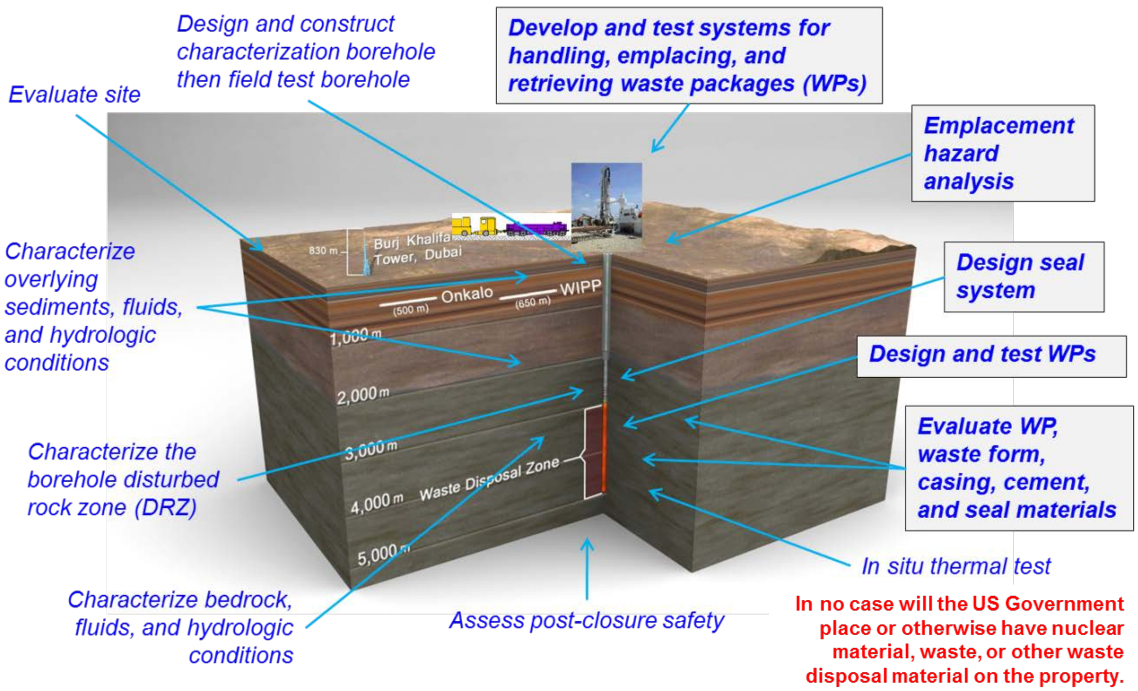


Figure 1-2. Objectives of the DBFT, with engineering objectives highlighted.

1.3.1 Scope of DBFT

A five-year schedule of major milestones for the DBFT has been established (DOE 2012; SNL 2014). Field activities are scheduled to begin after selection of a site and management contractor (DOE 2015). After selection there will be a phase in which drilling and borehole technology specialists, working with geoscientists and support personnel, plan the details of the characterization borehole (CB). The CB will be vertical and drilled to approximately 16,400 ft

(5 km) at a diameter of 8.5 inches, to evaluate drilling conditions and to perform characterization studies (Kuhlman et al. 2015). The drilling phase will include initial logging and downhole testing, and coring of selected intervals. The CB will be lined with steel casing from the surface to a depth of approximately 2 km, with open hole below that for testing. The testing phase will follow, and involve additional logging and testing (SNL 2015). The actual scope of testing could be impacted by borehole observations such as the distribution of permeability and the extent of borehole breakouts. Additional testing may be performed later such as a borehole heater test (*in situ* thermal test; Figure 1-2).

When sufficient experience has been acquired with drilling and testing in the CB, a decision will be made whether to proceed with drilling a larger-diameter FTB (or whether the CB can be used for the remaining DBFT field activities). The primary purpose of the larger borehole will be to demonstrate drilling and construction methods. The combination of 17-inch diameter and total depth of 16,400 ft in crystalline rock is at or near the margin of the envelope representing worldwide drilling accomplishments (Beswick 2008), although larger deep boreholes have been proposed (Beswick et al. 2014).

In addition to large-diameter deep drilling, engineering demonstration activities will include design and fabrication of test packages and handling equipment, package testing, and demonstration of package handling and emplacement/retrieval in the FTB. The demonstration will emphasize developmental aspects unique to possible future DBD. It will include fabrication and testing of test packages (simulated WPs not containing radioactive waste), integrated testing of handling and emplacement equipment, and downhole emplacement/retrieval of test packages. Instrumentation will monitor downhole conditions encountered by test packages, such as temperature and accelerations. The demonstration will also develop a working interface between nuclear materials handling specialists and borehole contractors (e.g., drilling, wireline logging) that would be required for future disposal operations. Design of test packages, instrumentation, and handling equipment will proceed in parallel with drilling and testing activities.

There may be a need for borehole seals during the thermal period (Hardin et al. 2016). Many sealing materials are available, and R&D is underway to understand the evolution of representative materials over hundreds to thousands of years. The current approach is to investigate the properties and stability of cementitious and clay-based materials (e.g., bentonite), starting with cements that are used in oil and gas wells because they are emplaced successfully in deep boreholes. Much can be learned in the laboratory about the properties and longevity of prospective sealing materials without the expense of *in situ* testing. A field test of seal emplacement could eventually be performed at full depth of up to 10,000 ft (3 km).

1.3.2 Performance Objectives for the DBFT

The foremost performance objective for conduct of the DBFT is to demonstrate safe operations in all aspects of the test. No radioactive waste will be used in the DBFT, but significant occupational hazards may exist. Whereas safety experience has improved for modern drill rigs since reforms were begun in the 1990’s (Hansen et al. 1993; API 2014), the processes and equipment used for the DBFT may be first-of-a-kind, or push the limits of existing technologies. Application of safety management to DBFT activities is addressed in the proposed project requirements (Section 2.3).

The FTB diameter is planned to be 17 inches at 5 km total depth. This is likely attainable using existing technology (Beswick 2008) although few similar boreholes have been drilled. Drilling and construction of the FTB will follow standard practices although the lifts involved may be large (but within the range of previous constructions). Successful drilling and construction of the FTB is also an important performance objective of the DBFT.

Another objective is to develop operational experience, to which all downhole activities associated with the DBFT will contribute. Various characterization methods will be tried, some of which may not have been used in the crystalline basement. Experience gained from the DBFT can be used to characterize other sites with similar geologic characteristics. Packaging and handling technologies used for DBFT test packages will be similar to current practices, but the packages will perform in the downhole environment. Emplacement and retrieval of test packages in the FTB will be novel, with some precedents in the oil and gas industry, but with new equipment and reliability objectives.

Another objective of the DBFT is to develop the sealing system for disposal boreholes, based primarily on laboratory investigations of sealing material behaviors, and modeling/simulation. Sealing requirements will be developed and emplacement methods will be developed for possible field demonstration.

Eventually, the DBFT boreholes will be made available to the scientific and engineering R&D community as a deep borehole underground laboratory. Heater tests, tests of seal emplacement and performance, or other tests can be conducted when planned DBFT activities have concluded.

1.3.3 DBFT Engineering Demonstration Design and Implementation Process

The engineering demonstration parts of the DBFT will begin with conceptual design, completed by this report, and proceed to preliminary and final design, fabrication, testing, and demonstration in the FTB. Sealing R&D will be conducted throughout this timeframe. These phases are planned to be executed over a 4-year period culminating in FY19 (Table 1-1).

1.3.4 DBFT Engineering Demonstration Roles and Responsibilities

The DBFT is funded and managed by the U.S. Department of Energy (DOE), Office of Used Nuclear Fuel Disposition. Site ownership and management will be provided under contract (DOE 2015). The site management organization will contract for, and coordinate drilling and all related services. Technical leadership of the project is the responsibility of the DOE, support by national laboratories and other technical organizations under the lead of Sandia National Laboratories (SNL). Engineering services will be contracted for the DBFT engineering activities (Table 1-1), which were initiated by SNL but will transition to the engineering support contractor, with the exception of sealing studies which will remain a multi-participant R&D effort.

Table 1-1. DBFT engineering demonstration multi-year program.

Activity	Time Frame	Engineering Services Contractor Support
Conceptual Design Development	FY15	✓
Conceptual Design Report (this report) • Requirements • Emplacement Options • Hazard/Risk Analysis • Test Package Concepts • Surface Handling/Transfer Concepts • Engineering Analysis	FY16	
Preliminary/Final Design • Design Publications • Design/Fabrication Specifications/Costing • Safety Manual/Procedures/Test Specifications • Transport Cask Integration	FY17*	✓
Fabrication	FY18*	✓
Shop Testing/Integrated Test Facility	FY18-19*	✓
Field Implementation	FY19*	✓
Sealing Studies	FY15-19*	
* Assumes availability of funding, and also that sufficient progress is achieved in other aspects of the DBFT such as siting and borehole construction.		

References for Section 1

Anderson, V. K. 2004. *An Evaluation of the Feasibility of Disposal of Nuclear Waste in Very Deep Boreholes*. SM Thesis, Dept. of Nuclear Science and Engineering, The Massachusetts Institute of Technology, Cambridge, Mass.

API (American Petroleum Institute) 2014. *API Commitment to Safety: Onshore Oil and Gas Extraction.* (www.api.org/environment-health-and-safety/health-safety/process-safety-industry/onshore-oil-gas-extraction).

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2. Basis for DBFT Design

This section summarizes the DBD safety case and expected preclosure and postclosure conditions, and presents technical information about the reference DBD concept, emplacement method options, equipment, and the requirements and assumptions proposed to move the design process forward. 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 the FTB and in disposal boreholes, for convenience in describing force, torque, temperature, power and other quantities, and for discussing results published elsewhere.

2.1 Summary of Deep Borehole Disposal Safety Case

Preclosure and postclosure risks 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). Thermal convection and the effects of seals are evaluated further in Section 5.3.

Preclosure Safety

The DBFT will support a 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 (off-normal events are discussed further in Appendices A and C). 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.

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). The CB will use state-of-the-art methods to characterize hydrologic, chemical, and isotopic signatures for interpretation of groundwater provenance and apparent age (Kuhlman et al. 2015).

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 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 deep borehole disposal. In addition, geochemically reducing conditions in the deep subsurface limit the solubility and enhance sorption of many radionuclides, leading to limited mobility in groundwater.

While the DBFT will not involve testing with or disposal of radioactive waste of any kind at the DBFT site, the postclosure safety case has been taken into account in developing the DBFT engineering demonstration and associated tests. Requirements, assumptions, test descriptions, and engineering analyses (Sections 2, 3 and 4) have been developed with a view to engineering a disposal system that meets postclosure safety objectives.

2.2 Preclosure and Postclosure Conditions for Deep Borehole Disposal

This section presents an overview of preclosure and postclosure conditions associated with DBD that could guide the selection of design solutions. The discussion at this stage is high-level, and a license application for DBD would have much more detail, including site-specific information. For postclosure, a license application could include a review of features, events, and processes (FEPs), and the basis for including or excluding the FEPs in performance assessment. Note that all conditions or FEPs discussed below may not be accounted for in developing the conceptual design of the DBFT.

Preclosure Conditions

DBD 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 U.S. 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. Near-surface burial facilities for disposal of low-level radioactive waste forms (particularly greater-than-Class-C waste) provide a reasonable model for site management and logistical considerations (Section 2.9).

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 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)

Equipment, procedures, and processes would be designed, developed, and implemented to prevent, correct, and/or mitigate the effects of these off-normal events. Some of these are included in the conceptual design for the DBFT. For example, the conceptual design of the test package described in this report includes a fishing neck to enable retrieval of the package from the borehole.

Conditions such as improper drilling or construction would be evaluated prior to waste emplacement. Similarly, borehole breakout is most likely during or shortly after construction, and would be evaluated.

Presently the DBFT system is not intended to investigate responses to natural events such as seismic ground motion or faulting, extreme weather, or flooding, which 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 also beyond the scope of the DBFT. Many of these conditions and off-normal events would be addressed as part of the siting, design, and licensing of a DBD site.

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 Ca^{2+} 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 5.3) show that for ^{137}Cs (half-life = 30.17 years) and ^{90}Sr (half-life = 29.1 years), which are the primary heat-generating fission products in SNF or HLW, temperature increases rapidly for a few months after emplacement, then approaches a peak in approximately 1 to 5 years. Boiling of fluid in the emplacement zone 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 ^{137}Cs and ^{90}Sr). 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 5.2 and 5.3.

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. Radiolysis and criticality would be analyzed as part of performance assessment for a DBD system, but are beyond the scope of the DBFT for which no radioactive waste will be used.

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% (Section 2.7.4), depending on brine composition. Some disposal concepts involve fluid-filled voids around packages or in the rock annulus (Section 2.7.4). 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 low permeability in the seal zone and the host rock around the borehole would attenuate buoyant convection (Section 5.3). 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 (Section 2.7.4). 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 (Section 3.2).

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 performance is included in the discussion of requirements (Section 2.3.10) and future R&D (Appendix D).

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 only enough water to corrode 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.

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.

As discussed in Section 2.7.4, 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.

Postclosure FEPs

The postclosure conditions summarized above are a subset of the FEPs that would be considered in a license application for a DBD project. Several exhaustive FEP lists have been developed over the years (for example, see Freeze et al. 2011). The basis for including or excluding these FEPs in performance assessment for the disposal system is beyond the scope of this report. However, the postclosure conditions that might be expected at a DBD site can be associated with FEPs that have been previously identified (Freeze et al. 2011). Table 2-1 lists the FEPs associated with the postclosure conditions (including those initiated by preclosure conditions) summarized above.

Table 2-1. Postclosure FEPs potentially relevant to DBD (adapted from Freeze et al. 2011).

FEP Number	Description	Associated FEPs
1.1.02.01	**Chemical Effects from Preclosure Operations**	• Water contaminants (explosives residue, diesel, organics, etc.) • Water chemistry different than host rock • Undesirable materials left • Accidents and unplanned events
1.1.02.02	**Mechanical Effects from Preclosure Operations**	• Creation of excavation-disturbed zone • Stress relief • Accidents and unplanned events • Enhanced flow pathways
1.1.08.01	**Deviations from Design and Inadequate Quality Control**	• Error in waste emplacement • Boreholes too close together at depth • Material and/or component defects
1.1.10.01	**Control of Repository Site**	• Active controls (controlled area) • Retention of records
1.1.13.01	**Retrievability**	• Related to postclosure safety
1.2.01.01	**Tectonic Activity – Large Scale**	• Uplift • Folding
1.2.03.02	**Seismic Activity Impacts Geosphere**	• Altered flow pathways and properties • Altered stress regimes
1.2.04.02	**Igneous Activity Impacts Geosphere**	• Altered flow pathways and properties • Altered stress regimes • Igneous intrusion
1.3.05.01	**Glacial and Ice Sheet Effects**	• Glaciation • Isostatic depression and rebound • Melt water and dilution of radionuclides in formation waters
2.1.03.01	**Early Failure of Waste Packages**	• Manufacturing defects • Improper sealing • Dropping a WP • Failure during emplacement operations
2.1.03.02	**General Corrosion of Waste Packages**	• Aqueous phase corrosion • Passive film formation and stability
2.1.03.04	**Localized Corrosion of Waste Packages**	• Pitting • Crevice corrosion • Stress corrosion cracking
2.1.07.05	**Mechanical Impact on Waste Packages**	• Waste package movement • Hydrostatic pressure • Internal gas pressure • Dropping a WP
2.1.08.02	**Flow In and Through Waste Packages**	• Saturated/Unsaturated flow
2.1.09.02	**Chemical Characteristics of Water in Waste Packages**	• Water composition (radionuclides, dissolved species, …) • Initial void chemistry (air/gas) • Water chemistry (pH, ionic strength, pCO2, ...) • Reduction-oxidation potential • Reaction kinetics
2.1.09.13	**Radionuclide Speciation and Solubility**	• Dissolved concentration limits

FEP Number	Description	Associated FEPs
2.1.09.51	**Advection of Dissolved Radionuclides in Boreholes**	• Advective properties (porosity, tortuosity) • Dispersion • Saturation
2.1.09.52	**Diffusion of Dissolved Radionuclides in Boreholes**	• Gradients (concentration, chemical potential) • Diffusive properties (diffusion coefficients) • Flow pathways and velocity • Saturation
2.1.09.53	**Sorption of Dissolved Radionuclides in Boreholes**	• Surface complexation properties • Flow pathways and velocity • Saturation
2.1.10.01	**Microbial Activity in Boreholes** **- Natural** **- Anthropogenic**	• Effects on corrosion • Formation of complexants • Formation of biofilms • Biodegradation • Biomass production • Bioaccumulation
2.1.11.01	**Heat Generation**	• Heat transfer (spatial and temporal distribution of temperature)
2.1.11.07	**Thermal-Mechanical Effects on Waste Packages**	• Thermal sensitization/phase changes • Cracking • Thermal expansion/stress/creep
2.1.11.11	**Thermally-Driven Flow (Convection)**	• Convection
2.1.12.01	**Gas Generation**	• Repository Pressurization • Mechanical Damage to Components • He generation from waste from alpha decay • H_2 generation from WP corrosion
2.1.13.01	**Radiolysis**	• Gas generation • Altered water chemistry
2.1.14.01	**Criticality In-Package**	• Formation of critical configuration
2.2.02.01	**Stratigraphy and Properties of Host Rock**	• Rock units • Thickness, lateral extent, heterogeneities, discontinuities, contacts • Physical properties • Flow pathways
2.2.05.01	**Fractures in Host Rock**	• Rock properties
2.2.05.02	**Faults in Host Rock**	• Rock properties
2.2.07.01	**Mechanical Effects on Host Rock**	• From drilling • Stress regimes
2.2.08.01	**Flow Through the Host Rock**	• Saturated flow • Fracture flow/matrix imbibition • Preferential flow pathways • Density effects on flow • Flow pathways out of host rock
2.2.08.06	**Flow Through Excavation Disturbed Zone**	• Saturated flow • Fracture/Matrix flow
2.2.09.01	**Chemical Characteristics of Groundwater in Host Rock**	• Water composition (radionuclides, dissolved species, …) • Water chemistry (temperature, pH, Eh, ionic strength …) • Reduction-oxidation potential

FEP Number	Description	Associated FEPs
		• Reaction kinetics • Interaction with engineered systems • Interaction with host rock
2.2.09.03	**Chemical Interactions and Evolution of Groundwater in Host Rock**	• Host rock composition and evolution • Evolution of water chemistry in host rock • Chemical effects on density • Interaction with engineered systems • Reaction kinetics • Mineral dissolution/precipitation
2.2.09.05	**Radionuclide Speciation and Solubility in Host Rock**	• Dissolved concentration limits
2.2.09.51	**Advection of Dissolved Radionuclides in Host Rock**	• Flow pathways and velocity • Advective properties (porosity, tortuosity) • Dispersion • Matrix diffusion • Saturation
2.2.09.53	**Diffusion of Dissolved Radionuclides in Host Rock**	• Gradients (concentration, chemical potential) • Diffusive properties (diffusion coefficients) • Flow pathways and velocity • Saturation
2.2.09.55	**Sorption of Dissolved Radionuclides in Host Rock**	• Surface complexation properties • Flow pathways and velocity • Saturation
2.2.09.61	**Radionuclide Transport Through Host Rock**	• Advection • Dispersion • Diffusion • Sorption
2.2.10.01	**Microbial Activity in Host Rock**	• Formation of complexants • Formation and stability of microbial colloids • Biodegradation • Bioaccumulation
2.3.07.01	**Erosion**	• Weathering • Denudation • Subsidence
2.3.08.03	**Infiltration and Recharge**	• Spatial and temporal distribution • Effect on hydraulic gradient • Effect on water table elevation

2.3 Functional and Operational Requirements for Disposal System and DBFT

This section presents requirements for DBD, and for the DBFT which must represent the engineering challenges associated with future waste handling, transport, transfer, emplacement, and possible retrieval for DBD. The discussion below (Sections 2.3.1 through 2.3.13) supports the requirements listed in Table 2-3, which is presented at the end of Section 2.3. This presentation of requirements is evolutionary and supersedes requirements given previously (SNL 2015; Hardin 2015).

The utility of the DBFT engineering demonstration will depend on how well it simulates actual conditions of disposal. This section reflects this “inheritance” by presenting parallel sets of requirements for waste disposal and the DBFT, with current gaps in available information identified by TBDs (to-be-determined items, tabulated in Appendix D). Note that TBDs may apply to DBD or the DBFT demonstration, or both, as indicated in Table D-1. Those TBDs associated with the DBFT will be addressed during design activities for the engineering demonstration, while a second purpose of this section is to inform the planning for borehole drilling, construction, and testing activities within the DBFT.

The information presented here follows typical preparations for engineering design. It includes functional and operating requirements for handling and emplacement/retrieval equipment, performance criteria, WP design and emplacement requirements, borehole construction requirements, and sealing requirements. Assumptions are identified if they could impact engineering design. Design solutions are avoided in the requirements discussion.

The basic description of the DBFT, and the reference design for a disposal system, generally follow the current project technical baseline (Arnold et al. 2011, 2013, and 2014; SNL 2014a). However, the prototype test packages developed for the DBFT, and the system to demonstrate emplacement and retrieval, will be similar to but not necessarily the same as described in this previous work. Importantly, this information will be updated as DBFT design proceeds.

The requirements from this report are presented in Table 2-3, and controlled assumptions are in Table 2-4. The following numbered subsections provide discussion and examples to clarify the requirements and assumptions.

Where information is TBD, the reasons include present lack of definition for: 1) future disposal mission with respect to waste forms; 2) siting and depths of boreholes; 3) future DBD project organization and scope; 4) regulations applicable to future DBD projects; 5) waste-specific and site-specific safety strategies; 6) confirmatory data collection associated with disposal boreholes; 7) future requirements that may be based on DBFT results; 8) long-term control and ownership of borehole sites; and 9) provisions for nuclear materials security and safeguards. It is expected that requirements and assumptions will be revisited when additional information is available in these areas.

2.3.1 Industrial Safety and Health Requirements

The most important requirements for the DBFT are to ensure worker health and safety, and to preserve environmental quality. Safety, health, and environmental quality analysis requirements for non-nuclear activities exist in various forms such as the DOE’s Integrated Safety Management System (ISMS; DOE 2008), the Environment, Health & Safety program of the American Petroleum Institute (API), the Oil and Gas Extraction Safety program (National Institute for Occupational Safety and Health), and the Engineered Safety program at Sandia

National Laboratories (SNL 2016). The broadest of these focus on both worker safety and environmental protection. Any of these overlapping programs can be adopted and used effectively in DBFT engineering design. The selection of one or another is not likely to affect the final design if safety and environmental precepts are followed. Accordingly, full implementation of the ISMS program of the sponsoring U.S. Department of Energy (DOE 2008, 2011) is identified as a DBFT requirement.

For waste disposal activities a broader framework would be used in design, encompassing radiological exposure and dose, nuclear criticality, nuclear quality assurance, nuclear material safeguards, and so on. The particulars of such a program are beyond the scope of the DBFT (TBD-01).

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., 10CFR20), including the requirement that worker doses are as low as reasonably achievable (ALARA). The particulars of such a program are beyond the scope of the DBFT, and are TBD (TBD-01).

The DBFT will not involve radioactive materials, except for sealed logging sources, which will be used in an appropriate manner and be removed after use. For the DBFT to simulate waste disposal operations, the test operations will be designed and implemented to clearly demonstrate the means of radiological protection, even though radiological protection is not required for demonstration activities. For example, actual package handling operations will make use of shielding, but for the DBFT such shielding may be simulated. To simulate shielded operations for the DBFT, the extent of shielding necessary to protect personnel will be determined in advance (Section 3.3.3).

2.3.3 Security and Safeguards Requirements

Safeguards and security of nuclear materials is beyond the scope of the DBFT (TBD-02). For the DBFT, security of field operations shall conform to standard practices of drill site management; nuclear material safeguards requirements are not applicable because of the absence of nuclear material.

2.3.4 Quality Assurance Requirements

The QA requirements for the ongoing Used Fuel Disposition R&D program are applicable to the DBFT engineering design effort (DOE 2012; SNL 2014b). The specific QA requirements for waste disposal are beyond the scope of the DBFT (TBD-03).

2.3.5 Other Statutory and Regulatory Requirements

The National Environmental Protection Act (NEPA) is applicable to any future federally supported waste disposal activities, and to the DBFT including site preparation, drilling, testing, and borehole plugging/abandonment activities. The type of NEPA assessment (e.g., categorical exclusion, environmental impact statement, or environmental assessment) for the DBFT will be determined and implemented prior to initiating field activities (TBD-04). Specific details regarding the application of the NEPA to DBD are not yet determined (TBD-04).

State and local permits are needed (e.g., for land use, drilling, or environmental controls) as appropriate, from cognizant jurisdictions. The types of permits needed vary with location, and may vary between the DBFT and any future waste disposal activities. State and local permits for the DBFT will be secured after the location is identified. Note that such permits typically implement statutory requirements for plugging and abandoning boreholes. Thus, although cementing, sealing, and plugging activities are not planned as part of the DBFT, eventually the CB and the FTB will be plugged and abandoned.

Waste disposal boreholes may be classified as injection wells in accordance with 40CFR144, but the applicability of this regulation to future deep borehole disposal projects is presently unclear (TBD-05). For the DBFT, no radioactive waste or hazardous waste will be transported to the site, nor will such wastes be introduced to the CB or FTB, so injection well requirements do not apply.

2.3.6 Functional Requirements

The DBFT has multiple objectives, including development and demonstration of scientific characterization methods for evaluating site suitability and evaluating the safety and feasibility of deep borehole disposal. Borehole drilling, characterization, and construction, and DBFT engineering development and implementation activities, will be integrated with the overall program and will be consistent with evaluation of the safety and feasibility of deep borehole disposal. The overall DBFT program (Section 1.3) will include characterization activities such as rock and groundwater sampling, flow testing, and geophysical logging. The DBFT engineering demonstration (Section 4) will simulate waste disposal with appropriate test packages and demonstrate the ability to provide protection from ionizing penetrating radiation. The characterization and engineering demonstration activities should not interfere with each other.

Future disposal activities will be performed in a manner consistent with long-term waste isolation, in accordance with a safety strategy that depends on the waste type and site-specific factors (TBD-06).

2.3.7 Operating Requirements

Operating requirements for actual waste disposal will be developed in large part based on experience from the DBFT, and hence are TBD (TBD-07).

Many of the operational requirements on the DBFT discussed below are inferred from expected features of a future disposal system.

Test packages will be fabricated and sealed at an upstream fabrication facility. Thus, test packages will be delivered to the disposal site sealed and in a condition ready for direct emplacement in the DBFT borehole(s). Welding is desirable (although not required) as a sealing method because it has been a preferred closure solution for mined geologic disposal packages in repository R&D programs.

Sealed sources may be used for well logging. Only purpose-built sealed sources shall be used for scientific testing or logging at the surface or downhole, and these shall be used in accordance with their instructions and shall be fully recovered and removed from the site at the conclusion of the DBFT.

Materials used in the CB and the FTB will be analyzed and approved before use. Material use will be logged as to quantity, date, location, and manner of introduction to the hole. These measures will help to ensure that scientific characterization data can be meaningfully interpreted and not challenged. Some of the materials controlled as part of the Material Control program will be chemical or stable-isotope tracers mixed with fluids used in the borehole. Other materials may also be tagged with tracers as deemed appropriate by scientific analysis. An effective and workable Material Control program could be adopted in future waste disposal operations to limit interference with future characterization data collection and limit potential impacts to waste isolation after waste borehole sealing and closure.

To prevent stuck test packages, a verification method such as wireline logging will be used immediately prior to package emplacement or retrieval operations to test the integrity of the borehole. Wireline logging may also be used periodically when package emplacement is not active, to monitor ongoing changes in borehole condition. The approach will be used and evaluated during DBFT test package emplacement/retrieval operations.

Accurate as-built dimensional drawings shall be maintained for all assemblies (e.g., downhole tools, test packages, etc.) and strings (e.g., casing, drill pipe, collars, etc.) introduced to the CB and FTB. The intended purpose for such drawings is for use in fishing operations.

2.3.8 Performance Requirements

Two basic performance requirements for the DBFT engineering demonstration are for test packages to maintain containment integrity (not leak), and for the handling and emplacement system to control test packages at all times without dropping packages or failing to retrieve them from the test borehole.

Engineering activities will be conducted so as to allow characterization of the hydrogeologic setting from the surface to total depth, including the overburden, seal zone, and EZ. For future waste disposal boreholes, the drilling and construction methods and characterization objectives are TBD and will be determined using experience from the DBFT (TBD-08).

Boreholes drilled for the DBFT and for future waste disposal may stand unused for long periods of time. The DBFT boreholes may become laboratories for subsurface research (see Table 2-4), while disposal boreholes may be idled during license proceedings, delays in waste preparation, and so forth. Because of the potentially long duration of active operations, a service lifetime of 10 years is adopted for the DBFT and is TBD for disposal (TBD-09). This service lifetime should be long enough to resolve the uncertainties involved with casing corrosion, formation creep, and other time-dependent degradation processes in the downhole environment.

2.3.9 Borehole Design and Construction Requirements

Guidance casing is required for DBD and for the FTB to avoid packages getting stuck and to facilitate package emplacement and retrieval (during the DBFT). Arnold et al. (2011) specified slotted or perforated casing in the EZ to allow for cementing the annulus behind the casing, and to allow borehole fluid heated by WPs to expand into the host rock rather than building up pressure that could damage plugs or seals. While guidance casing is required for DBD and the FTB, the manner of perforating the casing in the EZ is TBD (TBD-47). Options for EZ completion for DBD are presented in Section 2.7.4.

Borehole horizontal deviation is specified by Arnold et al. (2011) to prevent multiple disposal boreholes from intercepting at depth, and to promote heat dissipation. A maximum deviation of 50 m ensures that adjacent disposal boreholes do not intersect, and are at least 100 m apart over the extent of the EZ, if the collar spacing is at least 200 m. For the CB a more relaxed deviation of 100 m is specified because it does not represent the type of borehole intended for waste disposal. However, this does not preclude the possibility of deploying the test package handling and emplacement systems in the CB.

The requirement to limit dogleg severity will reduce the potential for stuck packages (or tubulars during drilling and construction). Dogleg severity (typically expressed in degrees per change in depth, e.g., degrees per 100 ft) reflects borehole curvature, not deviation. Permissible dogleg severity is determined as a function of borehole or casing diameter, diameter of strings being run in the borehole, bending stress, material properties (e.g., steel grade), spacing and type of tool joints (controls stiffness), and buoyant weight (particularly for assemblies lowered on wireline). The assumed value for maximum acceptable dogleg severity for the DBFT (Table 2-4) is based on expert judgment as to manageable conditions, but does not represent what may be achievable with a rotary steering system (RSS). Maximum dogleg for DBD will depend in part on drilling methods selected using DBFT experience (TBD-10). The importance of dogleg and the need to control it means that directional drilling capability should be assumed (TBD-11; Table 2-4).

As a practical matter all boreholes will have some deviation so that drill pipe, packages, wireline tools, etc., will slide or rest against the "low" side. This means that packages and downhole tools will generally contact the casing, so the internal surface of the casing should be smooth with uniform diameter over the full borehole length, and centralizers should be used where cementing is planned.

Test packages may be up to 11 inches in diameter (Section 2.3.10); therefore, borehole and casing diameters shall permit emplacement of test packages up to 11 inches in diameter with a radial clearance of up to 13/16 inches. For DBD, the radial clearance for WPs is TBD (TBD-14); hence, WP, borehole, and casing diameters are TBD as well.

Heater tests are not planned for the DBFT, so thermal expansion of fluids and solids will be minimal. For DBD, however, heat generated by the emplaced waste may lead to thermal expansion of fluids and solids. Casing, cement, and other features of EZ completion for DBD shall accommodate thermal expansion of fluids and solids due to waste heating without breaching packages, plugs, casing, or seals. Design features necessary to meet this requirement have not yet been specified (TBD-12).

In disposal boreholes the seal zone will be initially open and uncemented, regardless of the type of EZ completion. Both the guidance casing and the intermediate casing in this zone (nominally 2 to 3 km depth) will be removed so the borehole can be sealed after waste emplacement (Arnold et al. 2011). In the FTB the seal zone will also be uncemented, but the guidance casing and intermediate casing may be left in place, and no installation of seals or *in situ* testing of sealing methods for waste isolation is currently planned. For the DBFT CB casing removal is not required because the borehole will not be sealed. For DBFT follow-on testing activities consideration may be given to demonstrating casing removal.

The reference disposal concept calls for bridge plugs within the guidance casing, spaced about 200 m apart in the EZ, with approximately 10 m of cement placed over each bridge plug to bear the weight of WPs (see Section 2.7.4 for options discussion). The resulting cement plug would support emplacement of additional packages in the guidance casing (to prevent overloading the lowermost package), and support the guidance casing against the borehole wall (to prevent overloading the casing). Cement plugs installed in the EZ shall be designed for removal to facilitate waste retrieval.

For the DBFT, plugs will not be installed in the CB or FTB because they would interfere with availability of the boreholes for additional testing. This does not preclude installing cement at the bottom of either borehole as part of guidance casing installation, nor does it preclude installing plugs near the surface in preparation for closing and abandoning the borehole, as required by the permitting authority.

Blowout preventers (BOPs) are used during drilling, and may also be required by permitting authorities for borehole construction and downhole testing/logging activities. It is not known if a BOP will be required for all of these activities; therefore, for the DBFT, test package handling, transfer, and emplacement/retrieval equipment shall be configured so that these operations can be performed with or without a BOP in place (TBD-22).

2.3.10 Waste Packaging Requirements

For DBD, WP containment is required through all phases of disposal operations, until the borehole is sealed (TBD-19). Additional containment longevity may be required depending on the disposal environment, radionuclide half-life, and other properties of the waste (TBD-32, TBD-40). These considerations do not apply to DBFT test packages which will be retrieved immediately. However, test packages will be exposed to multi-molal concentrations of Cl, Na, Ca, and possibly Mg ions, so test package material shall be selected accordingly. The DBFT will demonstrate that packages can be designed, fabricated, loaded, sealed, emplaced and retrieved without loss or leakage. Packages will be inspected for damage and leakage after the conclusion of emplacement/retrieval operations.

Mechanical integrity means appropriate 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 TBD (TBD-48)

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 (Table 2-4). The minimum hydrostatic pressure at the bottom of the borehole is based on the density of pure water (ignoring temperature effect 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; TBD-15).

A minimum factor of safety of 2.0 with respect to yield strength, for numerical analysis of deformation in response to combined loading, 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 factor-of-safety (FoS) should be reasonably conservative, and comparable to other critical applications in pressurized systems (e.g., pipelines, 49CFR192). 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, API “5CT” collapse ratings take into account -12.5% variation of wall thickness (Arnold et al. 2011, Section 3.4).

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, and the consequences of a breached WP in DBD are comparable to, and possibly more costly than blowouts in oil and gas production, suggesting a greater factor of safety (Appendix C).

The consequences of accidental breach during operations include radiological contamination of the borehole, surface equipment, and the basement rock unit. The reference casing plan of Arnold et al. (2011) would prevent contaminated wellbore fluid from flowing to the overburden directly. For actual WPs, the design FoS will depend on results obtained in the DBFT (TBD-16).

Temperature rise from emplacement of waste will vary with waste characteristics and packaging. A maximum WP temperature of 250°C is assumed for stress analysis of DBD WPs (Table 2-4; TBD-18). For the DBFT, test packages shall perform at the maximum naturally occurring bottom-hole temperature assumed (Table 2-4). Note that for a given maximum package temperature limit, both the *in situ* formation temperature and the temperature rise due to waste heating are important. Thus, a greater rise might be accommodated at shallower depth in the EZ.

The magnitudes of peak temperatures will affect package design where the factor of safety is defined with respect to yield, and the yield strength decreases with temperature (Sections 5.1 through 5.3). Peak temperatures for DBD and DBFT test packages are assumed as discussed in Section 2.4.

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 DBFT: small, intermediate, and the large or reference size (Table 2-2). 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.

As discussed below, for the reference packages (test packages or disposal WPs) the maximum diameter is 11 inches, and for the small packages it is 5 inches. For the DBFT the large size would be used in the FTB, and the small size could be used in the CB if appropriate. Note that these diameters are reference values, and protrusions from the package surface may be permissible as discussed below.

The diameter of WPs depends on the diameter of guidance casing, and the specified radial clearance. Radial clearance between the packages and the casing internal 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 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 2-2). Radial clearance for WPs used in DBD will be determined using experience from the DBFT (TBD-14). Other package dimensions such as overpack IDs are discussed in Section 3.2.

Table 2-2. 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 (nominal) (m) (in)	0.216 8.5”	0.311 12-1/4”	0.432 17”
Guidance Casing OD (nominal) (m) (in)	0.178 7”	0.273 10-3/4”	0.340 13-3/8”
Guidance Casing ID (nominal) (m) (in)	0.162 6.366”	0.245 10.050”	0.321 12-615”
Package OD (nominal) (m) (in)	0.127 5”	0.219 8-5/8”	0.279 11”
Radial Gap (nominal) (m) (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).

Note that radial clearances for different size packages are given as nominal values in Table 2-2. 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 (Section 5.4).

Test packages for the DBFT will have smooth external surfaces, with API standard threaded connections at the ends. The smooth exterior is intended to prevent hangup on casing joints, shoes, collars, etc. The requirement also applies to waste disposal packages. 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 (TBD-44).

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 (including spent fuel as analyzed by Arnold et al. 2011). Limiting package length limits the weights of both the transportation cask and transfer cask, which is important because legal-weight truck transport of these components is an objective (Table 2-3). 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.

Package design is required to be extensible, i.e., such that packages can be readily made shorter or longer. Overall length for DBFT test packages with wireline latch and impact limiter attached, is limited to approximately 4.5 m or as required to fit within the LWT (legal-weight truck) transportation cask from NAC International (Section 3.3). The length of WPs for DBD will be determined in the future (TBD-13).

Test packages will have negative buoyancy in emplacement fluid of the maximum density (see assumptions on fluid density in Table 2-4) 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). The same requirement applies to actual WPs, but the maximum fluid density in disposal boreholes is TBD (TBD-15). The maximum weight of test packages and packages for DBD is discussed in Section 2.4.

At least one test package will be configured similar to test packages described above, but containing an instrument module to measure motion, temperature, and pressure during emplacement and retrieval downhole. Measurements will include 6-axis accelerations (linear and rotational). The instrumentation test package will have an operable closure for installation of and access to the instrument module in the field.

Definition of test package leakage criteria shall be determined in design activities for the DBFT (TBD-20). Repeated helium leak tests of the type used for pressure vessels (after charging the sealed vessel with helium at pressure) is a useful benchmark for leak testing performance. Such a test should be performed on one or more sealed test packages after fabrication, after pressure testing and drop testing, and after the field demonstration.

2.3.11 Package Surface Handling/Transfer Requirements

Shielding is required for future DBD operations, but the level of shielding depends on the waste form (TBD-37). The need for shielding in a DBD system will be recognized and accounted for in the DBFT demonstration, although shielding may be mocked up.

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. Design solutions for accomplishing this are discussed in Section 2.7.4. Specific well control requirements for the transfer cask and associated surface equipment for DBD and for the DBFT are TBD (TBD-38).

For the DBFT, test packages will be transport by legal-weight trucks. For DBD, the means of transport of WPs has not yet been determined (TBD-45).

2.3.12 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). For the DBFT demonstration, retrieval means that test packages will be emplaced, released, then reattached and hoisted from the borehole. This definition replicates all the emplacement and retrieval steps except those that could require installation and removal of plugs or seals. Regulatory requirements for retrievability of waste from DBD are TBD (TBD-39).

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 on waste disposal boreholes will depend on site-specific conditions and history of nearby drilling activities. For the DBFT, BOPs could be required especially if history is not available from prior drilling. Accordingly, test package emplacement and retrieval equipment will be designed to function with or without blowout preventers in place on the FTB wellhead.

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 (TBD-50).

For DBFT, the minimum density of any fluid in the borehole at any location, when packages are being emplaced, shall be that of water, and the maximum average fluid density from the surface to any depth in the borehole, shall be controlled (see Table 2-4). For DBD, 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 (TBD-15). These parameters control buoyant weight of packages, and borehole hydrostatic pressure.

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, etc. The fluid used in the DBFT demonstration shall be selected carefully, considering the many effects that the fluid has on borehole operation and package emplacement. The exact composition of the fluid has not yet been determined for either the DBFT or DBD (TBD-28).

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 (TBD-31). 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.

2.3.13 Borehole Sealing Requirements

In DBD boreholes the seal zone will be completed using multiple sealing materials, including a low-permeability material (e.g., less than 10^{-16} m^2 permeability) that seals against the borehole wall. Sealing material installed immediately above the EZ will function at temperatures up to approximately 200°C and will retain its properties throughout the thermal period, which could last on the order of a few hundred years after emplacement depending on the type of heat-generating waste. Note that seals would be installed above a 10-m cement plug above the top package in the EZ, and that because of heat dissipation only a portion of the overall seal zone would be subject to elevated temperature from waste heating.

Seal types could include one or more that resist mechanical loading, for example from borehole wall collapse, or from pressure differences in the borehole. Seals will be designed as a system with multiple, redundant components and materials to ensure system function even after failure of a single sealing element or material. The DBFT does not include any *in situ* emplacement or testing of seals. Requirements addressing compatibility between plugs and seals in the sealing zone, and other components of the DBD system are not determined (TBD-46).

Table 2-3. Requirements for the DBFT, and cross-walk with waste disposal requirements.

Waste Disposal Requirement	Deep Borehole Field Test Requirement
2.3.1 Industrial Safety and Health	
DBD Operational Safety Basis – – Requirements for radiological exposure and dose, nuclear criticality, nuclear quality assurance, nuclear material safeguards, etc. are beyond the scope of the DBFT and are TBD (TBD-01 and TBD-07).	**Integrated Safety Management** – The Department of Energy's ISMS policies and procedures shall apply to the DBFT.
2.3.2 Radiological Protection	
Radiation Exposure to Workers and the Public – Waste package loading, sealing, handling, transport, emplacement, and retrieval equipment and operations shall comply with applicable radiological dose standards (e.g., 10CFR20). Engineered measures shall maintain exposures as low as reasonably achievable (see TBD-01).	**Radioactive Materials –** Radioactive sealed sources will be used in an appropriate manner for well logging and removed after use. No other designated radioactive materials or any radioactive wastes will be used in the DBFT.
	Demonstrate Radiological Protection – DBFT test package handling, emplacement, and retrieval shall be performed so as to demonstrate that radiation exposure to workers could be limited effectively.
2.3.3 Safeguards and Security Requirements	
Nuclear Material Safeguards – Safeguards and security requirements for DBD of radioactive waste are TBD (TBD-02).	**Field Site Security** – Security of field operations shall conform to standard practices of drill site management. Nuclear material safeguards requirements are not applicable.
2.3.4 Quality Assurance Requirements	
Quality Assurance – QA requirements for DBD are TBD (TBD-03).	**Quality Assurance** – The Office Fuel Cycle Technology R&D, Office of Used Nuclear Fuel Disposition, QA program, or equivalent, shall apply to the DBFT.
2.3.5 Other Statutory and Regulatory Requirements	
NEPA – The National Environmental Protection Act is applicable to borehole disposal activities but specific details are not yet determined (TBD-04).	**NEPA** – The National Environmental Protection Act is applicable to test borehole drilling, testing, and borehole plugging/abandonment activities. The type of NEPA assessment will be determined and implemented prior to initiating field activities (TBD-04).
State/Local Administered Permits – Drilling, land use, and environmental permits are required, as appropriate, from cognizant jurisdictions.	**State/Local Administered Permits** – Drilling, land use, and environmental permits are required, as appropriate, from cognizant jurisdictions.
Injection Well Requirements – Applicability of injection well regulations such as 40CFR144 to deep borehole disposal of radioactive wastes is not determined (TBD-05).	**Injection Well Requirements –** Injection well requirements do not apply to the DBFT because no radioactive or hazardous waste will be introduced into either the CB or the FTB.

Waste Disposal Requirement	Deep Borehole Field Test Requirement
2.3.6 Functional Requirements	
Safe Disposal – Radioactive waste disposal activities will be performed in a manner consistent with long-term waste isolation, in accordance with a safety strategy that depends on the waste type and site-specific factors (TBD-06).	**Effective Characterization/Evaluation** – Borehole drilling, characterization, construction, testing, emplacement, and retrieval activities shall support evaluation of the safety and feasibility of deep borehole disposal.
2.3.7 Operating Requirements	
Operational requirements for waste disposal operations are TBD (TBD-07).	**Test Package Sealing** – Test packages shall be sealed at an upstream fabrication facility. Exception is the instrumentation test package which will have an operable closure (Section 2.3.10).
	Sealed-Source Well Logging – Only purpose-built sealed sources shall be used for scientific testing or logging at the surface or downhole, and these shall be fully recovered and removed from the DBFT site.
	Material Control – A Material Control Program will be implemented. Materials used in the CB and FTB shall be restricted to those on a list maintained by the on-site Project Manager.
	Material Inventory – Materials used in the boreholes shall be logged, recording type, quantity, date of use, location of use, and manner of introduction.
	Water Tracer – All fluids (including makeup water) that are introduced to the DBFT boreholes shall be tagged with one or more conservative tracers that are selected so that the presence of such fluid can be appropriately quantified in any solid or fluid samples recovered for analysis.
	Borehole Integrity Testing – A wireline log will be used to test the integrity of the path from the surface to emplacement depth, prior to test package emplacement demonstration.
	Borehole As-Built Drawings - Accurate as-built dimensional drawings shall be maintained for all assemblies (e.g., downhole tools, test packages, etc.) and strings (e.g., casing, drill pipe, collars, etc.) introduced to the CB and FTB. The intended purpose for such drawings is for use in fishing operations.
2.3.8 Performance Criteria	
Waste Handling and Emplacement System Performance – Waste packages shall provide containment, and shall be maintained in control at all times during emplacement operations (and retrieval, if necessary).	**DBFT Engineering Demonstration Performance** – Test packages shall provide containment, and shall be maintained in control at all times during emplacement/retrieval demonstration.

Waste Disposal Requirement	Deep Borehole Field Test Requirement
Drilling and Construction Methods – Drilling and construction of waste disposal boreholes shall be conducted using methods selected for successful completion, waste isolation performance, and achieving characterization objectives. Specific performance criteria have not yet been determined (TBD-08).	**DBFT Drilling and Construction Methods** – Drilling and construction of the CB and FTB shall be conducted using methods that will allow successful completion of engineering activities and will achieve characterization objectives.
Disposal Borehole Service Life – Borehole construction, completion, and associated surface facilities shall be designed with service lifetime sufficient to accommodate safe disposal operations and sealing. A specific lifetime has not yet been determined (TBD-09).	**FTB Service Life** – Service lifetime of the FTB shall be 10 years, considering casing corrosion, creep, and other significant time-dependent processes (TBD-09).
2.3.9 Borehole Design and Construction	
Guidance Casing – A casing of constant diameter shall be run from the surface to total depth of disposal boreholes (possibly in sections) for transit of WPs to the EZ. The manner of perforating the guidance casing is TBD (TBD-47).	**Guidance Casing –** A casing of constant diameter shall be run from the surface to total depth of the FTB, for transit of test packages to the EZ and back to the surface. The guidance casing will not be plugged, cemented, or removed for the DBFT. The manner of perforating the casing (prefabrication or *in situ*; size and number of perforations) is TBD (TBD-47).
Borehole Deviation – Waste disposal boreholes shall be constructed so that: 1) horizontal deviation does not exceed 50 m; and 2) maximum dogleg severity specifications are met (TBD-10).	**FTB Deviation** – The FTB shall be constructed so that: 1) horizontal deviation does not exceed 50 m; and 2) maximum dogleg severity is met (see Table 2-4).
	CB Deviation – The CB shall be constructed so that: 1) horizontal deviation does not exceed 100 m; and 2) maximum dogleg severity is met (see Table 2-4).
Casing Internally Flush for Emplacement – Guidance casing shall be internally flush with uniform diameter over the full borehole length.	**Casing Internally Flush for Testing** – Guidance casing shall be internally flush with uniform diameter over the full borehole length.
Disposal Borehole Diameter – Disposal borehole and casing diameters shall permit emplacement of WPs with sufficient radial clearance (TBD-14).	**FTB Diameter** – Borehole and casing diameters shall permit emplacement of test packages up to 11 inches in diameter, with radial clearance as discussed below and in Section 2.3.10.
Thermal Expansion in the Emplacement Zone – Casing, cement, and other features of EZ completion shall accommodate thermal expansion of fluids and solids due to waste heating without breaching packages, plugs, casing, or seals. (TBD-12).	**Thermal Expansion in Heater Test –** A heater test is not currently planned for the DBFT.
Sealing Zone – Permanent seal(s) shall be installed in a borehole interval directly above the EZ.	**Test Borehole Sealing** – Permanent seals that simulate those to be installed for waste isolation shall not be installed in the CB and FTB.
Seal Zone Casing Removal – Casing shall be removed from the borehole seal zone, exposing the rock where seals are to be set.	**Casing Removal from Test Boreholes** – Removal of casing from a designated seal zone in the CB and FTB shall be possible, although removal is not planned.

Waste Disposal Requirement	Deep Borehole Field Test Requirement
Emplacement Zone Plugging – Plugs shall be installed in the EZ to stabilize stacks of WPs and limit axial compressive loading of packages (see Section 2.7.4).	**Test Borehole Plugging** – Plugs shall not be installed in the CB or FTB in a manner that could interfere with availability of the borehole for additional testing.
Emplacement Zone Plug Removal – Plugs installed in the EZ shall be designed for removal to facilitate waste retrieval (see Section 2.7.4).	**Test Borehole Emplacement Zone Plug Removal** – Plugs shall not be installed in the EZ in the CB or the FTB, so there is no requirement to be able to remove them.
BOPs on Disposal Boreholes – The need for wellhead blowout prevention equipment in waste disposal boreholes is TBD (TBD-22).	**BOPs on DBFT Boreholes** – Test package handling, transfer, and emplacement/retrieval equipment shall be configured so that these operations can be performed with or without a blowout preventer stack in place (TBD-22).
2.3.10 Waste Packaging Requirements	
Waste Package Containment – Waste packages shall prevent leakage of radioactive waste (solid, liquid or gaseous) throughout the operational phase during transport, handling, emplacement, and borehole sealing. Also, no leakage of borehole fluid into packages shall occur during these activities (TBD-19).	**Test Package Containment** – Test packages shall prevent leakage of borehole fluid into the packages during repeated testing, emplacement and retrieval. Test packages will be inspected for damage and leakage after the conclusion of emplacement/retrieval operations.
Waste Package Containment Longevity – Containment lifetime after borehole sealing and closure shall be consistent with the licensed safety strategy (TBD-40).	**Test Package Containment Longevity** – Test packages will be retrieved before corrosion is expected to be important, so there are no requirements on corrosion resistance for test packages. However, test packages will be exposed to multi-molal concentrations of Cl, Na, Ca, and possibly Mg ions, so test package material shall be selected accordingly.
Waste Package Mechanical Integrity – Waste packages shall maintain mechanical integrity (structural, dimensional) during transport, handling, emplacement, plugging, and sealing. Mechanical load limits for WP design are TBD (TBD-48).	**Test Package Mechanical Integrity** – Test packages shall maintain mechanical integrity (structural, dimensional) during transport, handling, emplacement, and retrieval.
Emplacement Zone Pressure – Waste packages shall perform in borehole fluid (water or mud) with minimum pressure consistent with pure water density and borehole depth, and maximum pressure TBD (TBD-15).	**Test Emplacement Zone Pressure** – Test packages shall withstand the hydrostatic pressure in borehole fluid at a maximum pressure consistent with assumed borehole depth and fluid density (Table 2-4).
Waste Package Factor of Safety – FoS for mechanical integrity calculations will be based in part on DBFT results and is TBD (TBD-16).	**Test Package Factor of Safety** – FoS for mechanical analysis shall be 2.0 with respect to minimum yield strength (reduced for temperature effect), for loading conditions encountered in handling, transfer, emplacement, and retrieval operations.
Waste Package Temperature During and After Emplacement – Waste packages shall perform at	**Test Package Temperature** – Test packages shall perform at the maximum naturally occurring bottom-

Waste Disposal Requirement	Deep Borehole Field Test Requirement
the maximum waste-heated package temperature assumed, 250°C (Section 2.4; TBD-18).	hole temperature assumed (Section 2.4; TBD-17).
Waste Package Diameter and Radial Clearance – Disposal package diameter and radial clearance will be determined based on the DBFT results and are TBD (TBD-14).	**Test Package Diameter** – Test packages for the DBFT demonstration shall have a maximum OD of 11 inches. Small protrusions may be permitted if they do not interfere with emplacement or terminal velocity of free-falling packages in the borehole, or cause other requirements to be violated.
	Radial Clearance – For the DBFT, the radial clearance between the WP and the casing shall be between 11/16 and 13/16" (Section 2.3.10).
Waste Package Smooth Exterior – The exterior WP surface, including connectors, shall be smooth and free of features that could hang up on casing joints, hangers, collars, etc., when moving upward or downward.	**Test Package Smooth Exterior** – The exterior test package surface, including connectors, shall be smooth and free of features that could hang up on casing joints, hangers, collars, etc., when moving upward or downward.
Waste Package Connections – Waste package connections will be determined based partly on DBFT results (TBD-44).	**Test Package Connections** – Test packages shall have integral features for connection to: 1) wireline above; and 2) impact limiters below. Connections shall have sufficient strength to withstand mechanical loads during emplacement, retrieval, and fishing (using a drill-string).
Waste Package Length – Waste package length for DBD is TBD (TBD-13).	**Test Package Length** – Test package length shall be extensible by design, i.e., readily made shorter or longer. Package length for the DBFT will be limited to approximately 4.5 m (fits inside the LWT transport cask).
Waste Package Buoyancy – Waste packages, including the waste load, shall have negative buoyancy in borehole fluid (TBD-15) to prevent packages floating.	**Test Package Buoyancy** – Test packages, including any contained hardware or instrumentation, shall have negative buoyancy in borehole fluid of maximum density (Table 2-4) to prevent floating.
Downhole Instrumentation – Instrumentation to be used during DBD operations is TBD and will be based at least partly on DBFT experience (TBD-21).	**Instrumentation Test Package –** At least one test package for the DBFT will contain instrumentation to monitor emplacement/retrieval conditions downhole. The instrumentation test package shall have operable closure for insertion of the instrument module, and access to it in the field. Measurements shall include 6-axis accelerations, temperature, and pressure.

Waste Disposal Requirement	Deep Borehole Field Test Requirement
Waste Package Leakage – Leakage control requirements for WPs during operations are TBD (TBD-20).	**Test Package Leakage** – A leak detection strategy will be developed during design activities for the DBFT (TBD-20).
2.3.11 Package Surface Handling/Transfer	
Shielding – Shielding is required for DBD operations, but the level of shielding depends on waste form characteristics and packaging (TBD-37).	**Shielding in the DBFT** – The need for shielding will be recognized and accounted for in the DBFT demonstration, although the shielding itself may be mocked up.
Well Control for Disposal Boreholes – Well control functions for the transfer cask and attachments are TBD (TBD-38).	**Well Control Function of DBFT Transfer Cask** – The transfer cask and associated end fittings shall be part of the well control pressure envelope, and capable of withstanding and containing positive pressure during emplacement operations, without resort to blowout preventer(s) that could damage packages or wireline tools, or sever a wireline (TBD-38).
	Interchangeability of Well Control Equipment – Attachments to the transfer cask for well control, particularly at the upper end, shall be designed for interchangeability so that they can be changed out depending on conditions in the borehole, or permit requirements (TBD-38).
Transport for DBD – The means of transport for DBD is TBD (TBD-45).	**Shipping by Legal-Weight Truck** – Transportation casks (if used, loaded or unloaded) and transfer casks (unloaded) shall be movable using legal-weight truck transport.
2.3.12 Package Emplacement and Retrieval	
Waste Package Emplacement – Waste packages shall be emplaced at the intended positions in the EZ, and shall not become stuck anywhere else in the disposal borehole.	**Test Package Emplacement** – Test packages shall be emplaced at their intended positions and shall not become stuck anywhere within the FTB. Emplacement equipment shall be designed to function with or without a BOP in place.
Waste Package Retrieval – – Retrievability and reversibility (as applicable) requirements for future DBD are TBD (TBD-39).	**Test Package Retrieval** – The term retrieval shall be taken to mean that test packages are emplaced, released, reattached, hoisted from the borehole, and handled in reverse order of the steps that were used to emplace them.
Emplacement System Redundancy – Transfer and emplacement equipment shall have redundant means for holding WPs at the surface during staging so that single-point failures cannot result in a dropped WP (TBD-50).	**Emplacement System Redundancy** –Wellhead equipment, and apparatus for test package transfer and emplacement, shall have redundant means for holding test packages at the surface during staging so that to the extent practical, single-point failures cannot result in a dropped package (TBD-50).
Emplacement Fluid Density – The minimum density of any fluid in the borehole at any location, when WPs are being emplaced, shall be	**Emplacement Fluid Density** – The minimum density of any fluid in the borehole at any location, when packages are being emplaced, shall be that of water,

Waste Disposal Requirement	Deep Borehole Field Test Requirement
that of water, and the maximum density is TBD (TBD-15). These parameters control buoyant weight of packages, and borehole hydrostatic pressure.	and the maximum average fluid density from the surface to any depth in the borehole, shall be controlled (see Table 2-4).
DBD Emplacement Fluid – Fluid composition for DBD emplacement is TBD, and will be determined on consideration of properties, stability, and waste isolation (TBD-28).	**DBFT Emplacement Fluid –** Fluid composition for the DBFT demonstration shall be selected so that it does not contain solids that can settle or precipitate, potentially contributing to packages becoming stuck (TBD-28).
Bottom-Hole Assembly Weight Limit - The weight of the bottom hole assembly (WP, tool string, etc.) shall not exceed the service limit of the emplacement equipment, including an appropriate FoS (TBD-31).	**Bottom-Hole Assembly Weight Limit** - For the DBFT the wireline tension shall not exceed 12,000 lb fully deployed, including the maximum buoyant weight of the wireline, WP, and the wireline tool string.
2.3.13 Borehole Sealing	
Seal Performance (TBD-46): • **Permeability** – Seals shall form a low permeability barrier (less than 10^{-16} m^2) to fluid flow within the borehole. • **Seal-Borehole Contact** – Seals shall form a low-permeability contact with the borehole walls to prevent bypass flow at the interface. • **Borehole Seal Durability** – Seals shall perform at *in situ* temperature, or if installed proximal to the EZ, at up to 200°C through the duration of the thermal period. • **Seals Environment** – Borehole seals shall resist mechanical loading, retaining low-permeability properties. • **Redundant Seal Design** – Seals and sealing materials shall be designed to provide redundant performance.	**DBFT Borehole Plugging and Sealing** - The CB and FTB will be plugged and sealed at the conclusion of testing activities. Plugging and sealing shall be in compliance with the plugging/abandonment requirements of the pertinent drilling permits. No installation of plugs or seals for waste isolation is planned as part of the DBFT.

2.4 Design Assumptions for Disposal System and DBFT

The following discussion supports the assumptions identified in Table 2-4. All TBD items are tabulated in Appendix D.

Waste Forms for Disposal

Waste forms to be disposed of in deep boreholes are identified for the purpose of designing the DBFT. The assumed waste forms to be considered for the DBFT include granular HLW materials, and HLW in sealed capsules. The waste forms to be considered in a future deep borehole waste disposal system are TBD (TBD-23).

Borehole Depth

The depth of DBFT boreholes is assumed to be 5 km, to facilitate design of test packages and emplacement/retrieval equipment. The actual depth of the CB and FTB may be slightly different depending on the geologic setting. The borehole depth for waste disposal would depend on site characteristics, drilling capability, and the engineering design of the disposal system (TBD-24).

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

Maximum ambient bottom-hole temperature for the FTB 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 shown in Section 5.3 to be achievable, and is needed to limit thermal degradation of WP material yield strength (Section 5.1). 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 80°C. Thus, the maximum temperature rise is 80°C at the bottom of the hole and 140°C at the top of the EZ.

Maximum Package Weight

An assumption on maximum package weight is provided for handling system, emplacement system, and canister design (Table 2-4). Beginning with the reference design (Arnold et al. 2011) the loaded 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).

For the small packages (Table 2-2) 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.

Using higher strength tubing for the package body, the wall thickness can be reduced 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.

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).

The maximum weight of a WP for DBD is not yet determined (TBD-27).

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. For the DBFT there are no plug installations planned in the EZ (Section 2.3.9), so this assumption limits the maximum total number of test packages that could be emplaced in the FTB to 40. Emplaced packages will load the lowermost 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.

Future Uses for DBFT Boreholes

The DBFT CB and FTB may be plugged and abandoned at the conclusion of the DBFT, or they may be transferred (together or separately) to control by a different entity such as a university or State agency. Such a transfer could support research, groundwater resource development, or other application agreeable to the parties. Disposition of the boreholes will be determined at the conclusion of the DBFT.

Borehole Deviation and Dogleg

Maximum borehole deviation at total depth was originally set by thermal analysis and waste isolation performance assessment (Arnold et al. 2011, 2014). Dogleg severity is a different aspect of straightness that mainly impacts the installation or retrieval of casing. Casing has larger diameter than drill pipe and tends to be stiffer, increasing friction in dogleg sections. It also typically has less wall thickness and is subject to buckling. A maximum dogleg severity assumption of 3°/100 ft is based on expert judgment, and in combination with maximum deviation, should produce a borehole without casing installation or retrieval problems. The potential impact on casing installation is greater in the upper section of any borehole, so maximum dogleg severity in the upper 1,000 m is assumed to be 2°/100 ft. These values are marginal with respect to whether directional drilling equipment will be needed (TBD-11). In other words, they might be obtained using more conventional drilling equipment and methods, depending on site conditions, but they should be readily achievable using directional drilling.

Emplacement Fluid Density and Pressure

The minimum density of fluid anywhere in disposal boreholes (used for buoyancy calculations, not an average), and in DBFT boreholes when test packages are present, is assumed to be that of pure water. This is assumed at every point in the borehole rather than as an average because it controls the buoyant weight of packages and emplacement equipment in the hole. Oil-based muds may be used, but are assumed to be weighted such that the density is at least that of pure water during emplacement operations. This assumption could possibly be relaxed if package buoyant weight limits can be met, or after all packages are permanently emplaced in a borehole (e.g., to allow for settling of solids) as long as the borehole fluid continues to meet its performance criteria (Section 2.3.8).

The maximum average density (used for pressure calculations) of fluid present when packages are also present is assumed to be 1.3× the density of water (~10.8 lb/gallon, which is the maximum that can be achieved for mineralogical clay-based mud without adding weighting agents). This value is based on engineering judgment as to the maximum average fluid density that will be needed during emplacement of packages. The basement rock will be crystalline and significantly rock framework-supported (and not fluid supported) so lithologic overpressure is not expected. However, borehole fluid density will be adjusted to balance the formation fluid column, which may contain brine. If the natural formation brine is highly concentrated, the resulting emplacement fluid density could approach 1.3× the density of water especially at cooler temperatures before fluid becomes thermally equilibrated with the formation. Note that this density is used to compute static pressure, and that pressure transients can also occur during operations due to surge. Pressure surge can be limited with careful operations, but is one reason for the factor of safety on WP deformation.

Concentrated brine in the basement may have local density that exceeds 1.3× the density of water, in which case a stratification scheme might be used in the FTB borehole for the DBFT, to control the maximum average fluid density that determines downhole pressure. The maximum average fluid density in waste disposal boreholes is TBD (TBD-15).

Greater fluid densities may be used for drilling and completion activities, but packages will be introduced only after these activities are complete. An emplacement fluid program would be used to establish fluid composition and uniformity before emplacement operations. For the FTB, which will be based on the DBD reference concept, the borehole will be fully lined with casing (cemented in the overburden, mostly uncemented in the crystalline basement) before such flushing is done.

Finally, the overburden is assumed to be sediments that could, in principle, be overpressured (with respect to a column of groundwater) if they are not framework supported like granite. In the limit, overpressure in sedimentary sections can approach 1 psi per foot of total depth, which corresponds to the full weight of the overburden. However, this condition is unlikely in a geologic setting selected for waste disposal, because lack of an upward hydraulic gradient would be one criterion for siting (SNL 2014a) (TBD-42).

Wireline Cable Working Load

The weight of the bottom-hole assembly (WP, tool string, etc.) cannot exceed the service limit of the wireline cable, accounting for an appropriate FoS. For the DBFT, it is assumed that an electric wireline cable such as the Schlumberger Tuffline® will be used for test package emplacement. It has a safe working load of 26,000 lb or greater depending on configuration, with a torque-balanced design and polymer-locked armor to inhibit crushing. It does not require seasoning, does not require a capstan for loads up to 12,000 lb, and is rated for 24-hour operation at temperatures up to 230°C. To avoid the use of a capstan, it is therefore assumed that the bottom-hole assembly will weigh less than 12,000 lb. For DBD, the weight limit has not yet been determined (TBD-31).

Terminal Velocity

Engineering analyses were conducted for the following: terminal sinking velocity of a package dropped in a borehole (Section 5.4), energy needed for package breach (Section 5.6), and the use of impact limiters in limiting consequences from package drops (Section 5.5). For these calculations, it is assumed that a terminal velocity of 3 m/sec can be managed safely using impact limiters to arrest dropped packages without breaching (TBD-34).

Year in Which DBD Could Begin

For thermal analyses (Sections 5.2 and 5.3) 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 (TBD-35).

Permeability of Host Rock and DRZ

For the purpose of conducting thermal-hydrologic analyses (Section 5.3), permeability of the host rock and of the DRZ must be assumed. Values that were assumed for the analyses for the DBFT are given in Table 5-7. For DBD, the permeability of the borehole and the surrounding DRZ is TBD (TBD-36).

Table 2-4. Controlled assumptions for deep borehole waste disposal and the DBFT.

Controlled Assumptions	
Waste Disposal Assumption	**Deep Borehole Field Test Assumption**
Waste Forms for Disposal – Specific waste forms to be disposed of in deep bore-holes, at specific sites or in specific geologic settings, are TBD (TBD-23).	**Demonstrating Disposal of Waste Forms** – The DBFT will demonstrate technologies for disposal of test packages that are designed to contain small-volume, DOE-owned granular waste forms (e.g., Cs/Sr capsules, or calcined waste).
Disposal Borehole Depth – Borehole depth for DBD is TBD (TBD-24).	**DBFT Borehole Total Depth** – The CB and FTB will be 5 km in depth.
DBD Bottom-Hole Temperature and Temperature Rise – Bottom-hole temperature (and temperature rise dues to heat-generating waste) for DBD will depend on site-specific data, waste characteristics and packaging, etc. Peak WP temperature (e.g., for heat-generating waste) is assumed to be 250°C (TBD-18).	**DBFT Bottom-Hole Temperature –** Bottom-hole formation temperature is assumed to be 170°C (see text for basis; TBD-17).
	Temperature Rise – For thermal expansion calculations the maximum WP temperature rise is 80°C at the bottom of the hole and 140°C at the top of the EZ.
Disposal Package Weight – Waste package maximum weight for borehole disposal of radioactive waste is TBD (TBD-27).	**Test Package Maximum Weight** – The maximum weight in air is assumed be 4,620 lb, or 3,860 lb buoyant weight in pure water (see text for basis).
Waste Package Strings – When test packages are emplaced in the borehole by any method, the number of WPs in a stack not interrupted by a cemented interval is limited to 40 (TBD-41).	**Test Package Strings** – When test packages are emplaced in the borehole by any method, the number of WPs in a stack is limited to 40 (see text for basis).
Disposal Site Ownership – Long-term ownership and condition of sites for deep borehole disposal of radioactive waste are beyond the scope of the DBFT (TBD-26).	**Borehole Condition at Test Conclusion** – The CB and FTB will be left in serviceable condition, to the extent possible, for possible additional R&D or other uses (not waste disposal).
Disposal Borehole Directional Drilling – The need for directional drilling for disposal boreholes is TBD (TBD-11).	**DBFT Borehole Dogleg Severity –** For scoping of drilling tools and methods it is assumed that dogleg severity will be limited to 3°/100 ft throughout, and 2°/100 ft in the uppermost 1,000 m of the CB and FTB (TBD-10).
DBD Emplacement Fluid Density - Density of borehole fluid when WPs are present is TBD (TBD-15).	**DBFT Borehole Fluid Average Density –** Maximum average borehole fluid density (from surface to package depth) is assumed to be 1.3× the density of pure water. Minimum fluid average density is assumed to be that of pure water.
Terminal Velocity – A limit on terminal velocity of a WP has not been determined (TBD-34).	**Terminal Velocity** - For the purposes of engineering calculations discussed in this report, it is assumed that a terminal velocity of 3 m/sec can be managed safely without breaching packages.
Date of Waste Emplacement – The date of emplacement of waste in a DBD facility is TBD (TBD-35).	**Date of Waste Emplacement** – For the sole purpose of conducting thermal analyses, it is assumed that cesium and strontium capsules are disposed of in 2050.

Controlled Assumptions	
Waste Disposal Assumption	**Deep Borehole Field Test Assumption**
Permeability of Host Rock and DRZ – The permeability of the host rock and the surrounding DRZ is not yet determined (TBD-36).	**Permeability of Host Rock and DRZ –** For the purpose of conducting thermal-hydrologic analyses, the permeability of the host rock and the DRZ were assumed to be the values shown in Table 5-7.

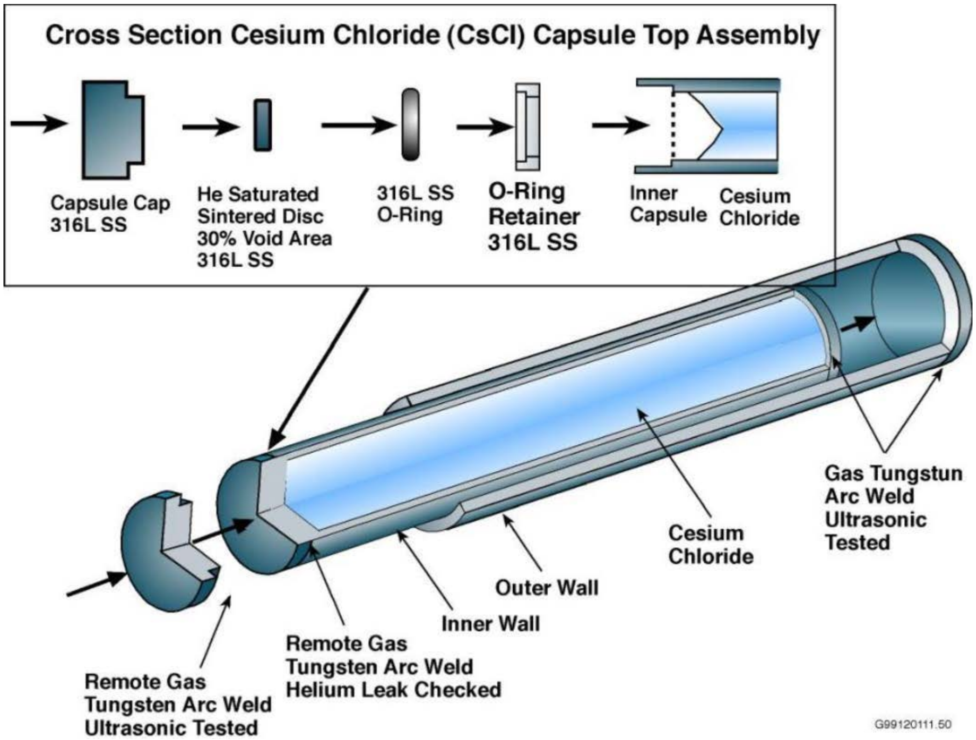
2.5 Waste Types

Two waste types have been mentioned in this report as 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 (Figure 2-1). 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 1995).



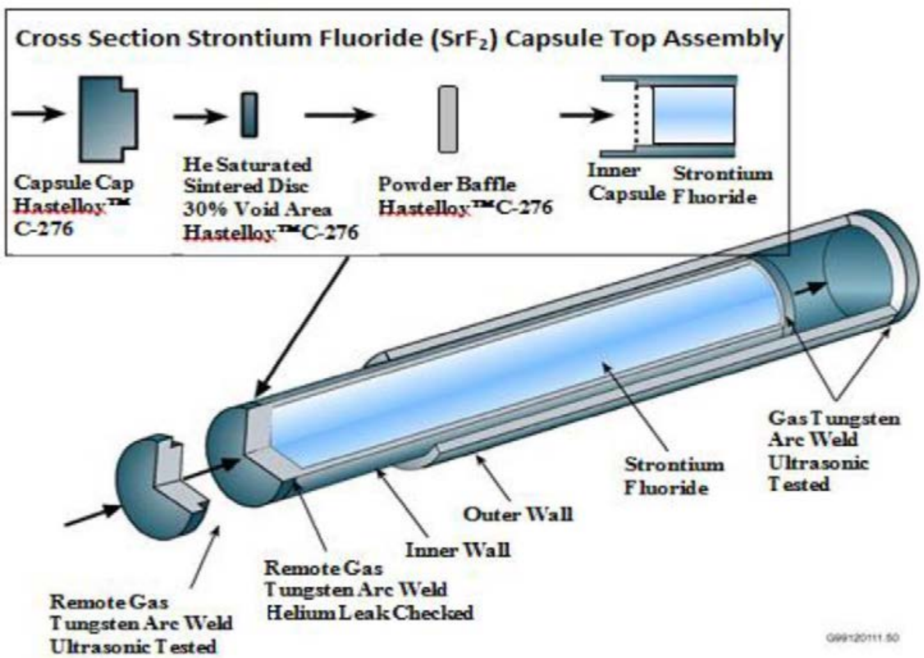


Figure 2-1. Cross-section of cesium capsule and strontium capsule (Covey 2014).

2.6 Waste Packaging Options

This section presents two basic packaging options, as well as options for other aspects of WP design. Options that are selected for the reference disposal concept are discussed in Section 3.2, as are material selection options.

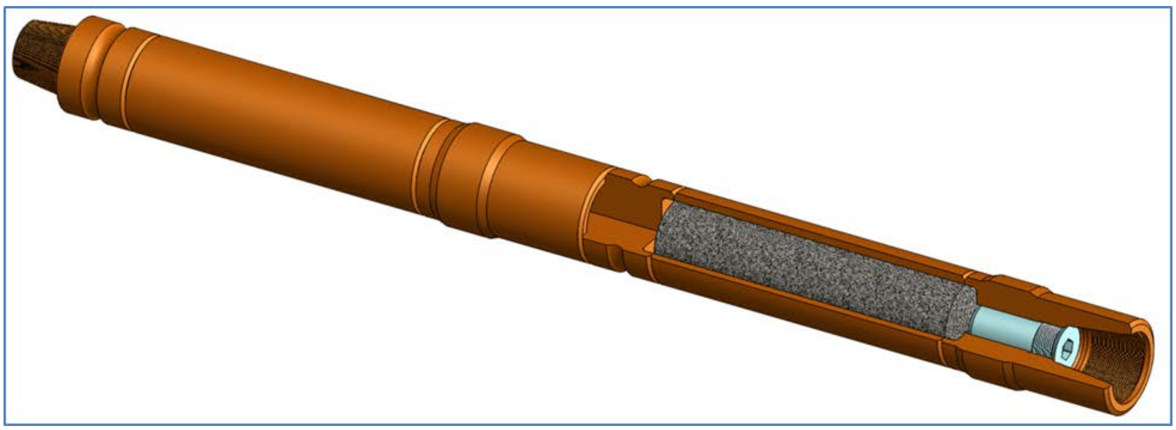
Two basic packaging concepts are presented here, either of which could be scaled to nominal outer diameters of 5, 8 and 11 inches (identified as small, medium, and large in Table 2-2):

- Flask-type WP for bulk waste (in the small size, this could include 2.6-inch OD Cs/Sr capsules)
- Internal semi-flush type package for canistered waste (in the small size, this could include 3.3-inch OD Cs/Sr capsules)

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

Flask-Type Packages

Each end of the flash-type package would be a plug with integral API connections (Figure 2-2). 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 2-2. Flask-type waste package concept, shown loaded with bulk waste.

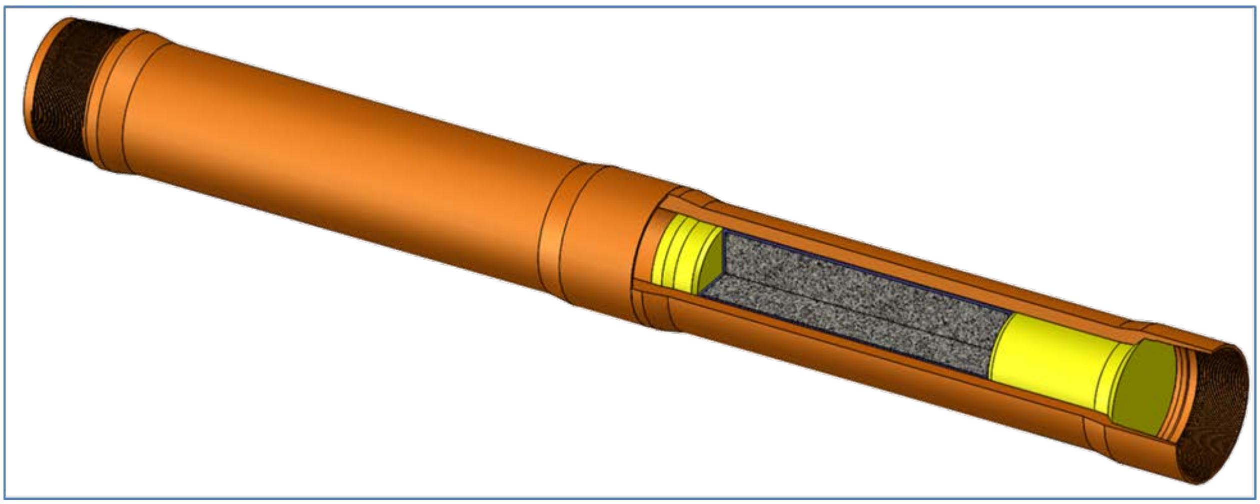
The package would have a box thread on top and a pin thread on the bottom. For the 10-3/4 inch OD package design, an API NC-77 or equivalent thread could be used. This arrangement would provide a smooth exterior package profile. Granular waste could be loaded through the fill port on the upper (box) 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 2-2) 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.

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 2-3 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 2-3. Internal semi-flush package concept.

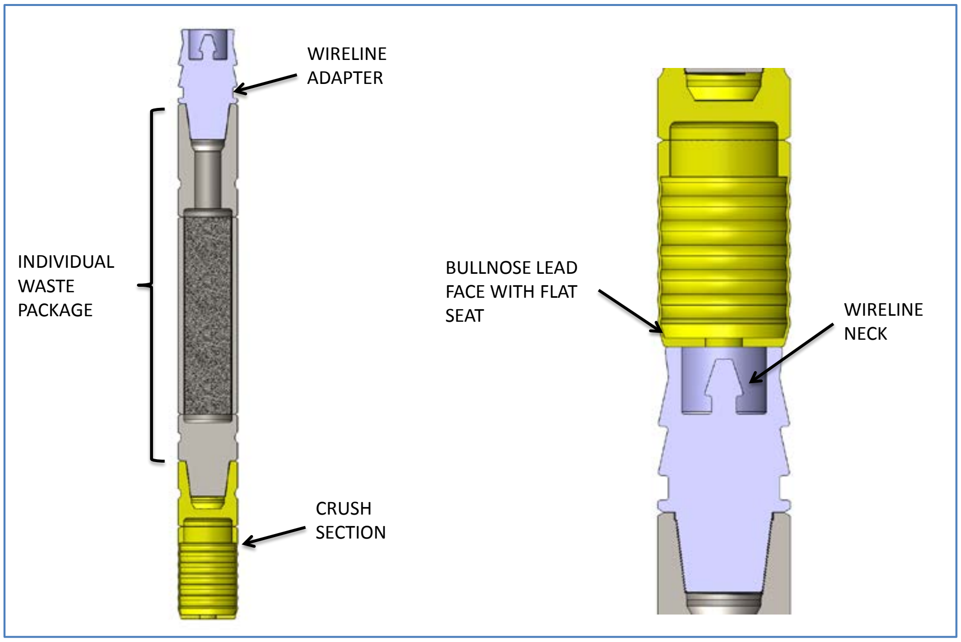
Canistered waste would be loaded through one end, then contained by a slightly tapered plug, with a seal or sealing weld. The OD of pre-canistered waste for the concept shown here would be limited to approximately 8.5 inches (for the large size package). Note that for a 10-3/4 inch nominal casing OD, 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.

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 2-4). 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 option (Section 2.9.2).



Note: Package aspect ratio shortened for illustration.

Figure 2-4. 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 5.5) is important in the risk analysis (Appendix A). 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® (releasable wireline cable head) 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.

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 2-2). 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 outer diameters shown in Table 2-2 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. The DBFT demonstration is intended to test the sensitivity of terminal sinking velocity to the radial gap, with a view to selecting tubing size and material grade for packages (TBD-14) (see Section 5.4).

Waste package length for DBD has not been finalized (TBD-13). 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.

Borehole Environment

All packaging concepts presented in this report are intended to ensure that the waste is isolated from the borehole, in an internal pressure environment of one-atmosphere, at downhole temperature, in a deep borehole containing fluid of prescribed maximum average density, as assumed in Section 2.4. Additional design requirements are presented in Section 2.3.

An alternative WP concept would not limit the internal pressure of the WP to one atmosphere, but would allow the internal pressure to increase as the external pressure increases, thereby reducing the pressure difference and reducing the required wall thickness. This could be accomplished by filling the WP with fluid such as water. Preliminary calculations were performed (Section 5.1.6) and indicate that the internal pressure can exceed 7,000 psi at 200°C and 9,600 psi external pressure (Figure 5-13).

Yield Strength

The reduction in yield strength with increasing temperature has been estimated from various sources. The American Society of Mechanical Engineers recommends a design factor of 0.78 for carbon and low alloy steels at 300°C (boiler and pressure vessel code). Various manufacturers also provide estimates of this design factor. Grant Prideco (2003) reports 74% for their 80 ksi yield strength casing at 200°C. Another source (BG Group 2001) recommends yield strength de-rating of 0.081% per °C for oilfield casing at operating temperatures above 20°C. The 110 ksi steel analyzed in Section 5.1 retains approximately 87% of its normal yield strength at 200°C (Renpu 2011). Linearly interpolating this result from 20°C to 170°C (Section 2.3.10) gives a reduction to approximately 90% of normal yield strength, which is the value used for FoS analysis in Section 5.1.

Besides strength of package structural materials, other aspects of downhole temperature include thermal stresses and the response of welds, temperature limits for materials used in seals, and so on. Oilfield equipment is typically designed for service to 150°C in deep boreholes, and special designs may be rated to higher temperatures (e.g., 200°C or higher for geothermal applications).

Safety Margin from Stress Analysis

Preliminary analyses of packaging concepts similar to those described above (SNL 2015) showed that use of API-schedule casing or tubing for packages might not produce the FoS required (Section 2.3.10; TBD-16), especially with reduction of yield strength at elevated temperature. There are remedies to this condition for the DBFT and for DBD. Higher grades of medium-carbon steel are available on the API schedules (e.g., P110 and Q125) although these typically require post-weld heat treatment to obtain the rated properties. In addition, the packaging concepts could be changed to allow WPs to have greater wall thickness, permitting use of different materials such as steel with lower yield strength but less stringent treatment requirements (e.g., steel pipe that can be field-welded for pipeline applications; see USS 2012). Although wall thickness trades against volume efficiency for DBD, this is less important for the DBFT which will not involve waste disposal. Also, volume efficiency could be improved by designing different packages for service at different depths in a disposal borehole, reflecting different temperature and pressure service conditions.

Another approach to optimizing volumetric efficiency mentioned by Arnold et al. (2014), would fill interstices within packages with a granular material such as silicon carbide. The intent would be for the material to assume part of the load imposed externally by hydrostatic pressure, as the steel envelope deformed inward. However, the granular material would still be highly compressible even with control of particle size and compaction, so it would not assume much load given the magnitude of the package wall deformation. A similar analysis of filling with liquid water is presented in Section 5.1.5.

2.7 Disposal Borehole Construction Options

Borehole drilling and construction are essentially out-of-scope for the DBFT engineering demonstration, with the exception that certain requirements (e.g., guidance casing, maximum dogleg severity), and features or modifications (e.g., perforations) may be incorporated to support emplacement/retrieval demonstration and associated testing. Another important area where construction options must be considered is the wellhead interface with test package transfer equipment, as discussed below.

2.7.1 Directional Drilling Options

Steering systems are potentially important for DBD and the FTB because straight holes are desired to limit rock damage, facilitate borehole construction, and minimize the likelihood that packages could become stuck. Maximum horizontal deviation and dogleg severity objectives have been set for the FTB (Table 2.4; TBD-10) and could be achievable without downhole steering. However, with steering systems the objectives could readily be met or exceeded. Steering can be accomplished using existing off-the-shelf equipment, configured for both rotary and downhole motor systems. Typical maximum service temperatures are 150 to 200°C which encompasses the range of bottom-hole temperature assumed (Section 2.4; TBD-17).

2.7.2 Diameter/Casing Options

A schedule of borehole and casing sizes for the EZ from 3 to 5 km depth in a future disposal borehole was presented previously (Table 2-2). Guidance casing is required for DBD and the FTB to facilitate emplacement and retrieval (Section 2.3.9) but options exist as to casing material, weight, perforation, and borehole construction details. The following high-level discussion of some of these options is background for the borehole construction aspects of the DBD reference concept (Section 3.1) and the FTB concept (Section 4.1).

To construct the EZ a telescoping diameter/casing plan must be used with graduated stages of conductor casing, surface casing, and intermediate casing. Sizes can be selected to allow at least one additional graduated intermediate stage for use to line an additional portion of the borehole if rock stability, lost circulation, or inflow problems are encountered during drilling. If used, the additional stage would step down to a size that is larger than the EZ diameter and can pass the EZ guidance casing.

Available casing materials include steel of various grades, stainless steels, titanium, aluminum, and even non-metallic options. For the FTB no requirements are placed on casing materials or dimensions except: 1) the ID of the guidance casing which contributes to radial gap (Section 2.3.10); and 2) smooth or flush internal casing surface (Section 2.3.9). Construction details for DBD boreholes are TBD (see Section 2.3.9; TBD-08, -09, and -12).

Casing or liner perforations are needed to accommodate cementing and fluid thermal expansion (Section 2.3.9; TBD-12). Vertically slotted casing has nearly the same tensile strength as blank casing, and can be perforated over its entire length except at joints. Alternatively, if fewer perforations are needed they can be drilled or cut before installation, or blank casing can be installed and perforated *in situ* with wireline perforation guns (shaped charges). Note that perforation guns can cause shards of casing to bend inward partly blocking the bore. Thus, use of perforation guns could be limited to borehole construction before any packages are emplaced, when there is a drilling rig available to ream the casing if necessary. Alternatively, perforation guns might be used after emplacing a stack of packages, in intervals where cement plugs are to be installed (but not too close to emplaced packages). Perforation options are discussed further in Section 2.7.4.

Other aspects of borehole drilling and construction including drilling method, drilling fluid, casing material and weight, and casing or liner installation, are beyond the scope of the DBFT. Drilling and construction details for DBD are TBD (Section 2.3.8; TBD-08).

2.7.3 Wellhead Equipment Options

Blowout preventers are used during drilling, and may also be required by permitting authorities for construction, testing, and any other activities. There are several types of BOPs including: 1) ram types that are configured to either seal or cut off round pipe, tubing, or tools; and 2) annular types that close on, but do not cut off the same types of hardware and also wireline cables. Ram-type BOPs (depending on the type and configuration) may be capable of damaging packages and wireline tools, and they are also likely to sever a wireline cable if actuated during package emplacement. Annular BOPs can close on circular objects and cables without damage, and are better suited to DBD disposal applications.

Once borehole drilling and construction are complete, the hole will likely be temporarily plugged near the surface, and the BOP stack replaced by a wellhead. This typically consists of high-pressure piping connected to the well (a cemented casing or tubing), one or more diverters to channel flow from the casing, a control valve or manifold, and other fittings such as casing hangers and flanges. The configuration for a particular well depends on the number of (concentric) casing or tubing strings present, their uses, and the expected pressures. One function of the wellhead is to allow fluids to be used in the borehole that do not have sufficient weight to balance formation pressure. Another function is to replace the BOP stack which can be relatively costly to operate and maintain.

For wireline work (electric wireline or slickline) in production wells, a means is provided to run tools and cable with the well under pressure. This typically consists of a set of grease tubes, which seal around the cable and can maintain the seal with cable running through. This type of hardware is discussed in connection with the reference disposal concept (Section 3.3).

BOPs may be present on the FTB or DBD boreholes during emplacement operations, therefore the surface handling and transfer equipment (particularly for the DBFT demonstration) should be designed to function with either a BOP stack, or a wellhead installation (which may also include a BOP) (Section 2.3.9; TBD-22).

2.7.4 Emplacement Zone Construction Options

This section describes some basic options for installing guidance casing including cementing, in the EZ of a disposal borehole. The manner of completing a disposal borehole may not be critical to the objectives for the DBFT engineering demonstration, except with regard to perforations in the guidance casing that could affect terminal velocity of falling WPs or strings of packages. Accordingly, the emphasis of this section is on the size, number, and distribution of perforations that would be needed to implement various options for EZ completion. These options are then considered in selecting a completion method for the reference disposal concept (Section 3.1) and in specifying perforations for testing in the DBFT demonstration (Section 4.1).

In the DBD concept of Arnold et al. (2011) the EZ would be completed using a 13-3/8 inch slotted guidance casing hung from above (anchored to a larger, cemented liner that terminates at the top of the EZ). Waste packages would be emplaced starting at the bottom, limited by the number than can be safely supported by the lowermost package without damage. That number was originally assumed to be 40 packages (total weight of 154,000 lb, which is analyzed in Section 5.1.1). In order to emplace additional packages, a cement plug would be installed in the casing to bear the weight of 40 more. The weight of these packages would be transmitted by the cement plug, to the casing. To avoid overloading the casing, additional cement would be installed in the annulus to further transfer load to the host rock. Thus, at intervals in the EZ cement is needed both inside the casing and in the annulus, to shift loads to the rock.

Recognizing that guidance casing is required (Section 2.3.9), this section develops four options for installing cement (including the original one from Arnold et al. 2011), and the perforation scheme needed for each.

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. Estimates of *in situ* temperature and pressure are consistent with the assumptions in Table 2-4.

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 2-5).

Table 2-5. 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 (Section 2.4).

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 2-5) 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.

Thermal Expansion After Emplacement of Heat-Generating Waste

The conditions relevant to this discussion are linear thermal expansion of casing, and volumetric expansion of borehole fluid.

The guidance casing would be hung in the borehole without cement, and reach thermal equilibrium with the formation before waste emplacement, so that thermal expansion would be limited to temperature rise from heat-generating waste. The coefficient of linear thermal expansion for steel varies with composition, but varies only slightly with temperature. For analysis the coefficient is assumed here to be 10^{-5}/°C over the full temperature range. Accordingly, the maximum thermal strain due to waste heating would be 0.14% at the top of the EZ and 0.08% at the bottom (using temperature rise from Table 2-5). Note that these are bounds for considering thermomechanical effects on the casing, because some heating and expansion of the casing will occur before cement plugs are set.

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 from Table 2-5). 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.

Steel Corrosion

Another potential cause for pressure buildup in the EZ is hydrogen gas from iron corrosion. Water in the EZ will react with iron in casing or WPs steel to produce hydrogen gas. Some of the gas would be dissolved in the fluid without changing its pressure, until the gas solubility limit is reached. Further gas production would cause formation of bubbles, displacing an equal volume of fluid. Unless gas or fluid is allowed to escape, the pressure could continue to increase limited only by the thermodynamic effect of the gas pressure on corrosion.

Grundfelt and Crawford (2014) developed a conceptual model for the hydrogen gas generation from anoxic corrosion of iron in steel:

$$3Fe\ (cr) + 4H_2O \leftrightarrow Fe_3O_4\ (s) + 4H_2\ (g) \qquad (2\text{-}1)$$

They calculated the equilibrium hydrogen partial pressure at which the reaction ceases (at thermodynamic equilibrium). Comparing several thermodynamic databases, and using assumptions about groundwater chemistry and temperature, they calculated the equilibrium partial pressure to be approximately 15,700 psi (107 MPa) at 100°C. This is an estimate, and a lower H_2 pressure could pertain because: 1) a different reaction dominates; 2) H_2 dissipates into the surrounding host rock; or 3) some dissipation occurs and mass transport limits the reaction rate. The significance of the estimate is that gas pressure in the EZ could conceivably exceed the fracture pressure or cause damage to engineered components of the disposal system. These possibilities are considered in the recommendation of a completion option from among those described below (Section 3.2).

Emplacement Zone Completion Options

Completion of the EZ would be a simple construction consisting of guidance casing, emplacement fluid, cement possibly with bridge plugs, and casing perforations. Important design questions addressed include the manner and extent of cementing, and the casing perforation scheme (both before and after casing installation). Note that the options presented here could be associated with differences in volumetric disposal efficiency, but such differences are small.

The following discussion applies to guidance casing of any size. The casing size and weight would be determined by borehole geometry and wall thickness, which in turn would depend on handling factors, internal and external pressures, and other loads. All EZ completion options discussed below would include it.

The EZ completion options discussed here differ principally in the manner of use of cement, and the types of perforations. Note that injection of cement or fluid around a stack or string of packages is generally ineffective if done from above, unless there is a return path for the injected fluid. Several approaches are available for cementing the guidance casing (summarized in Table 2-6):

- **Option 1: Poured Cement Plugs –** Before waste emplacement, emplacement fluid would be circulated throughout the EZ. A 200-m tall stack of WPs would be emplaced in emplacement fluid, and a bridge plug would be set above the packages (Figure 2-5). Cement would then be introduced at low pressure above the bridge plug, and gravity flow would displace the emplacement fluid inside the casing. Cement would flow through one or more perforations into the annulus, bonding the casing. The cement required for a 10-m plug would fill only a fraction of the length of 2-inch coiled tubing from the surface to 3 km, so a heavier cement formulation could be used without exceeding formation breakdown pressure (Table 2-5).
- **Option 2: Squeezed Cement Plugs –** A stack of WPs would be emplaced in emplacement fluid, and a bridge plug would then be set above the packages (as above; see Figure 2-5). A squeeze packer would then be set 10-m above the bridge plug, and cement would be injected under pressure through the packer (a multi-purpose cementing tool run on coiled tubing). Casing perforations in this interval would allow cement to flow into the annulus 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.

  The principal difference between options 1 and 2 is the control of cementing. For either option, cementing pressure would be isolated from WPs by the bridge plug, less than the fracture breakdown pressure, and within the range of coiled tubing. Casing centralizers would be used at each cement plug, and one or more perforations in the guidance casing would be needed for each cemented interval. Additional perforations would be used for dissipation of thermally expanding fluid after waste emplacement, and there would be no cement throughout much of the EZ to impede such dissipation. All of the perforations could be prefabricated at the surface before casing installation, or they could be cut *in situ* using a wireline perforating gun. Options 1 and 2 would tend to increase the rate of corrosion of steel by including more free water in the borehole and exposing more of the formation for possible inflow of additional water.

- **Option 3: Guidance Casing Fully Cemented During Construction, and Poured Cement Plugs –** With this option the EZ guidance casing would be installed as a fully cemented liner (i.e., fully cemented annulus) prior to emplacement of any WPs. The casing would be perforated *in situ* after cementing and before waste emplacement as needed to promote dissipation of thermally expanding fluid. Each stack of packages would be emplaced and a bridge plug set above them. Cement would then be introduced at low pressure above the bridge plug, and gravity flow would displace the emplacement fluid inside the casing.

  This option would maximize flexibility as to where cement plugs could be installed, and how many packages constitute a stack. Thus, it could be used to ensure that during an operational hiatus, packages that were already emplaced could be stabilized with cement. The effectiveness of the perforations for pressure relief after borehole closure would depend on fluid permeability in the cemented (and perforated) annulus. Also, explosive perforations could leave jagged metal obstructions in the emplacement path that would need to be removed (e.g., milled) before emplacement.

- **Option 4: Fully Cemented Casing and Packages –** With this option packages would be emplaced in emplacement fluid, but no bridge plug would be set above them. A squeeze packer would be set above the top WP in the stack, and cement would be squeezed downward through the stack of packages, through perforations in the guidance casing at the bottom of the interval, and back up the annulus between the casing and the borehole wall (Figure 2-6). All void space between packages and casing, and between casing and the borehole wall could, in principle, be fully cemented. After cementing, the casing above the cemented interval would be perforated, and the annulus above that point flushed in preparation for another stage of packages.

  With option 4 the cementing pressure would be closely controlled so as not to exceed the fracture breakdown pressure or collapse pressure for packages. The fully cemented guidance casing would be locked and unable to expand (producing thermal stress instead). Perforations would be limited to those used in cementing, which could limit dissipation of fluid pressure from thermal expansion. On the other hand, the amount of free water available to expand would be minimized by fully cementing the EZ. Another disadvantage is the possibility of mechanically coupling packages with stress changes in the host formation.

A 1983 DBD concept (Section 2.9) proposed emplacement of waste canisters in an open borehole (no guidance casing) lowered three at a time inside a conveyance casing, on a drill string. After emplacement, cement would be pumped down through the drill pipe and through the conveyance casing, encapsulating the canisters, and returning up the rock annulus. With this concept the EZ could be fully cemented, similar to option 4 discussed above, but without the benefit of guidance casing.

Another approach that was considered for fully cementing the EZ would be to cement the guidance casing, perforate at the bottom of an emplacement interval, emplace a stack of packages, then squeeze cement downward through the stack. Instead of a return path for displaced fluid and excess cement, injection would be done at the formation fracture pressure, fracturing the formation behind the perforation. The high injection pressure could contribute to package collapse, however, so this approach is not carried forward as an option.

The EZ completion options described above could be performed using either the wireline or drill-string emplacement modes (Section 2.9), and either a drill string or coiled tubing for cementing. Bridge plugs, if used, could be set with either wireline or coiled tubing (with coiled tubing they could be set with pressure instead of explosive charges). Cleaning of excess cement in the guidance casing in preparation for additional package emplacement, could be done with a gauge ring and junk basket. Option 2 is recommended in Section 3.1, and the steps for emplacement are discussed in Section 3.3.

Figure 2-5. Visualization of cementing options 1 and 2.

Emplacement Fluid

The borehole would be filled with fluid of specified weight (e.g., brine composition and concentration) to balance formation fluid pressure throughout emplacement, plugging, and sealing operations. Arnold et al. (2011) suggested a synthetic oil-based mud containing dehydrated bentonite, which would stay in the borehole after emplacement (options 1 through 3 above), and react with any water or brine inflow. Displacement of aqueous fluids by oil-based ones could inhibit corrosion of steel, and promote lubrication of packages during emplacement.

However, the oil-based mud formulation would not be in compositional equilibrium with formation brine, and settlement of clay and/or weighting agents could produce a lighter liquid phase with a tendency for upward buoyant convection. Also, the presence of a concentrated organic phase, including emulsifiers, would complicate understanding of corrosion and radionuclide transport. Brine is recommended as the emplacement fluid in the reference concept (Section 3.3).

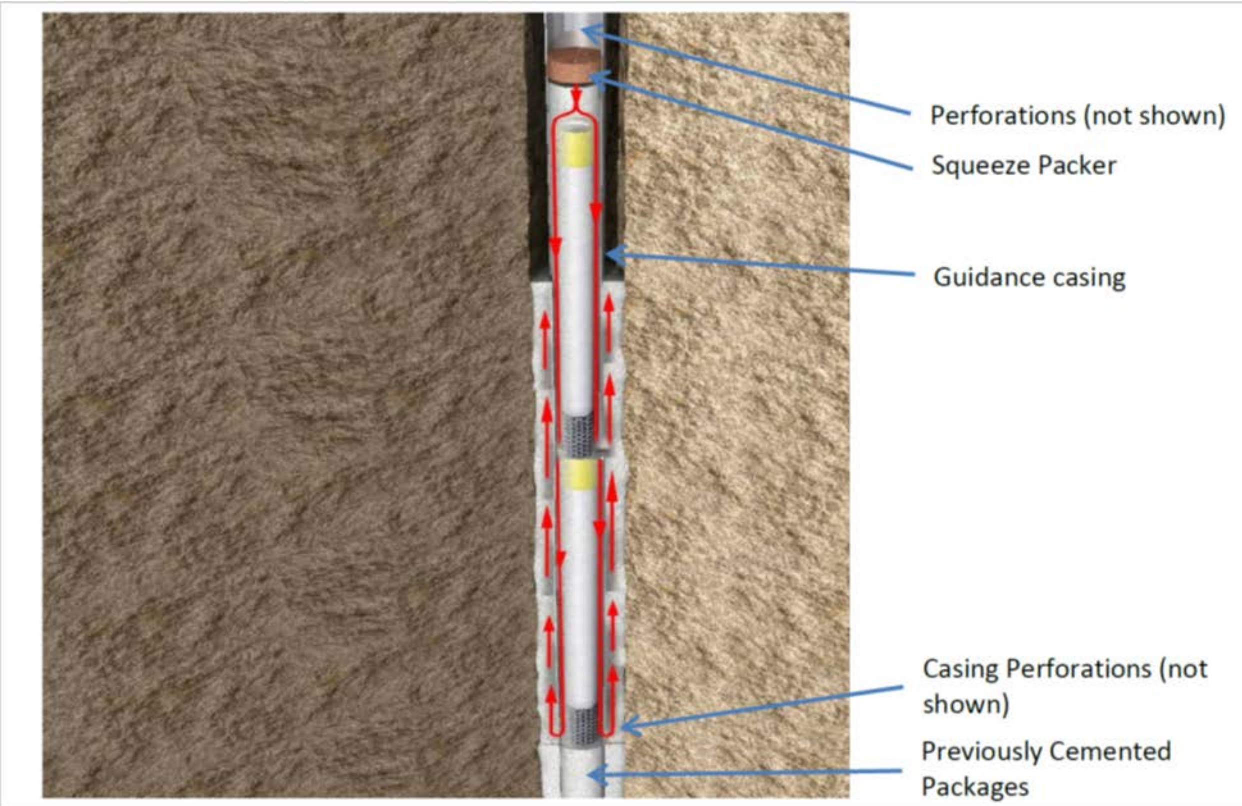


Figure 2-6. Visualization of cementing option 4.

Other choices for emplacement fluid could include aqueous mud (which might be selected for higher weight and chemical sorption of released radionuclides), or brine (similar to formation fluid). Another important characteristic of the emplacement fluid is compatibility with cement used in the EZ.

Guidance Casing Perforations

The 2011 reference concept (Arnold et al. 2011) specified slotted guidance casing in the EZ. This would tend to maximize the sinking velocity of packages or package strings that are accidentally dropped in the borehole, by facilitating bypass flow in the annulus. Guidance casing that is not slotted and only minimally perforated could better limit sinking velocity, and also control movement of debris into the casing. Given the insights gained from risk analysis of emplacement operations (Appendix A and SNL 2015) these functions are important for limiting the probability of packages becoming breached or stuck. Four factors affect the selection of perforation size, number, and distribution:

- **Perforations to Relieve Fluid and Gas Pressure –** These perforations can be small, just large enough to prevent clogging by corrosion products. The following scoping calculation is used to estimate the flow rate of expanding fluid. A 200-m stack of packages (uncemented, as in options 1 and 2 above) would include approximately 4,000 liters of fluid inside the casing, and 14,300 liters in the rock annulus. For analysis, assume that this fluid could expand 10% in one month during rapid heating. The corresponding average flow rate into the host formation to control thermal expansion would be less than 1 mL/sec. Simple transient well function analysis (de Marsily 1986, Section 8) shows that such flow rates could be achieved with a pressure rise on the order of 1 bar (permeability 10^{-16} m^2, specific storage 10^{-7} m^{-1}, interval height 200 m, borehole diameter 0.216 m, fluid viscosity decreased by elevated temperature). Pressure transients of this magnitude would not damage WPs, cement plugs, or seals.
- **Perforations for Poured Cement Plugs –** For option 1 the differential pressure driving cement through perforations is limited to that from just a few meters of cement depth. This differential pressure is an order of magnitude less than that used for small-scale squeezing, so the perforation openings need to be proportionally larger than used for option 2, to pass sufficient cement in a similar duration.
- **Perforations for Small-Scale Squeeze Cementing –** For option 2 above, one or more perforations of a few centimeters diameter would be sufficient to pass cement under a few bars pressure, at flow rates sufficient to fill the annulus of a 10-m cement plug (e.g., 50 liters per minute, to fill an annular volume of at least 700 liters, with a pumping time of 30 minutes for the entire plug, and a transit time from the surface of 60 to 200 minutes depending on tubing size).
- **Perforations for Large-Scale Squeeze Cementing –** For option 4, several perforations of the type described above would be needed to cement an interval of stacked packages plus the rock annulus, in a few hours. The same volume of cement used for a 10-m cement plug would cement about 3 packages plus the annulus. To fully cement an interval containing 40 packages in approximately the same time would require approximately 13 similar perforations (and possibly larger tubing, or pipe to deliver the cement).
- **Package Terminal Sinking Velocity –** As analyzed in Section 5.4, there is a direct relationship between the number, size, and distribution of guidance casing perforations, and the terminal sinking velocity if a package is accidentally dropped. A key reason for this is that the pressure transient ahead of a falling package is transmitted to the bottom of the borehole, so that bypass (leakage) flow can potentially occur in all perforations where pressure is elevated.

To summarize, for thermal expansion and gas pressure relief with options 1 and 2, the perforations could be small, on the order of 1 to 2 centimeters in diameter, and distributed along the length of the EZ. Spacing between these perforations could be on the order of 50 m to limit the effect on package terminal sinking velocity (Section 5.4).

For option 1, one or more additional, larger perforations would be needed near the top of the cement plug interval. For option 2 at least one additional perforation would be needed within the 10-m interval for each cement plug, preferably near the bottom of the interval.

For option 3 the EZ casing would be fully cemented throughout 2 km zone during construction, then perforated at intervals to allow for pressure relief after waste emplacement. The number and size of perforations would be selected only for pressure relief, and would not be constrained by package sinking velocity considerations because the annulus would be cemented. After perforating, casing gauge would be restored by drilling using a milling bit. All this would be done during construction with a drill rig on site, prior to emplacing WPs.

For option 4, large perforations would be needed at the bottom of the interval to cement each stack of WPs. These perforations would be made *in situ* prior to emplacing each stack, and not pre-fabricated, so as to limit package terminal sinking velocity. (If these perforations were prefabricated, there would initially be an array of large perforations open throughout the EZ, which could significantly impact sinking velocity according to the analysis of Section 5.4.) It would not be possible to make special perforations for pressure relief, however, the volume of fluid in the EZ would be limited to the cement porosity, and the perforations used for cementing would be available for pressure relief (with intervening cement along a long flow path). Fluid mobility in cured cement could limit the number of packages that could be cemented between perforations without allowing potentially damaging overpressure from thermal expansion or gas generation.

In summary, each cementing option would require a different perforation scheme. Perforations for pressure relief could be spaced about every 50 m for options 1 and 2, or at any spacing for option 3. Only the perforations used for cementing in option 4 would be available for pressure relief. Perforation diameter would be selected consistent with squeeze cementing and terminal velocity objectives (Section 5.4). The four options are summarized in Table 2-6.

Table 2-6. Emplacement Zone Completion Options

Cement Option	Pre-Fabricated Perforations	Construc-tion	*In situ* Perforations	Emplace-ment	Cementing/Plug Installation	Final State
1	2 cm dia. every 50 m (for fluid & gas pressure relief)	Hang casing	Large perfs. near the top of each cement plug interval (see TBD-47).	Nominally 200 m stack of packages	Set bridge plug, and set 10-m cement plug by gravity with overflow through perfs. into the annulus.	Emplacement fluid around WPs and in the annulus between the casing and the rock; 10-m cement plugs between WP stacks
2	2 cm dia. every 50 m (for fluid & gas pressure relief)	Hang casing	At least one large perf. near the bottom of each cement plug interval (see TBD-47).	Nominally 200 m stack of packages	Set bridge plug, set squeeze packer 10 m higher, and inject cement into the interval and through perf. into the annulus.	Emplacement fluid around WPs and in the annulus between the casing and the rock; 10-m cement plugs between WP stacks
3	None	Hang and fully cement casing	Perf. at intervals, for pressure relief only, before waste emplacement	Nominally 200 m stack of packages	Set bridge plug, and set 10-m cement plug by gravity.	Emplacement fluid around WPs; annulus between casing and host rock fully cemented; 10-m cemented interval between 200-m WP stacks.
4	None	Hang casing	Large perfs. at bottom of each stack interval, prior to emplacement	Nominally 200 m stack of packages	Set squeeze packer and inject cement through the stack, through the perfs. and up the annulus.	Cement around WPs and in the annulus between casing and host rock. No cement plugs (without WPs) are needed.

2.7.5 Sealing and Plugging Options

Figures 3-1 and 3-2 illustrate the primary components of the borehole sealing system. Depth dimensions for the sealing zone (shown as approximately 2 to 3 km) will depend on the depth of the overburden, the quality of rock in the upper crystalline basement, borehole construction details, and other factors. In general, the sealing zone for a DBD borehole would consist of at least 1 km of crystalline rock immediately above the EZ, in which all casing would be removed so that seals and plugs could be installed against rock at the borehole wall.

Sealing materials R&D is underway to understand the evolution of representative materials over hundreds to thousands of years (Brady et al. 2015). The current approach is to investigate the properties and stability of cementitious and clay-based materials, starting with cements that are used in oil and gas wells. Properties and longevity can be effectively studied in the laboratory without the expense of *in situ* testing. Future borehole sealing tests might be implemented in shallow test boreholes, and eventually at DBD sealing depths down to 3 km.

The primary interface between planned DBFT activities and possible future sealing tests is the need to remove casing above the EZ, without impacting casing from the EZ. This can be done using separate sections of casing and hanging the EZ casing below the sealing zone.

Alternatively, the guidance casing could be cut off above the EZ and removed. Another possible interface is compatibility of sealing materials with emplacement fluid or its residue after flushing of the sealing zone.

2.8 Surface Handling and Transfer Options

Although various concepts for safe disposal of packaged radioactive waste have been proposed over more than three decades, actual implementation has yet to be accomplished. Woodward-Clyde Consultants (1983) developed a reference design that included disposal boreholes with diameter of 20 inches and depth of 6.1 km, based partly on projections of drilling technology thought to be available by 2000.

The Woodward–Clyde (1983) study included a relatively detailed concept for surface handling facilities and waste packaging design. It would require a waste emplacement rig with an elevated drill rig floor, a shielded room area below the floor to position the shipping cask, and a subsurface basement to accommodate BOPs and the equipment used for assembling strings of WPs. The Woodward–Clyde study proposed that three canisters containing chopped spent fuel be brought to the site, already attached together in a rigid carrier and transferred as one to the borehole. The canisters would be short (less than 4 m long), but the resulting triplet of packages would have required a long transfer cask on the order of 13 m overall. This dimension carried over into the height of the rig floor, and the depth of the basement.

Several relevant design elements and procedures were successfully developed and implemented for the SFT–Climax on the Nevada Test Site (Patrick 1986; DOE 1980). The program demonstrated handling of commercial pressurized-water reactor (PWR) used fuel in a mined repository environment in crystalline rock. Canisters containing used fuel assemblies were lowered by a heavy-duty wireline through a 20-inch cased borehole into a shielded transfer vehicle in a gallery 1,400 ft underground. They were retrieved the same way after 3.5 years of underground storage. Each of the 11 stainless steel canisters had an OD of 14 inches and length of approximately 15 ft, and contained a single fuel assembly.

The SFT–Climax developed and deployed a purpose-built, double-ended transportation and transfer cask (Patrick 1986). It was not certified as a Type B shipping cask (it was deployed only on the Nevada Test Site), however, the design is instructive for DBD application. The top lid was made of steel approximately 7 inches thick, attached by a hinge and actuated by a double-acting hydraulic cylinder attached to the body. The bottom lid was a sliding door assembly with steel doors approximately 18 inches thick, electrically actuated. The Climax shipping cask was made mostly of steel, and weighed approximately 90,000 lb (45-inch OD, 18-inch ID, and 18-ft length). It was mounted to a flatbed on pivoting load jacks (Figure 2-7) so that it could be hydraulically upended for loading and for transfer of a canister into the borehole. Test operations were conducted successfully, with minimal radiation exposure to workers.

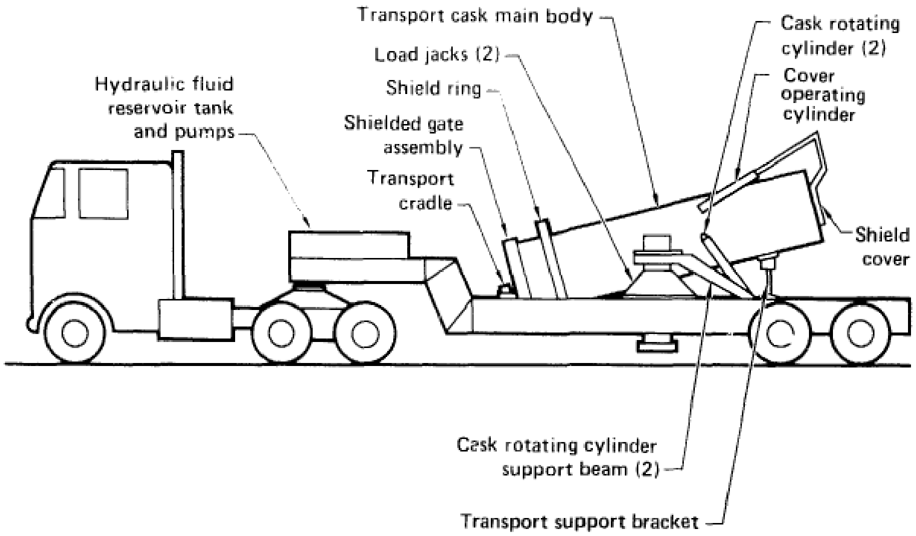


Figure 2-7. Transportation and canister emplacement system for the Climax spent nuclear fuel test (Patrick 1986).

While the SFT-Climax project was able to use a single cask for both transportation and transfer into the borehole, this would be difficult and likely not practicable for DBD. Waste for DBD would be delivered in licensed (Type B) shielded casks. Transportation systems include casks, impact limiters, and carriage pallets, would be designed for waste shielding and confinement. The function of transferring packages to the borehole, which requires a shielded vessel with openings at both ends, cannot be met by existing transportation casks. At least one Certificate of Compliance for a so-called double-ended cask has been issued (NRC 2015) for shipping relatively small quantities of activation-product waste forms. Developing a double-ended transportation cask for DBD packages is an optional approach, subject to the time and effort needed for licensing a new cask, and the technical challenge of demonstrating required cask performance.

A dedicated transfer cask (not licensed for transport) is another option. Such a cask would be shielded, and receive packages from the transportation cask at the disposal site, then transfer the packages to the disposal borehole. With a vertical disposal borehole, the transfer cask would also be positioned vertically to facilitate transfer. However, transfer from the transportation to the transfer cask could be horizontal or vertical, similar to dual-purpose canisters for spent fuel (Greene et al. 2013).

When installed on the wellhead, the transfer cask (or double-ended transportation cask) could function in an ambient pressure environment, or it could sustain large downhole pressures as part of the well-control pressure envelope. The former mode of operation would rely on borehole stability, emplacement fluid weight, and *in situ* formation pressure conditions to maintain well control. A mud surge tank would handle borehole fluid displacement and thermal expansion during operations. For safety this approach would rely on a BOP device below the wellhead flange, to close the borehole if overpressure conditions occurred during emplacement. One or more annular BOPs could serve this purpose and seal against the wireline cable, package, or the wireline tool section. Such a system would not permit emplacement operations in flowing boreholes (unlikely yet not impossible for DBD sites), and there would be some risk of damaging the wireline, package, or tool section if the BOPs were actuated.

The alternative is to make the transfer cask part of the well-control pressure envelope for the borehole. No BOP would be necessary (although one could be required by a permitting authority) with a wellhead installed. The upper end of the transfer cask would be fitted with a set of grease tubes to seal against the wireline cable. It would also have "lubricator" tube sections between the shield part of the cask and the cable seal, to hold the wireline tool section prior to lowering. With the transfer cask and wireline configured for lowering, the lower shield door or plug on the cask would be opened, the transfer cask attached to the wellhead, and the wellhead valve opened making a clear path to the wellbore. Illustrations of the arrangement and additional description are provided in Section 3.

The well-control approach is more conservative than the zero-pressure approach because control can be maintained without risk from closing a BOP, and packages could be emplaced even under flowing conditions. A technical challenge would be to devise an operable shield door for the lower end of the transfer cask, while maintaining the cask pressure-tight to the wellhead flange. A large ram-type BOP could do this, and be made part of the transfer cask, but the weight and size of such a device would be prohibitive. Another approach using a rotating shield door is described in Section 3 and recommended in Section 4 for the DBFT engineering demonstration.

The transfer cask must interface with the wellhead using some type of pressure-rated flange. Traditional oilfield flanges are bolt-ring types with provisions for welding to casing or tubing. Common variations include clamps for quick connection. For remote connection and release, automated bolt rings and automated clamps have been developed. An automated clamp is described in Section 3.3.

2.9 Emplacement Options

Several options for emplacing WPs in a disposal borehole have been proposed: drill string, wireline, conveyance casing, coiled tubing, and drop-in. These different methods are discussed in the following sections. It should be noted that the wireline emplacement option has been selected as the preferred option for the conceptual design presented here. The supporting analysis (SNL 2015) used the cost and risk models detailed in Appendices A through C, and is summarized in Sections 3.4 and 6. The other options are discussed to provide background on the selection of emplacement mode.

2.9.1 Drill-String Emplacement Option

In the drill-string emplacement option, 40 WPs would be threaded together near the surface and emplaced in a single operation using drill pipe. The following discussion is excerpted from a previous study (SNL 2015) and is presented here as background on the emplacement mode selection.

After drilling and construction of the disposal borehole is complete, and the drill rig moved off, a number of modifications would be made to create the integrated facilities needed to emplace strings of packages. Construction would include the subsurface "basement," surface pad installation, transfer carrier installation, emplacement workover rig setup, and installation of a control room and ancillary surface equipment.

Subsurface Basement Construction

The basement would serve two main functions: 1) shielding around BOPs and other equipment for handling packages, and 2) reducing the height requirement for the transfer cask, emplacement rig, and related equipment.

A basement excavation lined with reinforced-concrete would be constructed around the borehole casings (Figures 2-8 and 2-9); construction details would depend on site conditions. The basement lining would need to withstand surface loading by the emplacement rig, on the order of 10^6 pounds. The borehole casings would be temporarily plugged and the BOP removed. Basement equipment (i.e., "elevator" ram, BOP stack, additional valves, slips, tongs, equipment for handling emplacement fluid surge, and other monitoring and control equipment) would be lowered and assembled in place.

Taken together, the BOP stack (Figures 2-8 and 2-9) could include: 1) a blind-ram to close the borehole when packages are not being emplaced; 2) a 4-1/2 inch pipe ram to seal around the drill pipe if required during emplacement operations; 3) an elevator ram configured as a pipe ram to grip package strings at the joints; and 4) any other valving or preventer hardware required by permits. Shear rams or other closure systems that could damage packages or cause the drill string to part if inadvertently actuated would not be used or would be disabled.

The basement would have a ceiling at grade level to shield the rig above when packages are in the basement. The ceiling would also support the transfer cask during package transfers (at least 66,000 lb; see Section 3.3). It would consist of two or more thick, movable plates of steel or reinforced concrete. These would be keyed and bolted or pinned together in place, forming a load-bearing, removable platform with a central hole over the borehole, and shielded doors for worker access (Figures 2-8 and 2-9).

In the event of an equipment problem during emplacement operations, worker access would be provided through the shielded doors, or the ceiling could be disassembled and removed. In the unlikely event that packages get stuck in the basement interval, remote operations would be used to operate or repair the equipment.

Emplacement power slips would be installed below the receiving collar. The function of these remotely operated, hydraulically actuated slips would be to grip the package string and prevent vertical movement during string assembly or disassembly. A separate set of slips at or just below the rig floor would be used to hold the drill string as pipe joints are made up or broken down during trips into or out of the borehole.

The basement slips would be supported by a structural frame anchored to the basement walls and floor. These slips would support only a single string of packages (less than 200,000 lb) plus dynamic loads associated with engagement and disengagement of the slips. Remotely operated power tongs would be installed on the structural frame just above and below the power slips, for making and breaking joints in the string (Figure 2-10).

A fail-safe device in the form of a "breakaway sub" would extend from the basement power slips, to a point above the "iron roughneck" above the rig floor. The breakaway sub would be used to lower or raise packages to or from the basement. In event of an inadvertent attempt to pull a package through the transfer cask, against the stops, resistance from the receiving flange and the basement ceiling would be sufficient to cause the breakaway sub to fail in tension. The breakaway sub would also include load and torque sensors integrated with the safety interlock system on the cask door, basement power slips, basement tongs, and BOP stack. The interlock system would also include sensors that monitor for rotation of the package string in the basement and the borehole, when threaded connections are made up.

The tieback guidance casing would hang from the surface casing below the stack, along with the intermediate casing, consistent with the reference design.

After waste emplacement, sealing, and plugging the basement and wellhead equipment would be removed, and the borehole cemented up to the level of the basement floor. Basement equipment would be removed, casings cut off, and the basement backfilled to the surface.

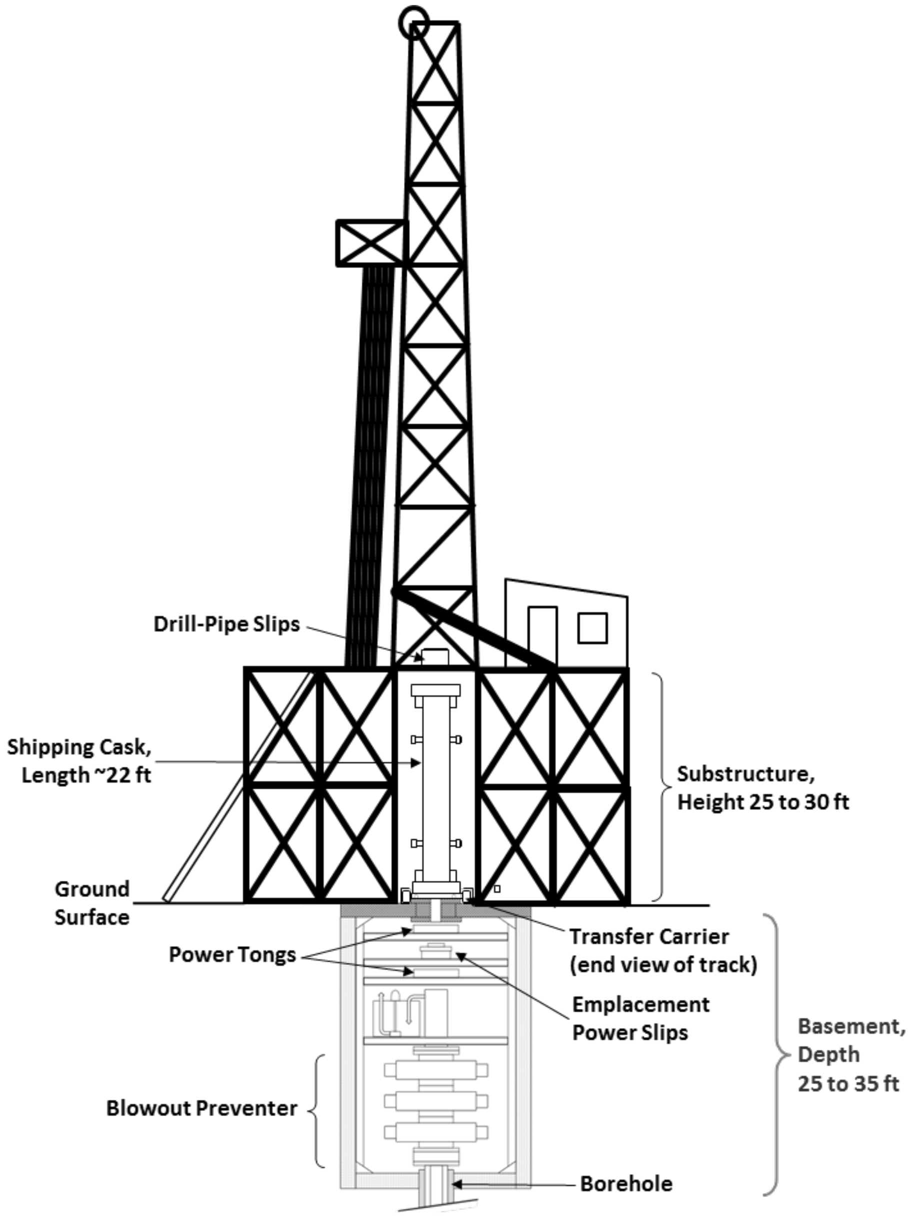


Figure 2-8. Schematic of emplacement workover rig, basement, transport carrier, and shipping cask in position for waste emplacement (not to scale).

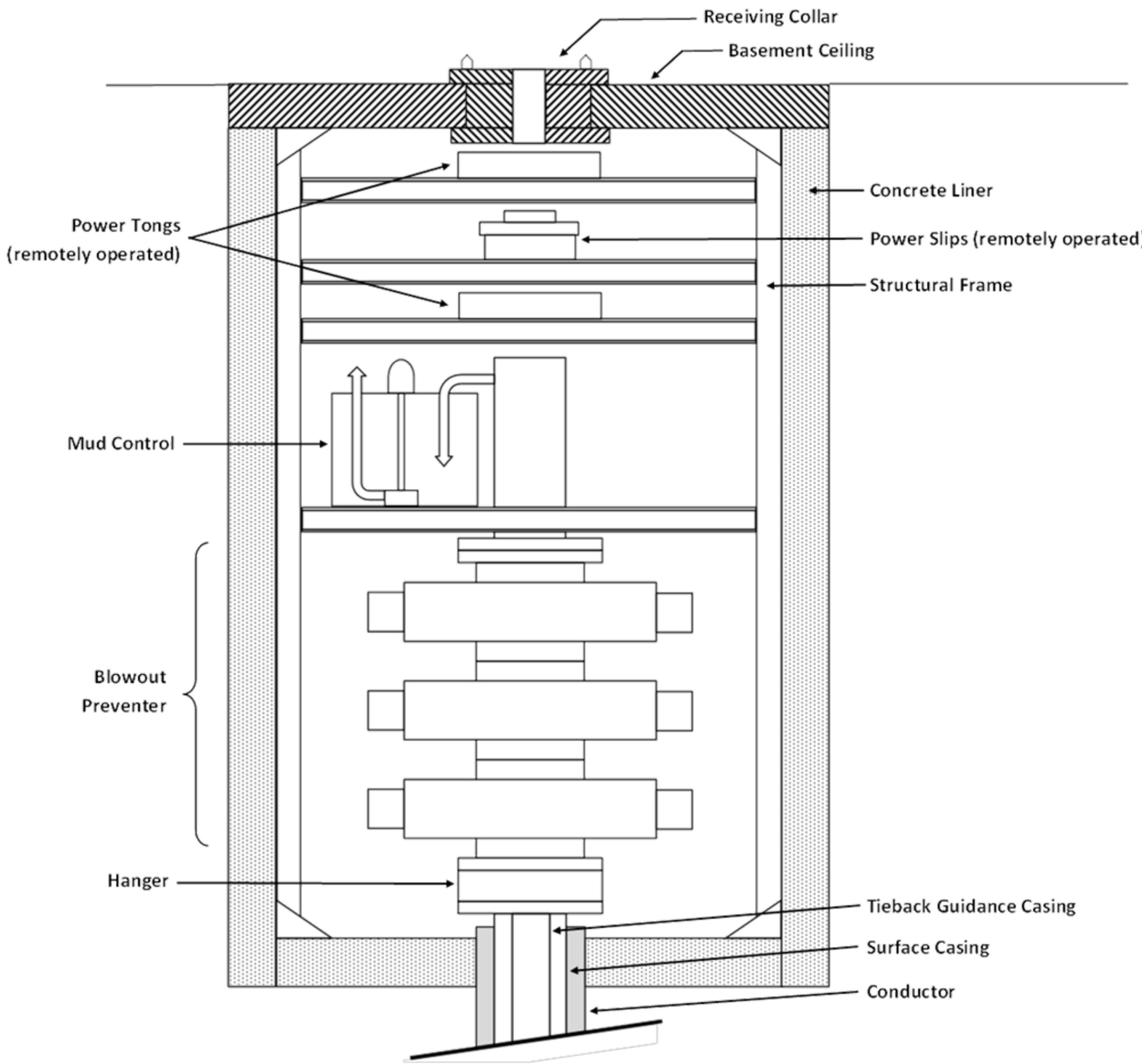


Figure 2-9. Basement concept for drill-string emplacement (not to scale).

Surface Pad

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

Transfer Carrier

Following the Woodward-Clyde (1983) concept, a track-mounted transfer carrier would deliver the transfer cask over the last 50-ft distance to the borehole. It would consist of a platform mounted to wheel trucks that run on a steel track and cannot be derailed. The track would be a rigid steel frame anchored to the surface pad. It would be approximately 6 ft wide, straddling the borehole, and precisely aligned (Figure 2-11).

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

Emplacement Rig

After the basement, surface pad, and transfer carrier track are installed and tested, the emplacement rig would be assembled above the borehole. The emplacement rig floor would sit well above ground level, standing on a steel-frame substructure. An open space within the substructure and around the wellhead would be configured for the transfer carrier. The substructure would have sufficient height to allow the shipping casks to be positioned vertically over the hole under the rig floor. An opening in the substructure that is approximately 7 ft wide and 26 ft high could provide passage for the transfer carrier and shipping cask.

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

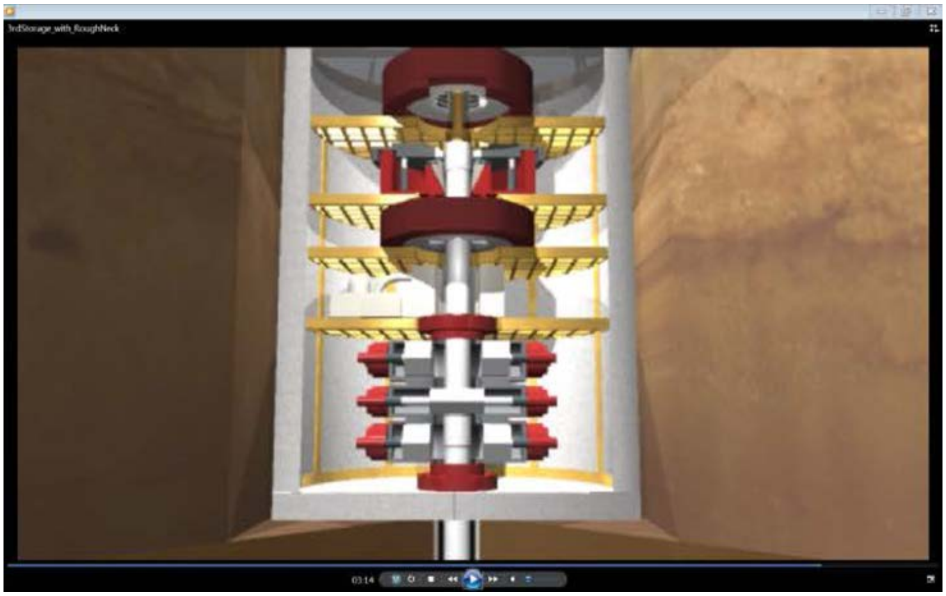


Figure 2-10. Cutaway visualization of basement including (from top down): upper tongs, power slips, lower tongs, mud control, three BOPs, and casing hanger.

Figure 2-11. Visualization of transportation/transfer cask mounted on transfer carrier, on a track under the rig floor, leading to the wellhead.

The combined weight of packages and drill pipe would be approximately 468,000 lb based on 154,000 lb buoyant weight for 40 packages in pure water, and 314,000 lb for drill pipe at 20 lb/ft. The heaviest lift for the emplacement rig would be removal of the guidance casing tieback (approximately 550,000 lb, assuming 10,000 ft of 13-3/8 inch casing at 54.5 lb/ft).

In deep boreholes the weight of drill pipe hanging in the borehole is an important consideration. Woodward–Clyde (1983) selected 4-1/2 inch drill pipe, which is available with tensile yield strength ranging from 330,600 to 824,700 lb depending on the weight and type of material (Grant Prideco 2003). Pipe joint strength generally exceeds that of the pipe because of increased external-upset wall thickness.

Making and breaking threaded drill pipe joints is one of the riskiest tasks in a drilling operation from the standpoint of worker safety and improperly made joints. Accordingly, a highly automated iron roughneck would be used to make and break drill pipe joints. This would not necessarily increase the speed of pipe joint operations but it would improve safety and reliability by reducing variability and the potential for human error.

Control Room and Ancillary Equipment

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

Handling and Emplacement Steps

Before the transfer cask is placed over the borehole, a borehole qualification procedure would be run 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 (details in Section 3.3). 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 assembled in strings of up to 40 using the basement equipment. The potential for damage to packages from power slips and tongs is undetermined (TBD-33). As discussed above, a release mechanism would be threaded onto the topmost package in each string. The package string would then be lowered on drill pipe to the bottom (or to the cement plug atop previously emplaced packages) and disengaged from the pipe. A bridge plug and cement would be set prior to the emplacement of the next package string. A stepwise description of emplacement steps that was used for hazard analysis was presented by SNL (2015).

The first (lowermost) package in a string of packages could be an instrumentation package. Telemetry from the instrumentation package to the surface could be battery powered, pressure activated, and electromagnetic without cables. If a package string were lowered into collapsed casing and became stuck, the instrumentation package could have a weak point or shear pin to facilitate removal of the remainder of the string. The instrumentation package could serve other purposes: 1) initiate the process of threading together the string at the surface; and 2) bear any damaging, concentrated loads associated with setting the string down on the bottom. Other measures to prevent load surge through the string when placed on bottom have also been considered, including a long crush-stroke impact limiter (Section 2.6).

After waste emplacement the same workover rig would remove the guidance casing tieback (approximately 540,000 lb as discussed previously) and the intermediate casing section from the seal zone (approximately 300,000 lb for 3,000 ft of 18-5/8 inch casing). The rig would then be used for seals emplacement and plugging of the disposal borehole.

2.9.2 Wireline Emplacement Option

In the wireline emplacement option, a single package would be emplaced in the borehole in a single operation using wireline. The following discussion is excerpted from a previous study

(SNL 2015) and is presented here as background on the emplacement mode selection (Section 3.4 and Appendix A). Wireline emplacement has been selected as the emplacement option for the DBFT (SNL 2015) but some of the details of this emplacement option have changed since the earlier study, such as further development of a concept for transferring WPs from the transportation cask to the transfer cask, and to the wellhead carousel (Section 3.3).

Packages for wireline emplacement (Section 2.6) 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.

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.

Wellhead Shield

The following description is written for an emplacement borehole with a remotely operated BOP stack on 24-inch surface casing. If no BOP is present, and the wellhead is limited to valves and piping, then the wellhead shield could likely be scaled down in both diameter and height. Further, the shield could be simplified if the wellhead is recessed sub-grade, which could be specified in the borehole construction details. Sub-grade installation of wellhead valving and other components in a “pit” is discussed further in Section 3.

A robust radiation shield would be constructed around the wellhead (Figure 2-12). The wellhead shield would support the weight of the transfer cask (at least 64,000 lb) and the package (up to 4,620 lb), with an appropriate FoS. Functionally, this interfacing flange would resemble oilfield applications, but remotely operated (Section 3.3). The entire wellhead shield, top plate and collar would be designed for removal, and destruction or reuse after emplacement operations.

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.

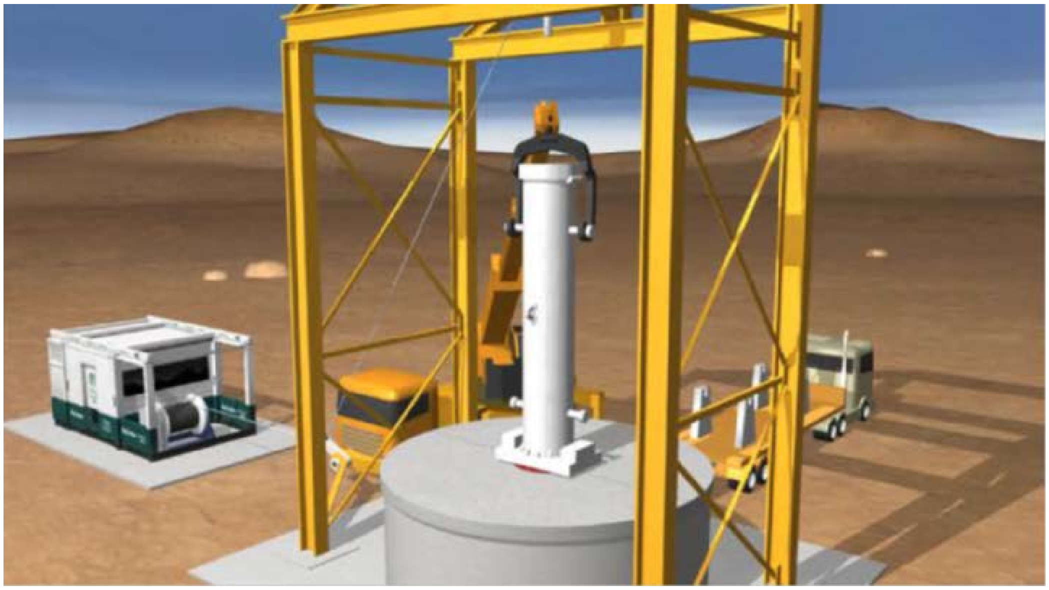


Figure 2-12. Schematic of wellhead shield, top plate, crane, transfer cask in position for waste emplacement, headframe, and wireline winch (not to scale).

Headframe

Alignment and support of the wireline sheave over the borehole will be provided using a prefabricated steel headframe, transported to the site in sections and assembled using a crane. The reason for using a fixed headframe instead of a portable crane, which is typically used in oilfield wireline logging, is the improved reliability and lower probability of failure during emplacement operations. A similar fixed headframe was used for the SFT–Climax (Patrick 1986).

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.

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 (details in Sections 3.3 and 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 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.

2.9.3 Emplacement Rate Discussion

Drill-String Emplacement Rate-of-Progress

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

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 (Section 2.3; TBD-14); 2) emplacement fluid density and viscosity (Section 5.4; TBD-15); and 3) package buoyant weight (Section 2.4; TBD-27). Terminal sinking velocity for single packages is estimated to be in the range of approximately 5 to 15 ft/sec (large reference packages in brine; Section 5.4). 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 (see Appendices A and B).

Logistical Controls on Emplacement Schedule

For costing of emplacement options (Appendix C) in support of the selection study, it was assumed that one shipping cask containing a WP can be delivered to a disposal facility each day. This estimate is based on operational experience at the Waste Control Specialists (WCS) site in Andrews, Texas. A paper describing the operation (Britten 2013) states that their initial handling rate was one package every four days, which later improved to three days (verbal communication). Three or more packages are active in the process, giving a total throughput of one per day.

This rate of emplacement (averaging one per day) has implications for logistics at a disposal facility. For a prototype disposal borehole, approximately 430 workdays would be needed to emplace 400 packages and 10 cement plugs (not accounting for holidays, weather days, and equipment down-time). This is reflected in the cost estimates for normal operations (Appendix C).

2.9.4 Coiled Tubing, Conveyance Casing, and Drop-In Options

Three other emplacement options are coiled tubing, conveyance casing, and drop-in options. These three are described briefly below; a comparison of these alternatives to drill-string and wireline emplacement is summarized in Table 2-7.

Coiled Tubing

The emplacement concepts described above could, in principle, use coiled steel tubing for emplacement instead of drill pipe or an electric wireline. Coiled tubing is available with electrical conductors (at additional cost) which could operate an electrically actuated releasable cable head. For the drill-string method, coiled tubing could replace the rig for emplacement operations, whereas for the wireline method it would replace the wireline cable and winch.

Coiled tubing is capable of pushing packages into the borehole; however, the risk of packages getting stuck increases if they are pushed through obstructions. The fatigue life of coiled tubing is on the order of a few hundred trips at most, particularly if they are deep trips that use most of the tubing in a coil. For example, using a “rule of thumb” that each 20,000-foot coil can service 300,000 ft of borehole, each coil would last no more than roughly 20 trips. Even using modern monitoring and replacement strategies that extended the number of trips to 50, approximately ten coils would be used for emplacing 400 WPs and installing cement plugs in a single deep disposal borehole.

Coiled tubing has greater strength than wireline, which could allow emplacement of several packages at a time, decreasing the number of trips and coils of tubing. However, emplacing more than one package a time necessitates the construction of a basement similar to that needed for drill-string emplacement (Section 2.9.1) with facilities for connecting packages together and supporting the string. Also, the extra weight of strings of packages could increase the severity of consequences from dropping a string during emplacement, or increase the size of impact limiters needed to mitigate those consequences (see Sections 5.1.5 and 5.5, and Appendix A).

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

Conveyance Casing

With drill-string emplacement, the basement equipment (and its reliability) would be simplified if packages were not threaded together. Rather, a section of casing would be hung from the basement slips, and loaded with packages using a wireline as described in Section 2.9.2. When the conveyance casing was full with up to 40 packages, it would be lowered into place using drill pipe. Advantages would include fewer joints to make up at the surface, and fewer gripping operations. However, the EZ would need to be uncased (i.e., no guidance casing) or else the diameter of packages would be reduced (with two layers of casing). The risk of package breach from dropping the conveyance casing, or drill pipe on the trip out would be comparable to the risk of package breach during drill-string emplacement.

Table 2-7. Summary of alternative DBD package emplacement modes.

	Meets Security Requirement	Multi-Package Emplacement Possible	Relative Operational Cost	Comments
Free Drop	No		$	• Impact limiter on every package • Status uncertain during descent
Electric Wireline	Yes		$$	• Impact limiter on every package
Coiled Tubing	Yes	✓	$$$	• Limited tubing life (less than needed to load a borehole) • Emplace packages threaded together • Don't force packages downhole
Drill String	Yes	✓	$$$$	• Heavy strings • Emplace packages threaded together • Complex "basement"
Conveyance Casing/Drill-String	Yes	✓	$$$$	• Heavy strings • Packages smaller • Not threaded but emplaced in stacks within a casing
✓ = Capable of multi-package emplacement, with a "basement" facility for assembling package strings.				

Drop-In Emplacement

With a guidance casing running from the surface to TD, and the borehole filled with an emplacement fluid with controlled properties, it could be possible to allow packages to sink freely into disposal position. Any security requirement to monitor package locations at all times would not be met with this option. Terminal velocity was estimated by Bates et al. (2011) to be on the order of 8 ft/sec for similar packages, and other estimates are developed in Section 5.4. Impact-limiter design performance could be readily verified. Terminal velocity depends on bypass flow through casing perforations, if present, and measurement of this effect is a recommended topic for DBFT engineering demonstration (Section 4.5).

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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. This reference disposal concept is intended to guide design of the DBFT engineering demonstration described in Section 4.

3.1 Borehole Drilling and Construction

Borehole drilling and construction for the DBFT 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). Current geothermal practice is relevant because geothermal resources are usually found in hard rock and because the flow rates in geothermal production require large-diameter holes. Given that comparison, drilling of disposal boreholes would likely be done with a large, modern, conventional drill rig with rotary pipe and hard-formation roller-cone bits (tungsten-carbide insert, journal bearing). Requirements on the minimum separation between adjacent boreholes, and dogleg severity (Tables 2-3 and 2-4) could necessitate directional drilling, and there are several ways to accomplish this using commercially available technology (Section 2.7.1).

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 (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 (TBD-19) would be based on longevity required (Section 2.3.9; TBD-09) for the site-specific chemical environment (TBD-32), taking into account the potential for damage from gas generation (TBD-43), and any requirement for containment after sealing and plugging of the borehole (TBD-40).

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; TBD-42).

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

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).

Table 3-1. Typical disposal borehole (and FTB) 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.						

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.

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.

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 in Section 2.7.4 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.

Emplacement Zone Guidance Casing

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). Because of the safety advantages of guidance casing it is required for DBD and for the DBFT (Table 2-3). The functions of guidance casing in the EZ include:

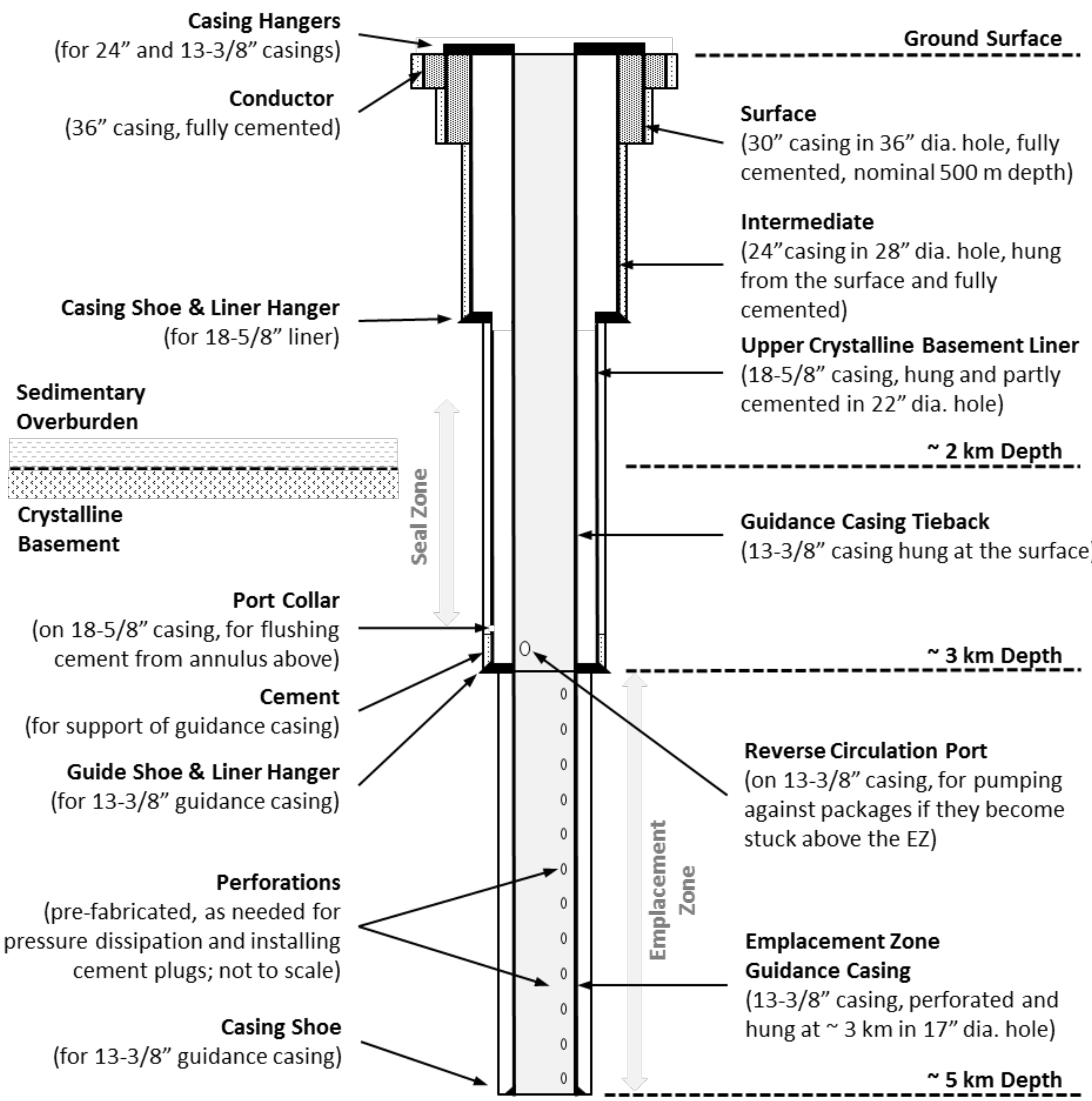
- Provide a clear, smooth path for package emplacement (Section 2.3.9)
- Prevent rock or cement debris from falling in the path
- Help to control surge pressure when packages are lowered or retrieved
- Align packages as they are stacked (limit offset loading)
- Facilitate placement of cement plugs and bridge plugs if used
- Limit terminal sinking velocity if a package is accidently dropped (Section 2.3.10)
- Facilitate recovery of packages in case of an accident (alignment and protection from rock debris; also recovery of stuck packages by pulling casing)

The guidance casing would be partially or fully cemented depending on selection of a completion option (see recommendation below). Perforations spaced along its length would be used for cementing and/or for relief of fluid thermal expansion after emplacement of heat-generating waste (TBD-47).

Whereas generation of hydrogen gas by steel corrosion has been identified as potentially important (Section 2.7.4), one way to mitigate the rate of corrosion and gas generation is through selection of material for the EZ guidance casing (TBD-19). The EZ guidance casing would have nearly 3 times the surface area of packages (although less thickness), so just considering the water present after emplacement, material selection could have an impact.

If the host rock is so impermeable as to the buildup of H_2 gas pressure in the borehole, then it would also limit formation fluid inflow, and the EZ could become starved for reactant water, eventually impacting the rate of gas generation. On the other hand, if the formation is sufficiently permeable that water availability does not limit the rate of corrosion, then dissipation of H_2 gas into the formation may be likely. Further understanding will depend on site-specific information (TBD-32 and -43).

Another possible remedy for gas generation is cementing as described for options 3 and 4 in Section 2.7.4.



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 (and FTB) schematic; hachured patterns indicate cement.

Borehole Fluid

The functions of borehole fluids include lubrication of drill string and wireline operations, flushing of cuttings during drilling, and flushing before and after cementing. The emplacement fluid would provide buoyant support to downhole tools and WPs. Borehole fluid can be replaced by circulating new or different fluid, and it can be stratified by placing heavier fluids deeper in the hole. Thus, the in the EZ of a waste disposal borehole during emplacement operations may have different properties than drilling fluid, or fluid used for testing.

Recommended EZ Completion and Other Changes from Previous Reference DBD Concept

The major changes in borehole drilling and construction from the reference concept of Arnold et al. (2011) are the drilling and emplacement fluids (based on aqueous brine and not oil-based mud), and EZ completion (adding cementing options 2 through 4 from Section 2.7.4, with associated perforation schemes). Options 2 and 3 would control the casing cement bond (without subjecting packages to cementing pressure) because cement would be injected into the annulus under pressure. Option 3 could limit H_2 gas generation by cementing the annulus, and option 4 would cement the casing ID and packages as well, but transport properties of the cement and the host rock would need to be verified. Option 4 would subject WPs to cementing pressure which would increase the risk of accidental breach.

Accordingly, option 2 (squeeze cementing of interval plugs) is recommended (TBD-49) because it is flexible and likely to achieve intended results for any borehole condition and geologic setting. With option 2 there would not be a need for slotted casing or large perforations, and the 10-m cement plugs could be located virtually anywhere in the EZ. Small perforations in the casing (approximately 2 cm diameter, spaced every 50 m) would be pre-fabricated, for leakoff of thermally expansive fluid and H_2 gas from corrosion (Table 2-6). The perforations used for cementing could be prefabricated or produced *in situ* using a perforating gun for additional flexibility in locating cement plugs (TBD-47). The effect of perforation schemes on the terminal sinking velocity of a package dropped in the borehole is analyzed in Section 5.4.4.

Disposal Borehole Sealing and Plugging

The seal zone would be the uncemented interval of the upper basement liner (Figure 3-1) especially within the basement where rock conditions could be best for sealing, but possibly including an interval of the lowermost overburden as well. The upper basement liner would be cut off just above the cemented portion at its bottom, and removed prior to sealing.

Seals would act directly against the rock surface, in a 22-inch diameter open borehole interval. At several locations, cement plugs would bracket a seal consisting of bentonite or bentonite and sand mixture (Figure 3-2). Ballast of silica sand or crushed rock would be placed between the lifts of cement and bentonite to limit chemical interaction. Bridge plugs would be installed at intervals to create API-type plugs or to partition segments. Additional discussion of sealing functionality is presented in Sections 1.3 and 2.7.5. Sealing requirements for DBD are identified in Section 2.3.13 (see TBD-46).

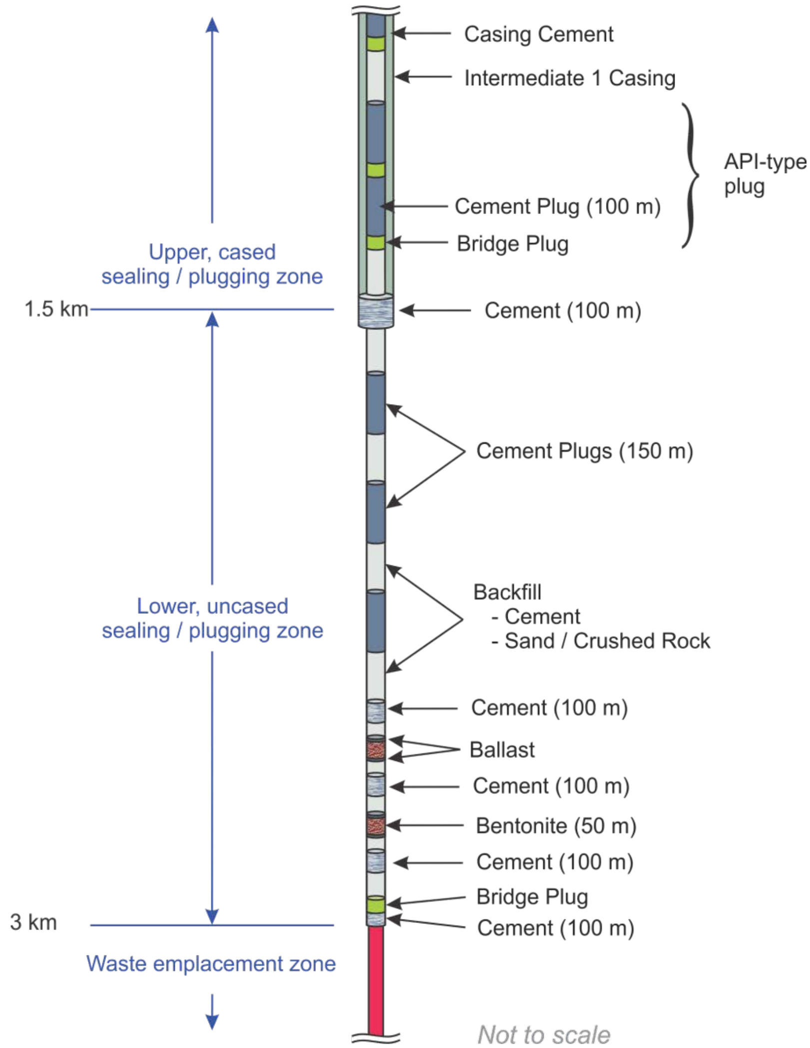


Figure 3-2. Borehole sealing, plugging, and backfilling concept schematic (Arnold et al. 2011).

3.2 Waste Packages

Waste package design for disposal would consider the tube section and the end fittings, which must have workable inner clearances and outer dimensions, while meeting pressure ratings and combined loading with an appropriate FoS. The following discussion elaborates Section 2.6, with specific information on WP design for DBD application.

In the following discussion threaded connections are discussed, by which the wireline latch and impact limiter would be attached. But 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 2-4).

Numerical stress analysis (Section 5.1) 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 5.1.5). 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 (Table 2-4).

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 3-3.

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. Package material selection is TBD for DBD (and for the DBFT engineering demonstration, Section 4.2) (TBD-19).

For maximum downhole pressure of 9,560 psi (Table 2-4), and steels that retain 90% of yield strength at bottom-hole temperature (Section 2.6), 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, Section 2.6). Such small margins are not included in the calculations discussed here.

For internal semi-flush concepts (Figure 3-3 and Section 2.6) 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 (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.

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 2-2.
[F] Inner dimension for API NC-77 thread.

For the flask-type concept (Section 2.6) 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 as discussed in Section 2.6.

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 Section 2.6 and Figure 3-3 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.

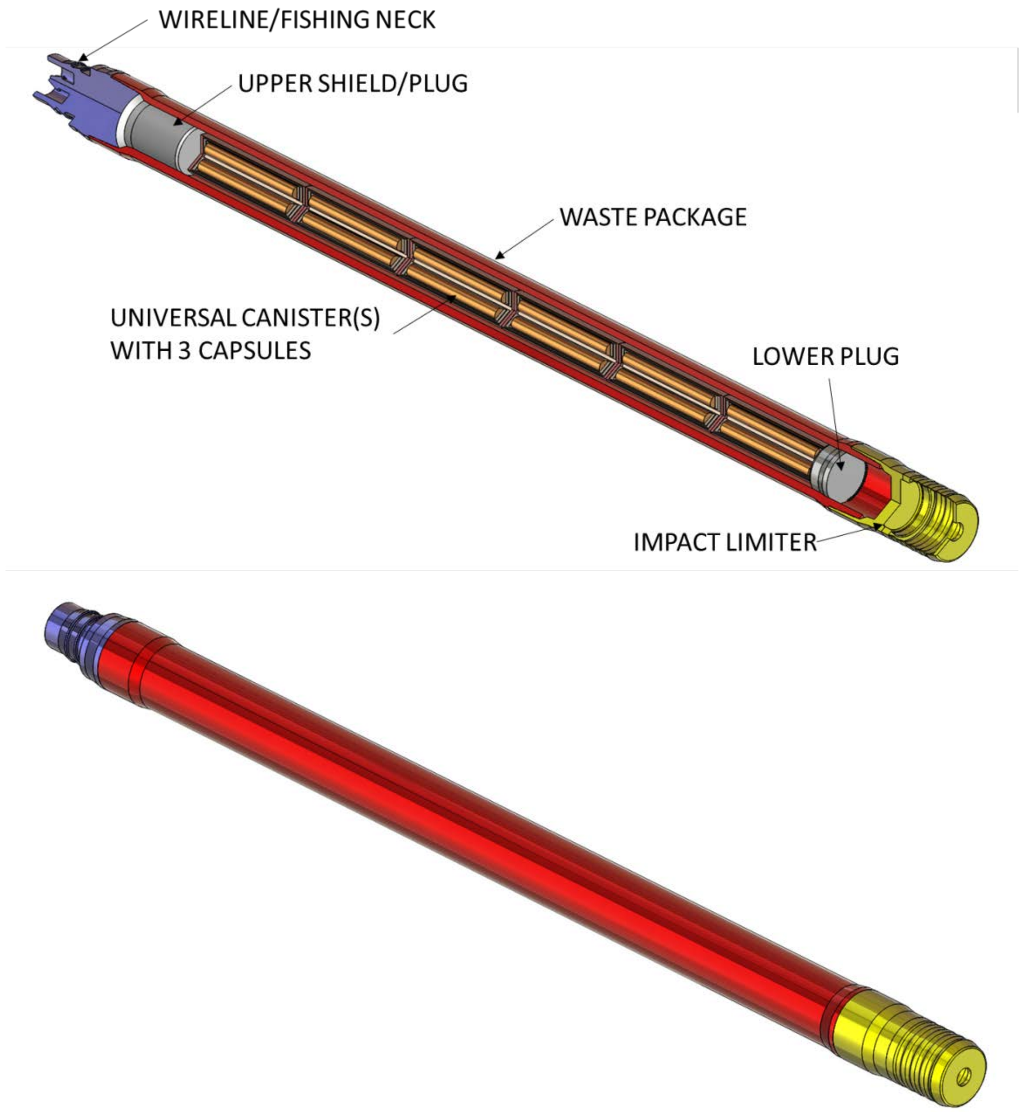


Figure 3-3. Schematic of medium-size internal semi-flush package for Cs/Sr capsules, with end fittings attached.

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. Adapting this concept for the DBFT engineering demonstration is discussed in Section 4.3.

3.3.1 Activity Sequence

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 3-4). 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 3-5). 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.

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.

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 3-6). 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 3-4. LWT cask being lowered into a horizontal cradle (ORNL photo).

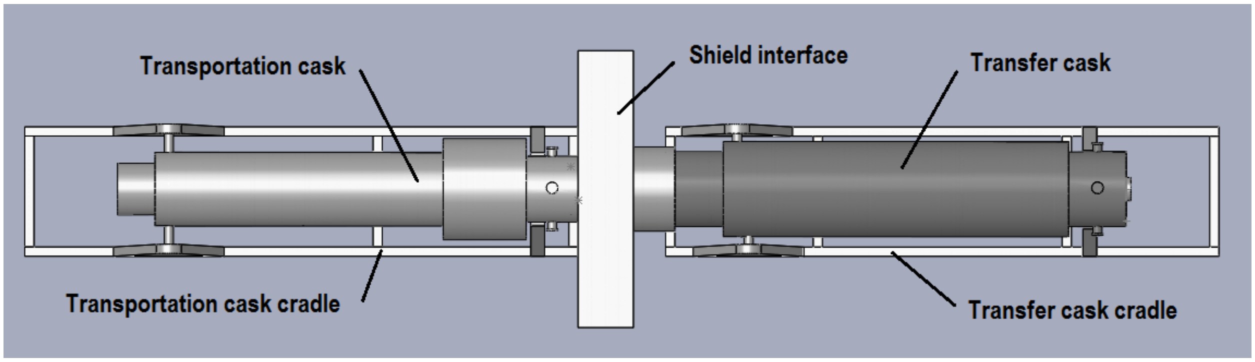


Figure 3-5. Casks in position for transfer of waste package.

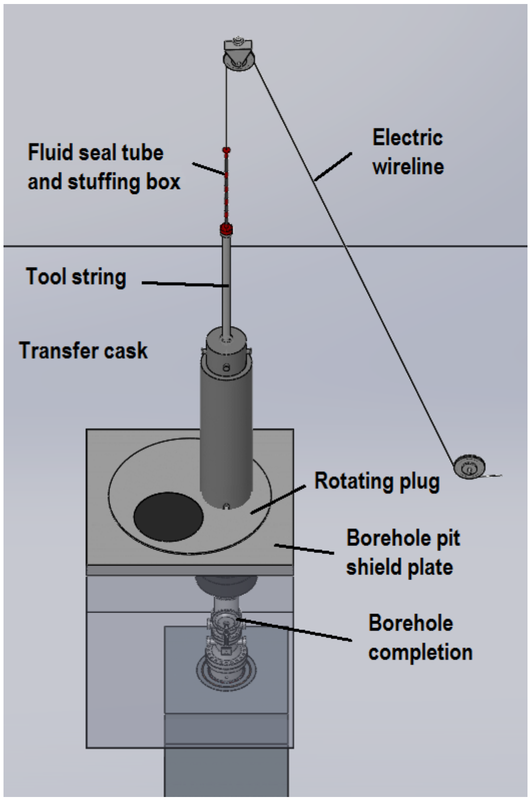


Figure 3-6. Transfer cask positioned over borehole.

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 (at the tool string location labeled in Figure 3-6, and labeled as lubricator in Figure 3-7). 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.

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 3-8.

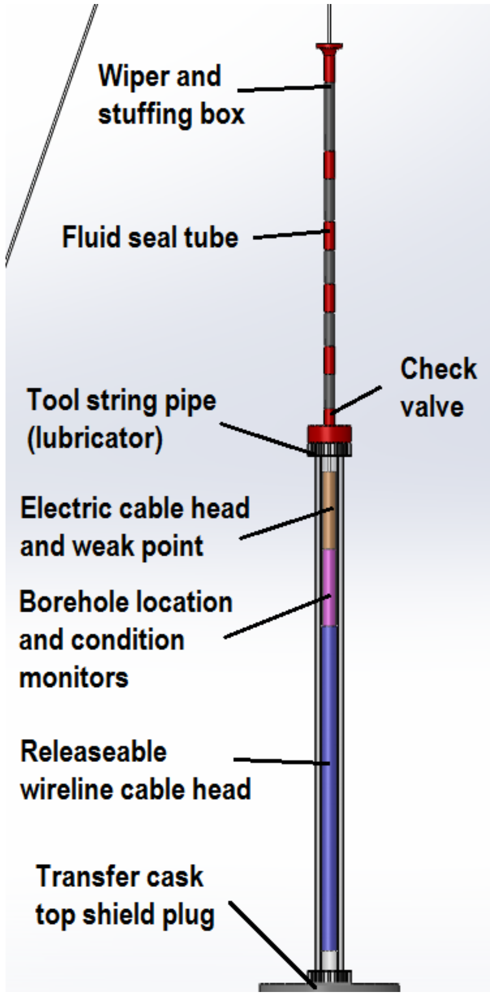


Figure 3-7. Tool string and wireline attached to top of transfer cask.

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 tool string containment tube (lubricator), the borehole valve would be closed and any fluid in the transfer cask would be drained.

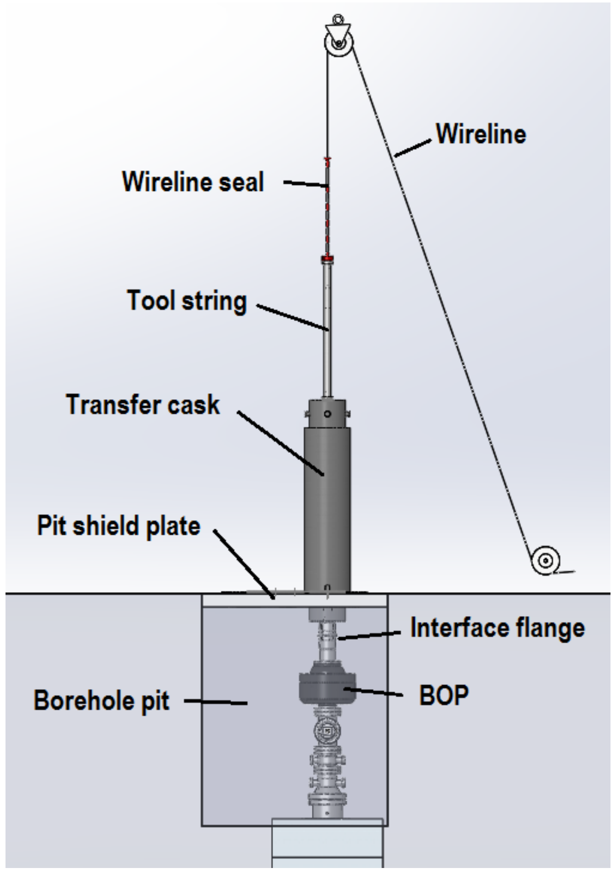


Figure 3-8. Cask over borehole, ready for package emplacement.

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.

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 process of setting plugs is not included in the scope of the engineering demonstration, but the design of the emplacement equipment must allow for plug installation, wireline logging, and other borehole related activities.

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 and Section 2.9). 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 as discussed in Appendix C.

Package Retrieval and Other Off-Normal Operations

Package retrieval from the borehole is a key requirement for DBD (and a key part of the DBFT engineering demonstration). 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 internal diameter, 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 3-3) is shown in Figure 3-9.

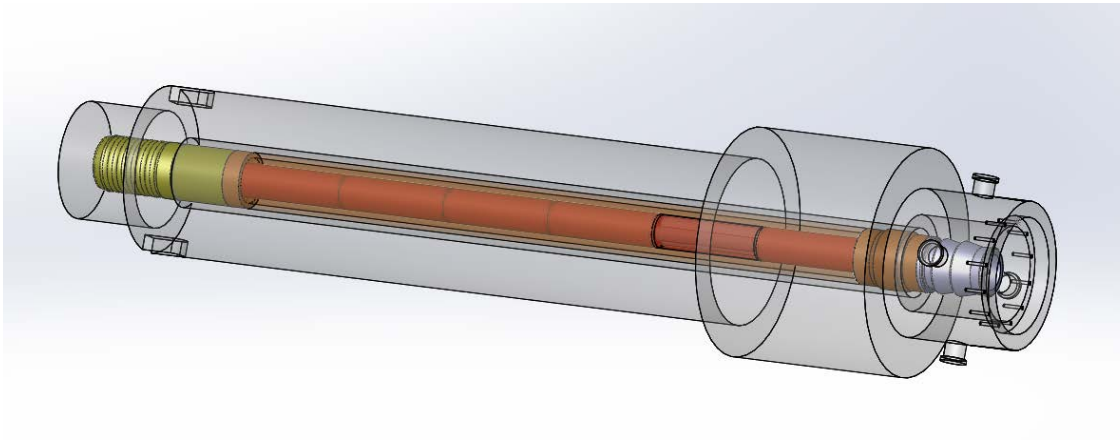


Figure 3-9. LWT transportation cask with waste package.

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 ISO-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 3-4. Similar cradles (Figure 3-10) would support the LWT cask and the transfer cask during transfer of packages and during cask maintenance operations.

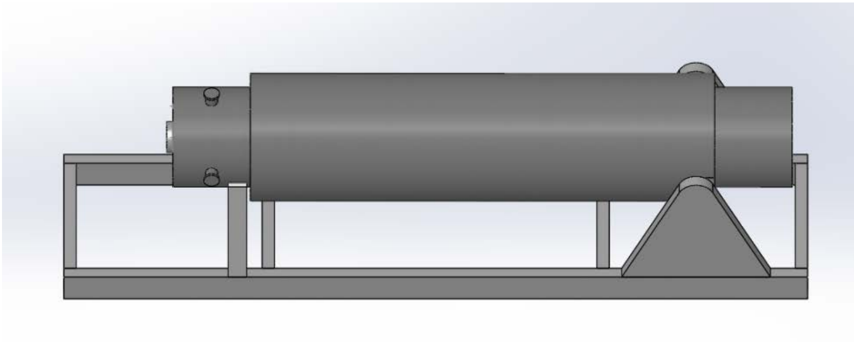
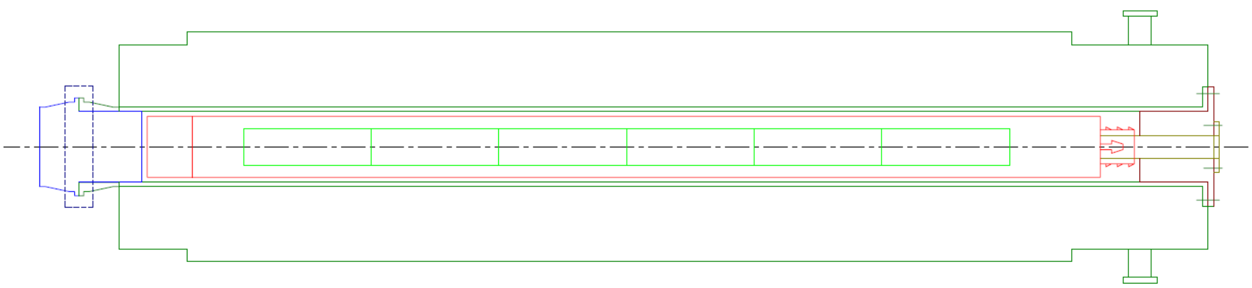


Figure 3-10. Cradle used for both LWT cask and the transfer cask.

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 3-10) 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.



Note: "Universal" canisters containing three Cs/Sr capsules each are shown schematically in green outline, overpack in red, and the transfer case lower end shield plug in blue. The upper end of the cask is to the right.

Figure 3-11. Key elements of the transfer cask.

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 3-11. The central cavity could be formed using a section of standard 14-inch, Schedule 80 steel pipe, which has the desired internal diameter, and flanges at either end.

A shielding analysis for Cs/Sr waste forms in a cask similar to the LWT transportation cask was performed (Section 5.7). 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 3-12). 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 3-12. Remotely-actuated Grayloc® flange connection system (ORNL photo).

The upper shield plug, seen to the right in Figure 3-11, 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 3-5). 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 3-13. 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.

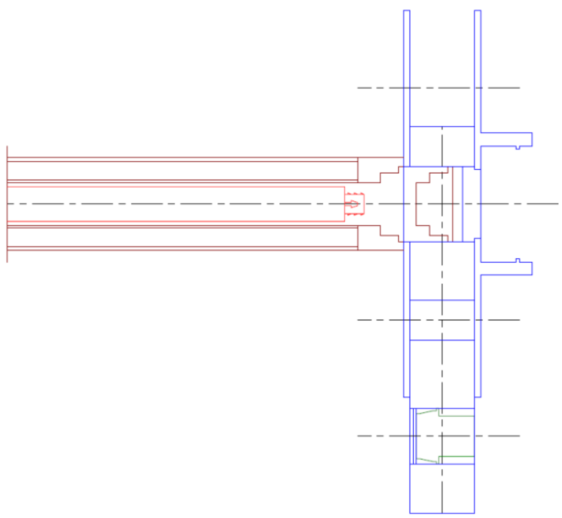


Figure 3-13. Transfer shield in first position for removal of LWT cask end shield plug.

The second position for the transfer shield would open a clear path for package transfer (Figure 3-14). 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.

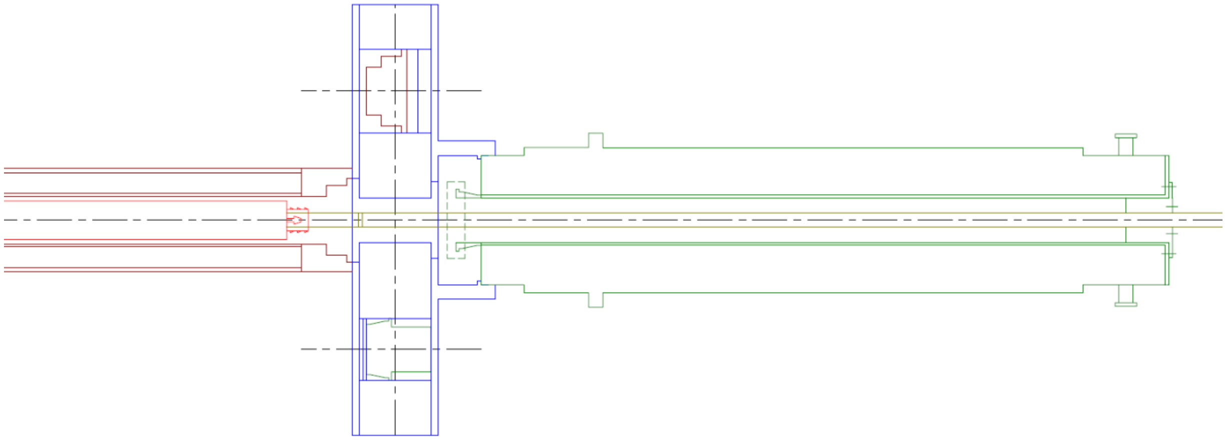


Figure 3-14. Transfer shield in second position for package transfer.

The transfer shield would then be slid to its third position (Figure 3-15). 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.

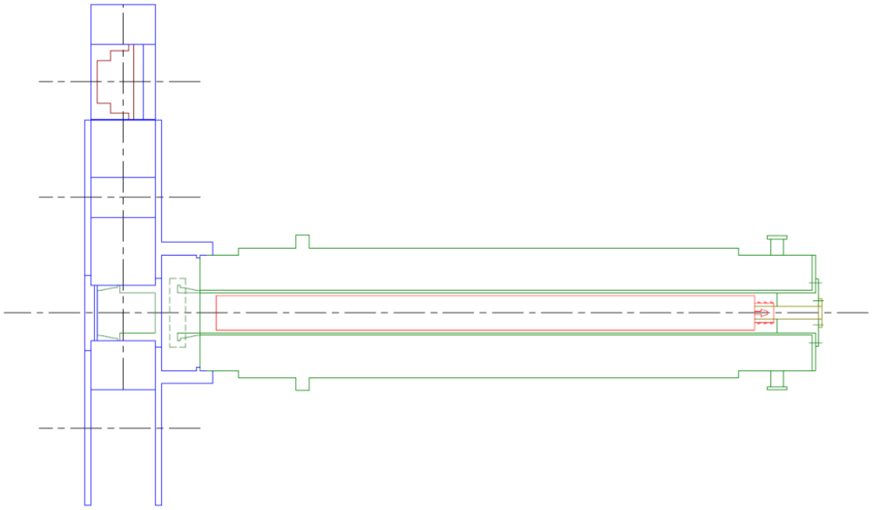


Figure 3-15. Transfer shield in third position for placement for closure of transfer cask.

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 3-16.

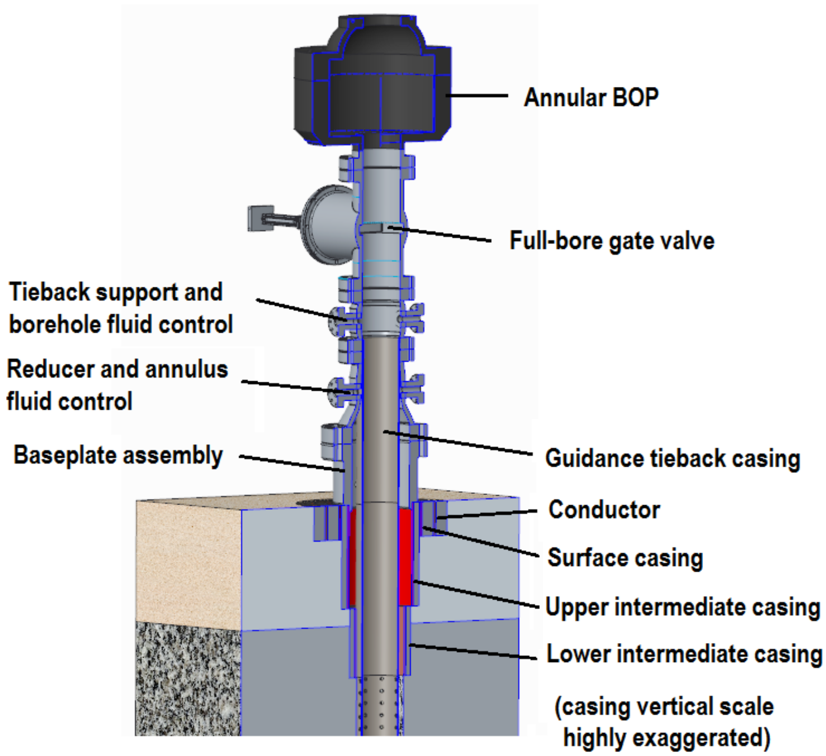


Figure 3-16. Wellhead configuration showing fluid control taps, closure valve, and annular BOP.

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 3-16). 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 (Figures 3-6 and 3-8), 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 3-17). In the present application, the carousel would serve to support and align the transfer cask, and as a maintenance shield (Figure 3-18). 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 3-17. Example of a rotating-plug maintenance shield used at ORNL.

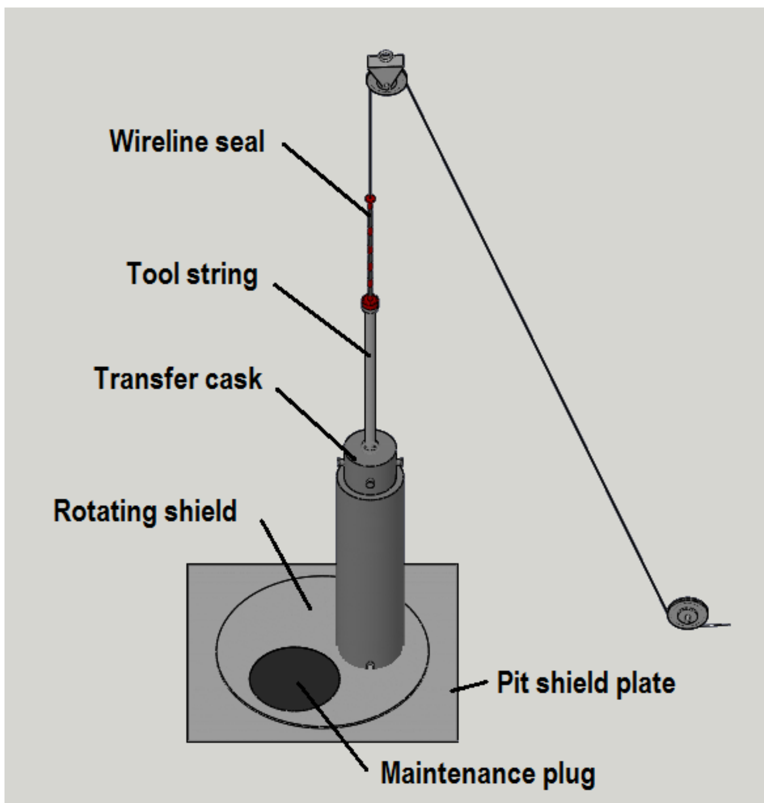


Figure 3-18. Transfer cask over the wellhead carousel and pit shield plate.

There are two key operating positions shown in Figures 3-6, 3-8, and 3-18. 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 3-18 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 3-17). 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 3-19. 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.

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 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 3-20 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 tool string containment tube or pipe (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-type shutoff or check valve is often used at the bottom of the flow tube; this can be closed should the wireline break and come out of the tube.

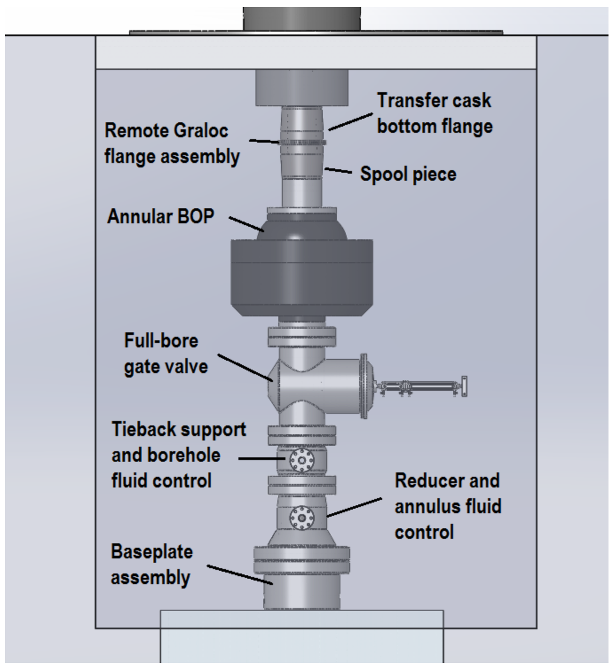


Figure 3-19. Overall pit arrangement.

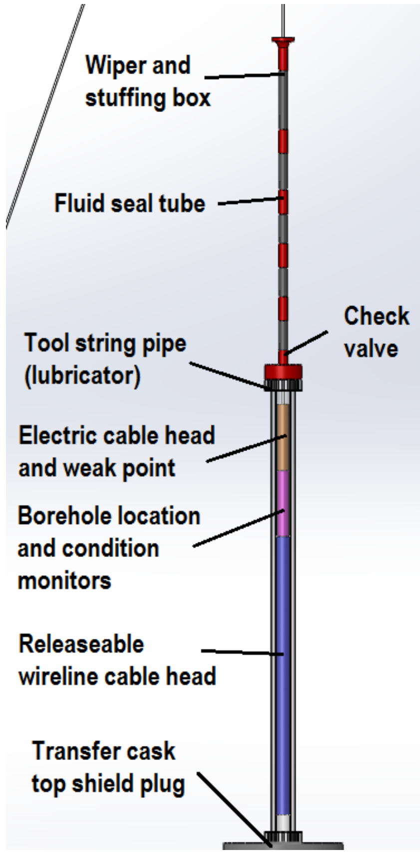


Figure 3-20. Wireline cable head, tools and remote disconnect.

3.3.8 Tooling for Supporting Operations

Other tooling would be developed for supporting operations, such as inspections of the wellhead or borehole, placement of interval plugs and seals, circulation of borehole fluids (especially if circulation were required in the lowest 2 km), fishing (recovery of one or more WPs), borehole and wireline maintenance, and ultimate plugging and abandonment of the borehole.

Specific tools for these supporting operations have not been selected. Operations such as sealing, plugging, and fishing could be conducted by first removing the pit shield plate and carousel (if no radioactive waste in the borehole is near the wellhead). Another approach that could maintain shielding, would dimensionally replicate the lower section of the transfer cask (from the latches down to the upper Grayloc® hub). Collars that fit closely around external-flush pipe or tubing at the wellhead would complete the shielding, and heavy drilling fluid could be circulated into the upper 3 km for well control.

One exception would be a fishing operation conducted for purposes of retrieving a package from the borehole. In this case, the wireline tool string containment tube would be mounted on top of the empty transfer cask in place of the upper shield plug. The transfer cask would be positioned over the borehole in the usual manner, and the recovered WP pulled back up into the cask. With the borehole valve closed, the lower shield plug replaced in the transfer cask, and side latch engaged, the wireline tool string would be disengaged and the top shield plug replaced. Every

WP would include a top shield plug (Section 2.6) that would help to limit radiation leakage during this operation.

3.3.9 Support Services

A range of support services, generally supplied by the site support contractor, would be required to execute the operations described in this chapter. These include:

- Electrical power, including backup power
- Water, both process and potable
- Site drainage
- Personnel support, including shelter and comfort facilities
- Emplacement fluid control system, including a surge tank and fluid makeup or disposal systems
- Hydraulic systems for BOP actuation (as required), grease tube operation, transfer equipment operation, etc.
- A data collection and functional safety (interlock) system with a centralized console
- Telecommunications services

Other site systems are required to support operations. The pit would be constructed as part of borehole construction, along with any necessary footers for the shield structure and headframe, and footings for the cask transfer cradles. Other site services would include, but would not be limited to:

- A laydown area for temporary staging of trucks, trailers, and casks
- A pad of sufficient size to allow for unloading transportation casks, performing cask-to-cask transfers, and lifting the transfer cask onto and off of the wellhead carousel. Note that use of a compacted gravel pad (in lieu of more resistant surfaces) for WP handling operations could be taken into account in the analysis of consequences from accidental cask drops.
- A washdown station to clean borehole fluids out of the transfer cask after each operation

3.4 Emplacement Method

As described in Sections 2.9 and 3.3, the reference disposal concept uses an electric wireline to emplace WPs one at a time. The availability of modern wireline cable is a key aspect of this concept. The multi-conductor electric wireline cable would be Schlumberger Tuffline® (or equivalent), which has a safe working load of 26,000 lb or greater depending on configuration, with a torque-balanced design and polymer-locked armor to inhibit crushing. It does not require seasoning, does not require a capstan for loads up to 12,000 lb, and is rated for 24-hour operation at temperatures up to 230°C. Cable heads with weak points, suitable for DBD emplacement operations are available from the cable vendor.

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).

Location tools such as a casing collar locator, logging tools such as the gamma ray log, and monitoring devices such as gamma detectors and fluid samplers, would be placed in the tool string middle section (Figure 3-20).

A headframe would support an upper wireline sheave above the borehole, and a lower sheave near ground level (Section 2.9). 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.

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.

Selection of the wireline option is supported by an emplacement mode cost-risk study (Appendix A). In this study, an expert panel reviewed two emplacement modes (wireline and drill-string, see Section 2.9) and worked through a hazard analysis to identify what could "go wrong" during emplacement. The panel then identified and categorized the basic events using fault trees, and assigned probabilities of occurrence. They then identified what steps could be taken if one or more WPs became stuck in the borehole during emplacement, and estimated probabilities for the possible outcomes from "fishing" to retrieve the packages. Finally, they reviewed the estimated costs and other impacts associated with normal and off-normal events. Some of the study results are summarized in Table 3-3; see Appendix A for details, and Section 3.7 for assumptions that were made about wireline emplacement, such as the use of a fixed headframe for wireline sheave support.

Table 3-3. Emplacement mode selection study results summary.

Measure	Results [A]	
	Wireline	Drill-string
Probability of incident-free emplacement of 400 WPs	97.83%	99.24%
Cost for successful emplacement with normal operations	23.5	41.9
Expected value of costs ($ million), considering both normal and off-normal events	23.7	43.9
Expected total time of operations (days), considering both normal and off-normal events	430	434
Probability of radiation release	1.35E-04	7.08E-03

[A] Results calculated using baseline inputs. Sensitivity results are discussed in Appendix A.

The likelihood of emplacing 400 WPs without incident (without a drop, and without getting stuck) is better for drill-string emplacement, primarily because of the greater probability of getting stuck using a wireline. However, the probability that an off-normal event occurs leading to breach of a WP is about 52 times greater for the drill-string option, mainly because of: 1) the high incidence of breach if a pipe string or string of packages is dropped in the borehole during drill-string emplacement; and 2) the effective use of impact limiters on single packages to mitigate the consequences of drops during wireline emplacement.

Although the costs of remediating some off-normal outcomes are estimated to be high (Appendix C) the probabilities of most of these are relatively low, so the expected cost in Table 3-3 for each option is dominated by the cost for normal operations.

Other methods of emplacement that were considered for the reference disposal concept include free drop, coiled tubing, and conveyance casing, as discussed in Section 2.9. The “free drop” method was not considered further because it would not meet a security requirement that package locations be monitored at all times. The coiled tubing option was not considered further for other reasons discussed in Section 2.9. The use of a conveyance casing was not considered further because it is similar to drill-string emplacement in terms of probability of WP breach, and requires either a larger borehole or a smaller WP.

The reference disposal concept calls for 10-m cement plugs within the guidance casing, spaced about 200 m apart in the EZ (Section 3.1; also Arnold et al. 2011). Cement plug installation is therefore part of emplacement operations, and would be done using wireline tools and coiled-tubing as discussed in Section 2.9. A squeeze cement method with casing perforations is recommended in Section 3.1 for bonding the guidance casing to the host rock, for mechanical support of the WP loads.

The steps for emplacing a WP in the EZ of the borehole in this conceptual design are given 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.

1. Open the wellhead valve (or BOP).
2. Verify the condition of the borehole by running a gauge ring with junk basket, and other logs as discussed above.
3. Close the wellhead valve.

4. Pull the transfer cask out of the transfer shield pocket.
5. Rotate the transfer cask to a vertical orientation using a portable crane.
6. Place the wellhead carousel in the first position, the one that is used for removing the transfer cask shield plug (Figure 3-18).
7. Lower and secure the transfer cask into the opening of the wellhead carousel.
8. Remove a small plug in the top shield of the transfer cask.
9. Attach a tool string containment tube to the top of the transfer cask.
10. Attach the wireline latch to the top of the WP.
11. Verify the wireline latch is secure by performing a pull test, leaving slack in the line.
12. Remove the lower transfer cask shield plug by remote operation.
13. Rotate the carousel to the second operating position, over the borehole.
14. Take up the slack in the wireline and release the side latch.
15. Open the wellhead valve.
16. 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.
17. Set the package on the bottom, or on the previous package emplaced.
18. Disconnect the wireline tool string from the WP by activating the electromechanical release.
19. Hoist and re-spool the wireline and tool string. The ascent rate of the wireline would be 4 ft/sec.
20. Close the wellhead valve.
21. Drain any fluid in the transfer cask.
22. Rotate the carousel back to the first position and reinsert the lower shield plug in the transfer cask.
23. Disconnect the tool string containment tube from the transfer cask.
24. Move the transfer cask to a wash-down area for cleaning, inspection, and preparation for receipt of another WP.
25. Clean and inspect the tool string and its components, and prepare the tool string and its components for the next use.
26. Repeat steps 1 through 25 to emplace additional packages.
27. 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).

Support services and facilities are addressed in Section 2.9, and include a headframe. The wireline winch and logging equipment would be portable and self-powered. Any other support services or facilities that could be needed, would be provided in the list presented in Section 3.3.9.

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, while normal and off-normal conditions are described further in Appendix C. 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. Appendix C describes off-normal operations in support of the emplacement mode selection study (Appendix A) and develops five general off-normal outcomes from emplacement operations:

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, as discussed in Appendix C, 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 as discussed in Appendix C, 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 (Section 5.4) 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 (Appendix B) 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. Appendices B and C discuss these mitigating factors in more detail.

3.6 Disposal System Architecture

System architecture for the disposal borehole, and for waste packaging, handling and emplacement/retrieval, is presented in Tables 3-4 and 3-5. This architecture is intended as a starting point for future design development, functional analysis, project management, and risk analysis activities. It does not include all aspects of borehole drilling and construction, or field site infrastructure, but it does include disposal borehole configuration prior to the start of emplacement. It is presented for the disposal system, with the expectation that the DBFT will fit within the same architecture, possibly with omission of non-essential features. The architecture conforms to the emplacement mode recommendation developed above (wireline emplacement, Section 3.4).

Table 3-4. System architecture for disposal borehole.

Architecture Outline (Subsystems)	Applicability Discussion	
	Disposal	Deep Borehole Field Test
Borehole – Subsurface		
Depth/Diameter	See Section 3.1.	FTB construction will fully represent important features of the disposal boreholes.
Casing/Liner Plan		
Overburden Interval		
Seal Zone		
Disposal Zone		
Guidance Casing Tieback		
Mud Check Valve		
Liner Hanger/Guide		
Plug and Cement – Emplacement		
Drillable Bridge Plug	See Section 3.1.	Not required for demonstration. No cement plugs are planned to be installed at depth in the FTB.
Cement Handler		
Coiled Tubing Unit		
Sealing		
Liner Removal	See Section 3.1.	Not required for demonstration. No seals or plugs are planned to be installed at depth in the FTB.
Low-Permeability Seals		
Support Plugs		
Borehole Plug and Abandon		
Cement Plug	See Sections 3.1 and 3.4.	Plugging and abandonment of DBFT boreholes is foreseen but not explicitly planned (see assumptions, Table 2-4).
Surface Completion		

Table 3-5. System architecture for waste packaging, handling, and emplacement/retrieval.

Architecture Outline (Subsystems)	Applicability Discussion	
	Disposal	**Deep Borehole Field Test**
Waste Package/Overpack		
Tubular Section	See Section 3.2.	Use the same packaging design concepts for DBFT as are intended for disposal.
Shield End Plug		
Structural End Plug		
Closure Plug		
Threaded Plug		
Welded Plug		
Wireline Latch/Fishing Neck		Package attachments will be fully simulated to demonstrate wireline emplacement.
Impact Limiter		
Instrumentation Package	See Section 3.2.	Not required for demonstration, but instrumentation specific to design evaluation (e.g., dynamic pressure on the surface of dropped packages) could be included in the DBFT (Section 4.2).
Sensors		
Telemetry		
Weak Point		
Basket	See Section 3.2.	Not required (bulk inert material can be added to test packages for weight).
Package Transportation		
Shielded Transportation Cask	See Section 3.3.	Transfer of the test packages from a transportation cask to the transfer cask can be simulated.
Package Surface Handling/Transfer		
Shielded Transfer Cask	See Section 3.3.	A transfer cask with mock-up shielding can be used to limit the cost of the demonstration, and either loaded directly with packages at the DBFT site, or loaded elsewhere and used for transportation also (no radioactive waste).
Lower Shield Plug		
Upper Shield Plug (with small plug for insertion of tool string containment tube and for pulling WP through transfer shield)		
Side Latch		
Waste Package Transfer Shield		Both the transportation and transfer casks will rest on a horizontal cradle as the WP is pulled from the transportation cask into the transfer cask with the
Sliding shield slab		
Mechanism for removing bolted		

Architecture Outline (Subsystems)	Applicability Discussion	
	Disposal	Deep Borehole Field Test
upper shield plug from transportation cask	See Section 3.3.	grapple on the extension tube.
Extension tube with grappling mechanism		
Cradles for transfer cask and transportation cask		
Cask Lift and Up-Ending		Transfer cask handling features of the system would be fully simulated. Shielding could be mocked-up to save cost and weight.
Lifting and Rotation Restraints		
Cask Placement and Anchoring		
Waste Package Staging (Borehole)		
Wellhead Carousel	See Section 3.3.	Cask support and mud surge control will be fully simulated, including valving.
Mud Control		
Blowout Preventer	See Sections 3.1 and 3.3.	Design will include BOPs unless it is clear that they will not be required by permitting authorities.
Wireline Winch	See Sections 2.9 and 3.4.	Wireline winch functions will be fully simulated.
Wireline Sheave Support	See Sections 2.9 and 3.4.	A crane could be used in lieu of the headframe described in Section 2.9.
Shielding	See Section 3.3.	Shielding (e.g., pit) can be mocked-up as appropriate, to limit the cost of the demonstration while demonstrating novel features of the concept.
Backup Power Supply	Backup power is included as a mitigating factor in hazard analysis (Appendix B).	Backup power will not necessarily be needed for demonstration if it can be shown that loss will not cause undue risk to workers, breakage of critical equipment, or inadvertent test package drops.
Emplacement		
Wireline	See Sections 2.9, 3.3 and 3.4.	Wireline functions will be fully simulated, for demonstrating wireline emplacement. This includes engineering development of the electromechanical package release mechanism, impact limiters, and other critical components.
Tool String Containment Tube		
Fluid Control System (grease tube and stuffing box)		
Cable		
Cable Head		

Architecture Outline (Subsystems)	Applicability Discussion	
	Disposal	Deep Borehole Field Test
Wireline Tools (gamma-ray, casing collar locator, fluid sampler)		
Electromechanical Release		
Weak Point		
Motor-driven spool system		
Headframe or Crane		
Backup Power Supply	Backup power was considered a mitigating factor in hazard analysis for a disposal system (Appendix B).	Backup power will not necessarily be needed for demonstration if it can be shown that loss will not cause undue risk to workers, breakage of critical equipment, or inadvertent test package drops.
Borehole Qualification	See Section 3.3.	Borehole qualification procedures will be fully simulated in the DBFT.
Acoustic Caliper		
Gauge Ring/Junk Basket		
Safety Control (Interlocks)		
Visual Indication	Prevent dropping packages during staging.	The safety control system is not necessarily needed for DBFT demonstration of wireline emplacement because the consequences from off-normal events that occur during the demonstration are inherently much less than those that occur during waste disposal. DBFT operational risk without a safety interlock system is addressed by a sensitivity study (Appendix A).
Position Sensors		
Rig Draw Works Tension and Travel	Prevent and mitigate overtension and over-spooling.	The safety control system is not necessarily needed for DBFT demonstration of wireline or drill-string emplacement, as noted above.
Wireline Winch Tension and Speed		
Wireline Logs and Samplers	Detect downhole radiation leaks (see Section 3.4).	Radiation detection is not required for demonstration, although locator logs (e.g., gamma-ray, casing collar locator) are needed to demonstrate wireline emplacement.
Control Station	See Section 2.9.	Not required for DBFT demonstration because the duration of operations will be limited.
Backup Power Supply	Backup power is included as a	Backup power for the functional safety system is not

Architecture Outline (Subsystems)	Applicability Discussion	
	Disposal	**Deep Borehole Field Test**
	mitigating factor in risk analysis (Appendix B).	necessarily required for DBFT demonstration, primarily because no radioactive materials will be used, and also because a limited version of the functional safety system may be used.
Monitoring and Measurement		
Emplacement Fluid Level	See Sections 2.9 and 3.4.	Monitoring will be fully simulated for demonstration of wireline emplacement.
Acoustic Emission		
Casing Condition		
Wireline Condition		
Radiation Detection		Radiation detection not required for demonstration.
Dummy Packages		Not required with use of test packages for demo.

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3.7 Disposal System Design Enhancements

A number of design enhancements were identified as clearly risk-significant in conjunction with the emplacement mode selection study (Appendix A):

a) Emplacement zone completion and guidance casing perforations, consistent with multiple objectives (Sections 2.7.4, 3.1, and 5.4).

b) Emplacement fluid selection consistent with EZ completion, and terminal sinking velocity in the event of a dropped package (Section 5.4).

c) Design WPs for a range of temperature that could be encountered with heat-generating waste (Sections 2.6, 3.2, and 5.1).

d) Develop downhole release mechanisms for wireline or drill-string emplacement (Section 3.3).

e) Design impact limiters to achieve needed performance without contributing to getting packages stuck on trips in or after impact (e.g., permitting retrieval by not snagging) (Sections 2.6, 3.2, and 5.5).

These potential enhancements will be addressed as part of preliminary and final design for the DBFT engineering demonstration.

The following list was assumed to be part of the DBD concept for the risk analysis described in Appendix A. Some of these enhancements are also recommended to be included in the DBFT (Section 4.6):

1. Use an emplacement fluid that does not contain mud or other solids that can settle, producing solids that could cause packages to become stuck (Section 3.1).
2. Add a reverse circulation port on guidance casing just above 3 km (Section 3.1, Figure 3-1) to permit reverse circulation to exert upward force on a package that gets stuck above the EZ.
3. Run gauge ring with junk basket after every cement job, before waste emplacement (Section 3.4).
4. Prior to waste emplacement, run a qualifying log suite including an acoustic caliper log (for casing collapse and wear, and sludge buildup), shielded gamma ray (detect radioactivity in fluid signifying a leak), fluid sampler (more sensitive than gamma ray detection near packages), and casing collar locator (as needed) (Section 3.4).
5. Run pressure-actuated bridge plugs on coiled tubing or drill pipe, instead of explosive-actuated wireline bridge plugs. Bridge plugs would be located close to the uppermost package in a stack.
6. Use a fixed headframe instead of a mobile crane, to hold wireline sheaves for emplacement (more reliable) (Figure 3.4).
7. Specify that power supply and interlock connections to wellhead equipment and the transfer cask are incorporated in the same cable/plug.
8. Specify no splices in wireline.
9. Specify wireline sheaves with cable locks to prevent jump-off.

10. Specify that backup winch power supplies, hydraulic and electrical, are available on-site.
11. Specify a hydraulic cable-tension limiter on the wireline winch, set below the downhole tool passive weak point setting, for surface operations.
12. Use very slow speed on trip in (0.5 ft/sec max.) to avoid cable hangup and breakage, especially at less than 1 km depth. Limit speed to 2 ft/sec deeper (Section 3.4).
13. If wireline packages become stuck, release the wireline and mobilize a drill rig (Appendix C). Don't "strip" the wireline within pipe (lowering pipe over the wireline) because the risk from losing control is greater than that from the package dropping.
14. Make the remote package release operable only without load so the tool string (with package) must be either on the bottom or stuck to release.

Additional enhancements for drill-string emplacement exclusively, are listed in Section A.2.

References for Section 3

Arnold, B.W., P.V. Brady, S.J. Bauer, C. Herrick, S. Pye and J. Finger 2011. *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011-6749. Albuquerque, NM: Sandia National Laboratories.

Arnold, B.W., P. Brady, M. Sutton, K. Travis, R. MacKinnon, F. Gibb and H. Greenberg 2014. *Deep Borehole Disposal Research: Geological Data Evaluation, Alternative Waste Forms, and Borehole Seals*. FCRD-USED-2014-000332. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

4. DBFT Conceptual Design Description

The safety case for deep borehole disposal, requirements for DBD and the DBFT, design assumptions, and a description of two waste types are presented in Section 2, along with options for waste packaging, borehole construction, handling and transfer, and borehole emplacement/retrieval. Selection of preferred options and the current conceptual design of a DBD system are described in Section 3. This section describes the conceptual design of the DBFT engineering demonstration, consistent with the background information presented in Sections 2 and 3.

The scope of the DBFT engineering demonstration is summarized as follows:

- Design one or more test packages that meet DBFT requirements.
- Fabricate at least three, and possibly more, test packages for use in leak testing, pressure testing, drop testing, an integrated test, and demonstration of emplacement and retrieval in a deep borehole.
- Perform leak testing, pressure testing, and drop testing on one or more test packages.
- Select or develop a test package transportation system, or mockup, as appropriate.
- Develop a transfer/emplacement system that includes and/or represents technical features needed for DBD.
- Select oilfield wireline tools and, as needed, design tool modifications for wireline emplacement and retrieval.
- Interface with the DBFT site management contractor to identify deep borehole site infrastructure requirements for the engineering demonstration.
- Fabricate, assemble, and shop test the transfer/emplacement system mockup.
- Perform an integrated test to demonstrate fit and function of test packages, transportation system, transfer/emplacement system mockup, wireline equipment, etc., before demonstration in a deep borehole.
- Perform the DBFT engineering demonstration, including emplacement and retrieval of one or more test packages in a deep borehole.
- Collect and publish test results, including test data, observations, and recommendations for future design and development activities.

These activities will be accomplished in FY17 through FY19 starting with preliminary design, and proceeding to final design, fabrication and testing, integrated testing, and field demonstration.

One use for the simple architecture developed in Section 3.6 is to show what features of the disposal system will be included in the DBFT engineering demonstration (Tables 3-4 and 3-5).

The remainder of this section (Sections 4.1 through 4.5) discusses how the DBFT will approach FTB construction, test package design, handling and transfer hardware, emplacement and retrieval equipment, the integrated test, and the field demonstration. A list of design questions is provided at the end, as a guide for follow-on preliminary design activities.

4.1 FTB Drilling and Construction

Details of drilling and construction for the FTB are discussed elsewhere (Kuhlman et al. 2015) and are subject to change when the Drilling and Testing Plan is developed (DOE 2015). The FTB conceptual design represents the configuration of future disposal boreholes, as currently conceived based on generic (non-site specific) information. The reference FTB design concept including casing plan (but not including perforations discussed below) is depicted in Figure 3-1. The FTB configuration will be similar to disposal boreholes, and will provide a guidance casing for emplacement/retrieval of test packages. As noted in Table 3-4, no cement plugs or seals will be installed in the FTB. Any plugging and abandonment that may be required by the permitting authority is not explicitly planned as part of the DBFT. As stated previously (Section 2.3.13, TBD-46) the details of the seal zone design will be determined after the DBFT demonstration (no seals installation testing is currently planned).

Surface construction for the FTB will include an access road, a drill pad, and support services sufficient to support drilling of a 5 km borehole. Typical drill pads on this scale have security fencing and access control, sufficient space for drilling activities, a compacted gravel base under working and traffic areas, water and electric power (e.g., water tanks and electric generators), parking and laydown areas, and comfort facilities. Such facilities will be sufficient for the DBFT engineering demonstration. A discussion of facilities and utilities needed for surface handling and transfer is given in Section 3.3.9.

As discussed in Section 3.1, the FTB design for the DBFT will depart from the reference DBD concept in two ways: emplacement fluid and guidance casing perforations.

Emplacement Fluid

The emplacement fluid will be similar to formation brine, with uniform composition over the full length of the FTB. The salt composition and brine weight will be selected for similarity to formation fluid, and to limit fluid inflow and outflow. For example, the emplacement fluid could be NaCl brine unless Ca is found to be a significant component. Using a uniform fluid column to balance formation fluid density that may vary with depth, means that some intervals could be overbalanced and others underbalanced. Emplacement fluid density can be selected to balance pressure in a particular depth interval, depending on formation permeability structure (i.e., occurrence of flowing fractures).

FTB Guidance Casing Perforation Scheme

Analysis of terminal sinking velocity for WPs (Section 5.4) has identified several hypotheses that will be tested in the FTB by varying the number, size, and spacing of casing perforations. The test will consist of freely dropping a test instrumentation package, and recording 6-axis motion (Section 4.1). An impact limiter will prevent damage to package integrity, and the package will be retrieved by wireline.

Each perforation is envisioned as a circular opening to be drilled or cut prior to casing installation. The hypotheses and assumptions to be tested include:

- Terminal velocity in unperforated casing, as predicted by numerical and analytical models (Section 5.4).
- Rapid attainment of terminal velocity is expected because the predicted terminal velocity of approximately 3 m/sec would be reached in 0.3 sec without fluid resistance; representing fluid resistance by a generous multiple of this time, the distance traveled to terminal velocity is a few tens of meters.

- Package movement will be smooth, and not subject to significant rotations or collisions with the casing.
- Terminal velocity has limited dependence on fluid viscosity, because resistance is dominated by form drag.
- Terminal velocity will increase when perforations exist ahead of a sinking package, but the effect will diminish for perforations farther ahead (the analysis in Section 5.4.3 assumes no decrease of the effect with distance).
- Terminal velocity will increase markedly with increased size of perforations, and decreased spacing between them.
- Terminal velocity is relatively insensitive to the presence of perforations behind a sinking package because pressure there is nearly hydrostatic and flow in the annulus behind the casing is inefficient.

To test these hypotheses, the following perforation scheme is recommended proceeding downward from the surface (depths are generic and consistent with Figure 3-1):

- **Interval 1: Tieback (0 to 3,000 m) –** Unperforated, which will test terminal velocity predictions (approximately 2 m/sec), including the rapidity at which terminal velocity is reached, the effect of viscosity (decreases with increasing temperature at depth), package rotation and collisions with the casing, and the effect of perforations ahead (without perforations behind).
- **Interval 2: From 3,000 to 3,250 m –** Perforations 5 cm in diameter spaced every 10 m (one per section of casing). This is the maximum extent of perforations anticipated. It will cause the test package to accelerate, and it will maximize the contrast with the unperforated casing above.
- **Interval 3: 3,250 to 3,500 m –** Unperforated, to test the deceleration of the test package and the effect of perforations behind, maximized by the extent of perforation in Interval 2.
- **Interval 4: From 3,500 to 3,750 m –** Perforations 2 cm in diameter spaced every 10 m (one per section of casing). Terminal velocity will increase, but less than Interval 2.
- **Interval 5: From 3,750 to 4,000 m –** Perforations 2 cm in diameter spaced every 50 m (one every fifth section of casing). Terminal velocity will decrease, and the effect from perforations ahead will begin to decrease.
- **Interval 6: From 4000 to 4,250 m –** Perforations 1 cm in diameter spaced every 10 m (one per section of casing). Terminal velocity will decrease.
- **Interval 7: From 4,250 to 4,500 m –** Perforations 1 cm in diameter spaced every 50 m (one every fifth section of casing). Terminal velocity will further decrease, approaching the value for unperforated casing at this depth.
- **Interval 8: From 4,500 to 5,000 m –** Unperforated, which will slow the test package, limiting the intensity of its impact on the bottom.

Preparation of the emplacement fluid will require circulation to homogenize it over the full depth, then thermal equilibration without circulation for a few days or weeks. The fluid must be stable and not form precipitates, or contain solids that settle during this time period. Wireline entries to qualify the borehole (junk basket, acoustic caliper, temperature, and pressure) will cause some mixing, and emplacement/retrieval demonstration runs will cause more mixing, but the overall thermal profile needed for testing terminal velocity will be sufficient (the profile can be restored by additional waiting time).

FTB Decision

The DBFT project plan calls for a decision on whether to drill the FTB, based on drilling experience with the CB (SNL 2014). A decision not to drill the FTB will be accompanied by a decision whether to perform the DBFT engineering demonstration in the CB instead, or to find another existing borehole, or not to continue with the demonstration. Use of the CB would require installation of guidance casing (Section 2.3.9 and Table 2.3-3), and it would change the test package diameter and certain other dimensional aspects of the DBFT demonstration. The description of DBFT activities in the following sections is based on availability of the FTB as represented in Figure 3-1.

4.2 DBFT Test Packages

The DBFT engineering demonstration will use test packages that meet requirements specifically established for the demonstration (requirements are discussed in Section 2.3.10 and summarized in Table 2-3). The test package design will include features that could be used in packaging for disposal of cesium/strontium (Cs/Sr) capsules now stored at the Hanford site. Specifically, the length or diameter of test packages need not be optimized for capsule disposal, but the materials, closure design, and fabrication methods will be suitable. Material selection is TBD for the DBFT packages (TBD-19). No actual waste or other radioactive material will be used in the engineering demonstration.

The DBFT engineering demonstration will develop and test more than one packaging concept if resources permit. For example, the flask-type and internal semi-flush concepts presented in Sections 2.6 and 3.2 have important differences that could affect performance, and are potentially important to waste generators. Impact limiters and wireline latch fittings will be developed and used on all test packages. Test packages will be designed for downhole pressure, *in situ* temperature, and other requirements and assumptions identified in Sections 2.3 and 2.4.

Two or more test packages will be fabricated, sealed, and leak tested (TBD-25). One or more of these will be subjected to drop testing and external pressure testing, with additional leak testing to verify performance (in addition to borehole emplacement/retrieval). Multiple test packages will be fabricated to demonstrate repeatable fabrication and testing results, and for destructive testing. No basket is needed for these test packages, and the required weight can be obtained using a bulk filler material. The extent of testing, and the number of test packages required, will be determined in final design.

In addition, the DBFT will develop the design for a test instrumentation package with a closure that can be opened and resealed in the field (be welded), and an instrument module (6-axis motion including rotations, pressure, temperature). One or more test instrumentation packages will be fabricated and subjected to appropriate testing to verify performance prior to deployment in the demonstration. The dimensions of the test instrumentation package, including weight, will be closely similar to the test packages described above. Either one of the test package designs (e.g., flask-type or internal semi-flush) could be adapted for use as an instrumentation package.

Impact limiters and wireline latch/fishing overshot attachments will be tested on every package (test package or test instrumentation package) that goes into the borehole. Impact limiters may crush on every trip in, so multiple impact limiters will be fabricated for each package.

4.3 DBFT Package Handling and Transfer

All features of the transfer cask and related equipment described in Section 3.3 will be demonstrated. This includes equipment for package receipt, handling, transfer from the transportation cask to the transfer cask, interfacing with the wellhead, and emplacement/retrieval operations. In addition to the major features of the system such as cradles, transfer shield, carousel, and shielded wellhead pit, the scope also includes minor features such as trunnions, rigging, shield plugs and related equipment, cask side latches, horizontal transfer equipment, plug handling equipment in the pit, package kneeling jacks, and so on. Many of these details are briefly described in Section 3.3, but all of them will be defined during the DBFT engineering design process.

One uncertainty associated with transfer cask design for the DBFT (and for the DBD as well) is the pressure rating for the well control function (TBD-22). Whereas heavy shielding for a system to handle radioactive waste for DBD could readily meet any reasonable internal pressure specification, mockup shielding (or reduced wall thickness) used for the DBFT demonstration transfer cask may not be so robust.

If an existing transportation cask is used such as the NAC LWT® cask (Section 3.3.2) then the transfer system must interface with that cask without modifying it. Alternatively, the transportation cask may be mocked up for demonstrating transfers. Also, all components of the system must work in both directions so that packages can be retrieved from the borehole and reloaded into the transportation cask.

Transfers between the transportation cask and the transfer cask will be performed horizontally (Figure 3-5). Each cask will rest on a cradle that facilitates both axial alignment and axial movement (each cask must be moved away from the transfer shield interface at some point in the process; Section 3.3.4). One effective way to align and support the cradles, and the transfer shield interface between them, is to anchor steel rails to the surface and affix small flanged wheels on each cradle, with brakes to limit movement. The rails would be pre-fabricated as parts of a steel frame, and attached to footings or to a reinforced concrete slab. The dimensions of such a slab would on the order of 5 m wide and 15 m long.

A portable crane will be used to load and unload the transportation cask and the transfer cask, cradles, and other equipment (Figure 4-1). The same crane will be used to up-end the transfer cask and lift it onto the carousel over the wellhead. Cranes of this type and capacity are often used at oilfield drilling sites and do not require pads for operation. Rather, they can operate effectively (with outriggers) on the compacted, high-load areas of gravel drill pads.

The wellhead pit (Figure 4-1) will be a shielded enclosure around the wellhead, constructed mostly below grade. Shielding may be mocked up (e.g., thinner walls) for the DBFT. The pit will provide structural support to the carousel/maintenance shield, around its circumference as well as by a central column situated a short distance from the wellhead (not shown in Figure 3-19). It will provide for remote control of wellhead valving, including the main valve on the wellbore and smaller valves for mud control. As noted previously (Sections 2.8 and 3.3) a BOP may not be required for the DBFT engineering demonstration, but if one is required then an annular BOP with diameter sufficient to pass test packages will be incorporated in the wellhead (Figure 3-19). The wellhead pit will also allow access independent of the carousel, for repair and maintenance.

The carousel may be made lighter for the DBFT because shielding is not required. It will include kneeling jacks to lower the transfer cask onto the wellhead flange, and latches to stabilize attachment of the cask. Related equipment would include remotely operated tongs for removing and replacing the transfer cask lower shield plug.

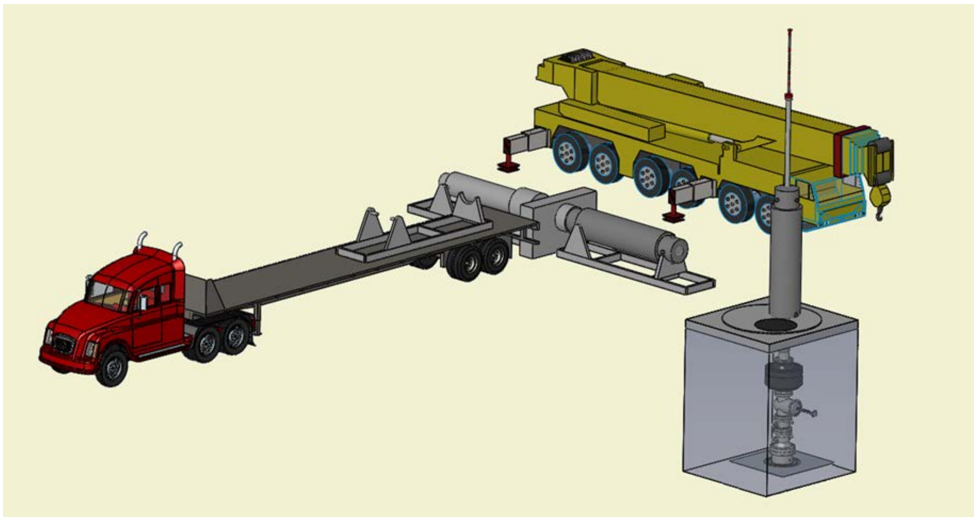

Figure 4-1. Schematic arrangement of transportation and transfer casks (aligned for package transfer), crane, and wellhead pit.

4.4 DBFT Package Emplacement and Retrieval

All features of the wireline system and related equipment for package emplacement and retrieval (Sections 3.3 and 3.4) will be demonstrated. This includes many components that are commercially available such as the wireline cable and winch, cable head, tool string, and sheaves. It also includes the tool string containment tube (i.e., "lubricator" section), and grease tubes, if these are required to maintain the well control pressure envelope.

One component that may not be off-the-shelf is the electromechanical release mechanism (Sections 2.9 and 3.3.7). Modification may 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; and 3) the system has appropriate ratings and can be attached to the wireline tool string.

The handling and emplacement equipment used in the DBFT can be simplified, if appropriate to focus available resources on those aspects of emplacement operations that are developmental and/or most risk significant. For example, among the risk insights presented in Appendix A, cable failure due to overtension is particularly risk-significant for wireline emplacement.

Impact limiters could substantially limit the consequences of drop events, preventing accidental WP breach. Credit for impact limiters on single packages was taken in the risk analysis for wireline emplacement (Appendix A). The effectiveness of impact limiters will be evaluated for the DBFT by dropping an instrumented test package with an impact limiter, then retrieving it for inspection. The test would be similar to the "drop-in" method of emplacement (Bates et al. 2011).

For the DBFT demonstration two additional capabilities would be required that would not be needed for DBD:

- The means to unload test packages from the transportation cask (or mockup) without using the transfer cask. Fixturing is needed to hold the transportation cask upright, with the upper shield plug removed. The crane would then be used to grapple and hoist the test package, and lay it down on a purpose-built rack or skid. The capability would also be used for instrumentation test packages, and operations to open these and retrieve the instrument module would be performed with the package in the rack.

- The means to release the instrumentation test package within the emplacement fluid, near the top of the borehole, for the free-drop test. Enhancements identified in Section 3.7 (item 14) include engineering the electromechanical release mechanism to be releasable only when not under load. For the free-drop test the same (or similar) mechanism would be used, with modification, for package launch and retrieval off the bottom.

The safety control system (interlocks; Table 3-5) will be minimized for the DBFT. The consequences of dropping packages or getting them stuck during the DBFT demonstration, while serious, are much less costly and hazardous than for disposal of radioactive waste. If resources permit, the safety control system could be designed in detail and simulated in software. For the DBFT, existing interlocks on the emplacement equipment (e.g., wireline winch controls) will provide some protection from loss of power, other equipment malfunctions, and human error.

Monitoring and measurement for the DBFT demonstration will fully simulate waste disposal, to understand the occurrence and effects from potentially significant events identified in risk analysis. Continuous monitoring of the FTB will help to evaluate whether casing collapse can be detected, the nature of fluid movement (e.g., surge, leak-off, and natural background), and the condition of critical equipment such as wireline cable. Radiation monitoring is not necessary.

4.5 DBFT Integrated Test and Field Demonstration

Before the engineering demonstration at the DBFT field site is conducted, an integrated test of the engineered components will be performed. The purpose of the integrated test is to identify and resolve any equipment operability or interface issues at a location with access to shop facilities. Test packages and components of the transfer/emplacement system, including a mockup borehole, crane, and wireline setup, will be brought to the integrated test facility (ITF). The integrated test will be the last opportunity for adjustment, modification, and maintenance prior to demonstration at the DBFT field site. It also is an opportunity to check the condition of rented equipment such as the wireline cable, winch, and downhole tools.

The engineering demonstration at the DBFT field site will be conducted within a reasonable time after completion of the integrated test. The focus of the field demonstration will be on: 1) test package transfers; 2) placement of the loaded transfer cask over the test borehole; and 3) emplacement and retrieval. Associated activities, such as running the acoustic caliper log and running the gauge ring/junk basket before each emplacement activity, will also be performed.

The demonstration will include a free-drop of the test instrumentation package in the borehole to test the function of the impact limiter and to validate predictions of terminal velocity and impact deceleration. A recommended list of demonstration activities in the order to be performed is presented below:

1. Occupy field site and establish services.

2. Mobilize DBFT equipment and receive shipments.
3. Establish data acquisition and control facilities.
4. Connect surface monitoring equipment (fluid level, acoustic emission).
5. Set up crane, transfer station with transfer shield and cask, and wireline truck.
6. Perform qualification logs (acoustic caliper, gauge ring/junk basket, temperature, pressure).
7. Receive test package #1 in transportation cask.
8. Implement transfer and emplacement steps (Section 3.3.1), to emplace test package #1 on the bottom and retrieve wireline.
9. Reset electromechanical release for package pickup.
10. Reenter borehole with wireline through empty transfer cask, and latch test package #1.
11. Implement transfer steps in reverse, retrieving test package #1 into transfer cask on wellhead.
12. Transfer test package #1 from the transfer cask back to the transportation cask.
13. Unload test package #1 from transportation cask and place in a storage rack.
14. Complete washdowns and inspections, and replace consumed items.
15. Receive test package #2 in transportation cask, and repeat steps 8 through 14.
16. Repeat emplacement and retrieval demonstrations, with test packages 1 and 2, as appropriate.
17. Place instrumentation test package in rack, install instrument module, and seal package.
18. Receive instrumentation test package in transportation cask, and repeat steps 8 through 11, retrieving instrumentation test package into transfer cask on wellhead.
19. Reset electromechanical package release mechanism so it can be released without load.
20. Repeat emplacement steps (step 8) but lower the instrumentation test package only into the emplacement fluid near the top of the borehole.
21. Release the instrumentation test package to freely drop, and retrieve wireline.
22. Repeat steps 9 through 14 for instrumentation test package.
23. Unseal instrumentation test package, recover instrument module, and upload data.
24. Demobilize DBFT equipment and ship equipment to disposition site.
25. Review effectiveness of demonstration, procedures, and safety measures.
26. Review acquired data from monitoring, logging, and instrument module.
27. Issue final report.

References for Section 4

Bates, E.A., M.J. Driscoll and J. Buongiorno 2011. "A Drop-in Concept for Deep Borehole Canister Emplacement." *Proceedings of the 2011 International High-Level Radioactive Waste Management Conference*. Albuquerque NM. April, 2011.

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Kuhlman, K.L., P.V. Brady, R.J. MacKinnon, J.E. Heath, C.G. Herrick, R.P. Jensen, M.J. Rigali, T. Hadgu and S.D. Sevougian 2015. *Conceptual Design and Requirements for Characterization and Field Test Boreholes: Deep Borehole Field Test*. FCRD-UFD-2015-000131 Rev. 1. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

SNL (Sandia National Laboratories) 2014. *Project Plan: Deep Borehole Field Test*. FCRD-UFD-2014-000592, Rev. 0. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

5. 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 5.1 and Section 5.6 present 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 5.2 and 5.3 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 5.4 presents analyses of the terminal sinking velocity of a WP, which are used to support selection of a perforation design for guidance casing (Section 4.1). Section 5.5 analyzes the behavior of impact limiters and their ability to mitigate the consequences from dropping a WP, which are part of WP design (Sections 2.6 and 3.2). Section 5.7 presents shielding calculations that support transfer cask design (Section 3.3.3).

5.1 Package Stress Analysis

Stress analyses were performed for four WP options based on the configurations discussed in Section 2.6. Finite-element stress and thermal analyses of selected package concepts were performed using SolidWorks Simulation® software. Analyses were conducted at ambient surface 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) (Section 2.6).

The dimensions of each of the four WP options analyzed are shown in Table 5-1. 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 internal diameter captures the reduction in the opening due to the fill port sealing plugs for each of the options.

Table 5-1. Waste package dimensions for stress analysis

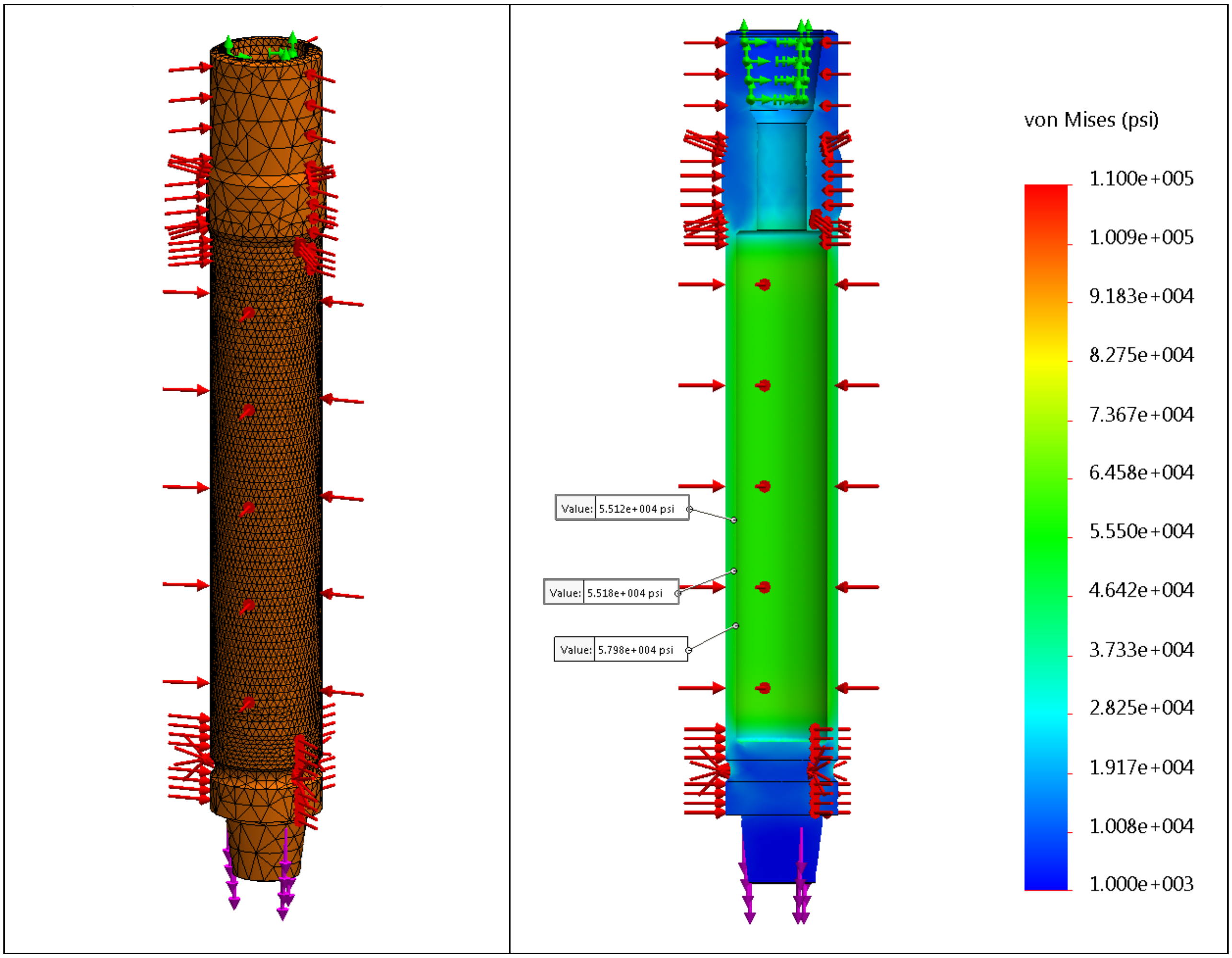
Package Design Concept Option	Nominal OD (in)	Nominal ID (in)	Max External OD (in)	Min Internal ID (in)	Weight (lb) [A]
1	10.75	8.75	11.50	6.00	2415
2	10.75	8.75	11.46	8.75	2200
3	5.00	4.00	5.40	2.8	510
4	5.00	4.00	5.36	4.0	500
[A] Listed weight provides 197 in (5 m) internal cavity length, without waste.					

Note that the following calculations used a downhole hydrostatic pressure of 9,600 psi, compared to the value of 9,560 psi assumed in Section 2.3.10 and discussed in Section 2.6 (the results presented here are not significantly affected by the difference).

5.1.1 Stress Analysis for Packaging Concept Option 1

A stress analysis of the design was performed using SolidWorks Simulation. Hydrostatic 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 5-1. 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.

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. This is less than the FoS requirement in Table 2-3. An alternative material choice would be a Q125 grade casing or equivalent which would provide a FoS of approximately 2.0.

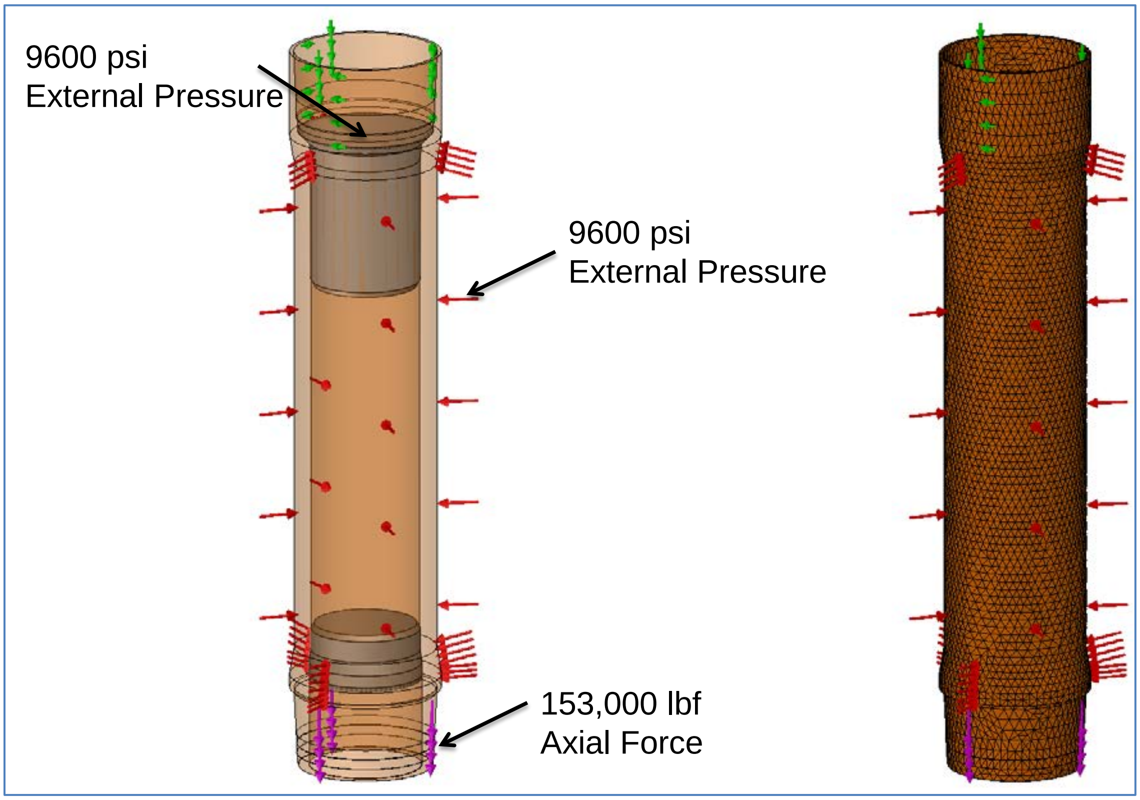


Note: Package aspect ratio shortened for illustration.

Figure 5-1. Option 1 stress analysis with 9,560 psi external pressure and 154,000 lb tension.

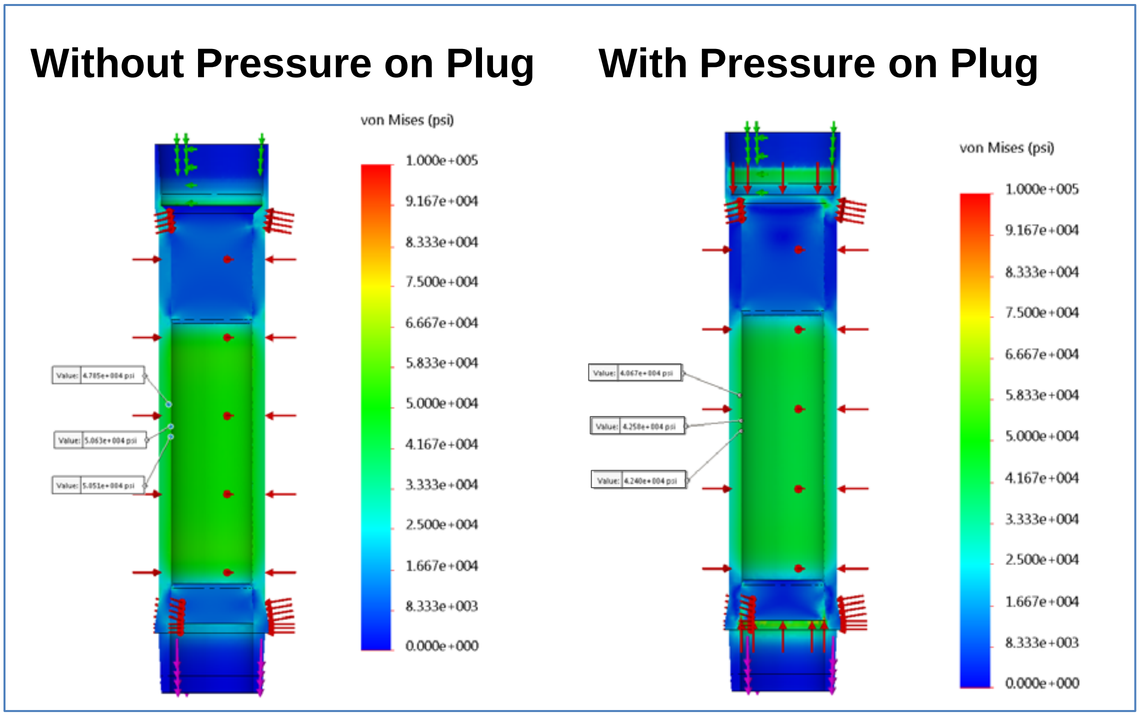
5.1.2 Stress Analysis for Packaging Concept Option 2

Two configurations were analyzed: 1) threaded connections between packages leak, so that borehole pressure reaches the internal plugs (Figures 5-2 and 5-3); 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 5-3). 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 5-2. Option 2 simulation loads and mesh.

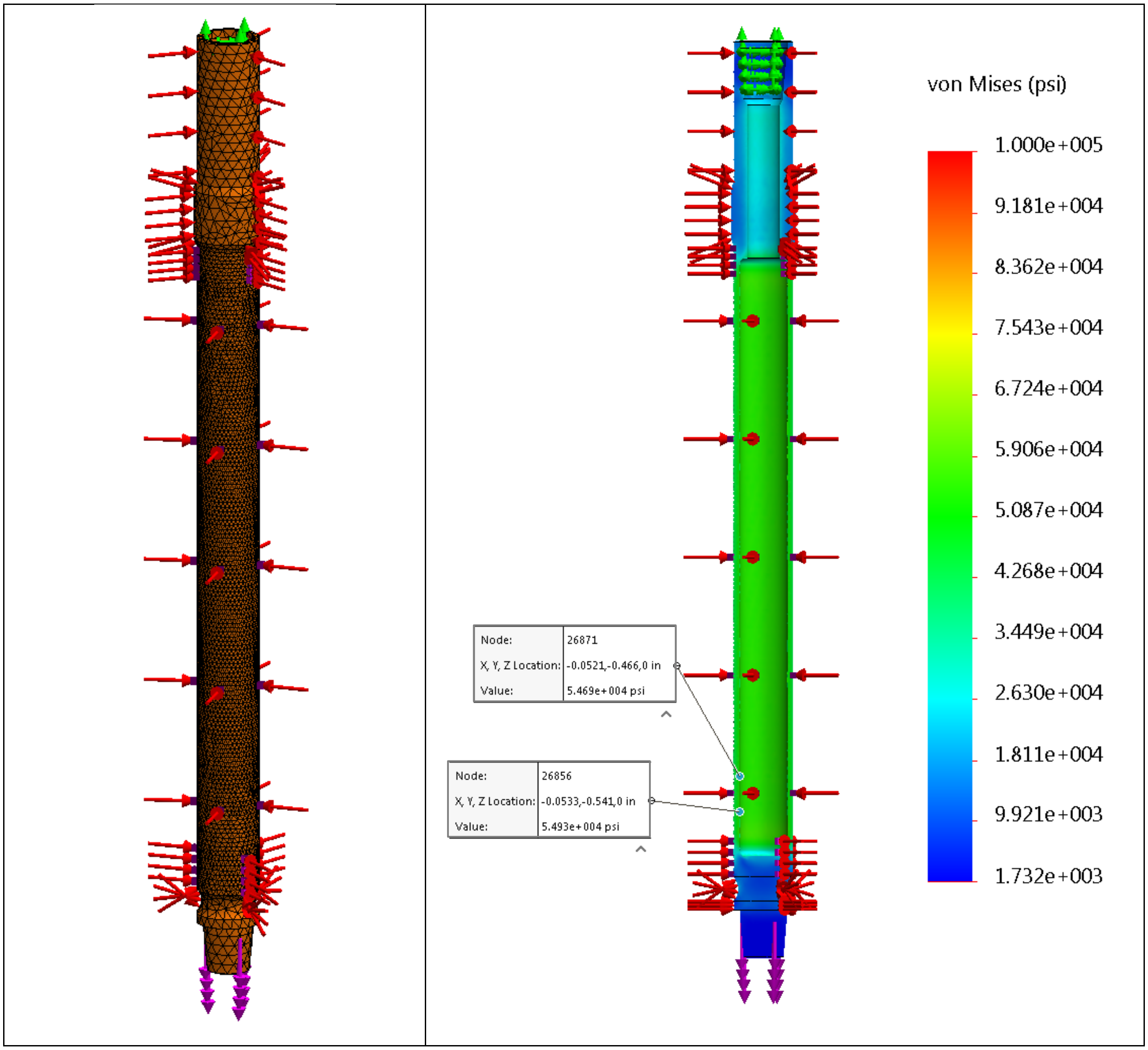


Note: Package aspect ratio shortened for illustration.

Figure 5-3. Option 2 stress analysis.

5.1.3 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 5-4). 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).



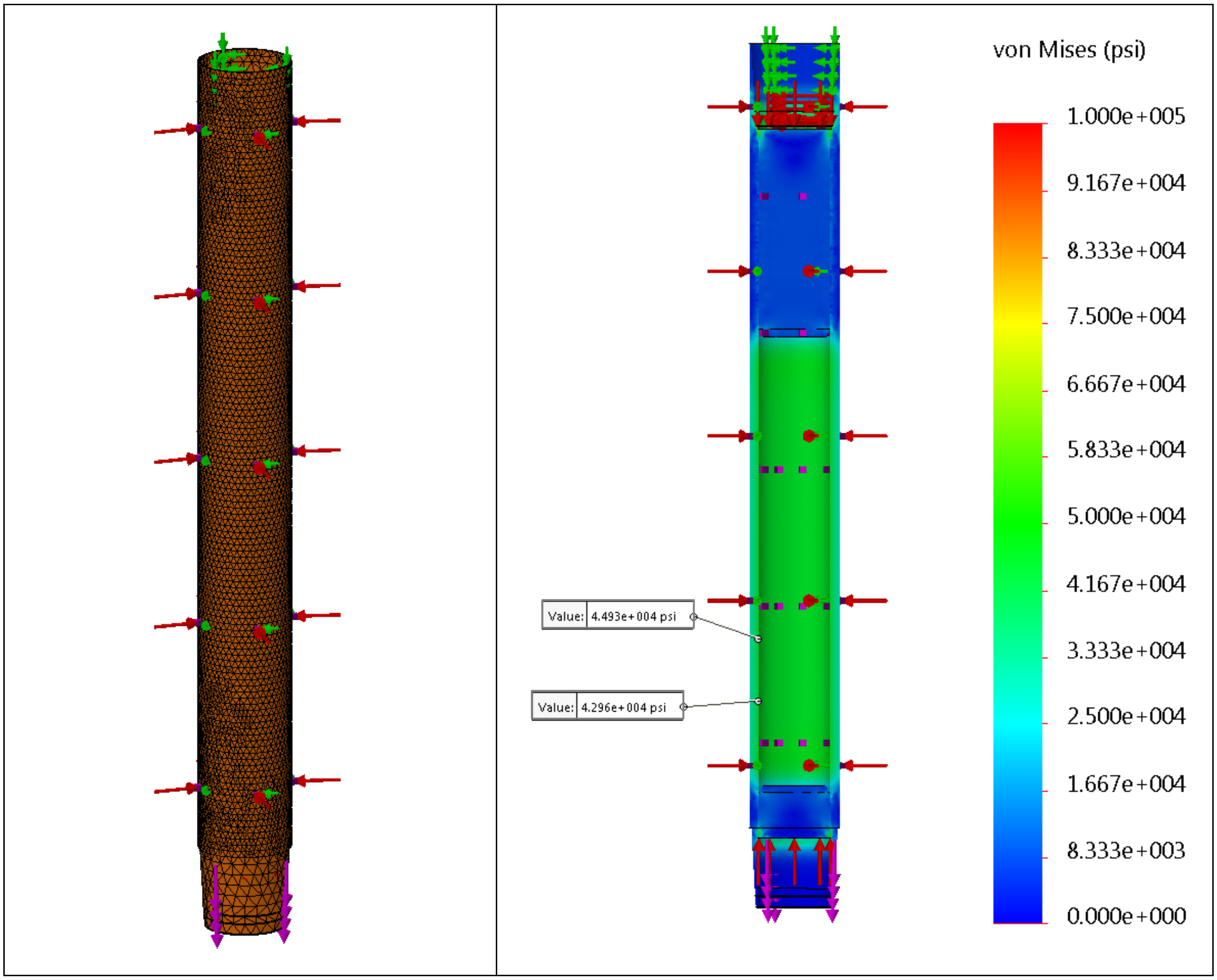
Note: Package aspect ratio shortened for illustration.

Figure 5-4. Option 3 stress analysis.

5.1.4 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 5-5). 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 5-5. Option 4 stress analysis.

5.1.5 Package Mechanical Response Analyses

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. 5-1. 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.

$$P_{yp} = 2Y_p \left[\frac{\left(\frac{D}{t}\right) - 1}{\left(\frac{D}{t}\right)^2} \right] \qquad (5\text{-}1)$$

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):

$$Y_{pax} = Y_p \left\{ \left[1 - \frac{3}{4}\left(\frac{S_A + P_{ax}}{Y_p}\right)^2 \right]^{1/2} - \frac{1}{2}\left(\frac{S_A + P_{ax}}{Y_p}\right) \right\} \qquad (5\text{-}2)$$

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).

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, Section 4.1). 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 not likely decrease the effective diametral clearance if the tool string has smaller diameter.

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

$$KE = \frac{1}{2} m v^2 \qquad (5\text{-}3)$$

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

$$U = \frac{E \cdot A \cdot \delta_{\max}^2}{2L} \qquad (5\text{-}4)$$

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

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

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

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

$$\delta_{\max} = \sqrt{\frac{m \cdot v^2 \cdot L}{A \cdot E}} \tag{5-6}$$

The corresponding maximum stress is given by

$$\sigma_{\max} = \sqrt{\frac{m \cdot v^2 \cdot E}{A \cdot L}}\,. \tag{5-7}$$

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 5-6. 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 5-6.

A similar estimate of impulse forces was made for small (slim) packages containing eight Cs/Sr capsules arrayed end-to-end (Tables 2-2 and 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 5-7.

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 5-8. 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.

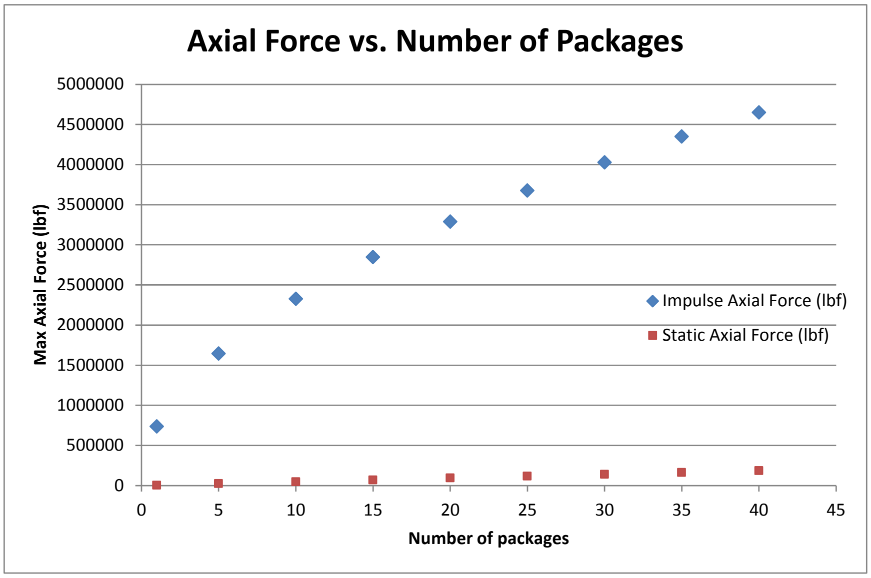


Figure 5-6. Static and impulsive axial force due to falling waste packages (reference package).

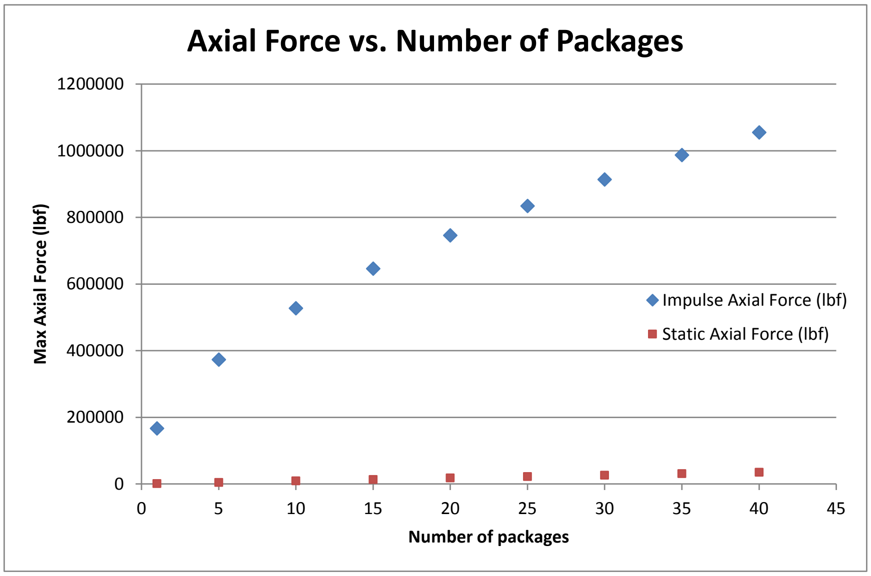


Figure 5-7. Static and impulsive axial force due to falling waste packages (small package).

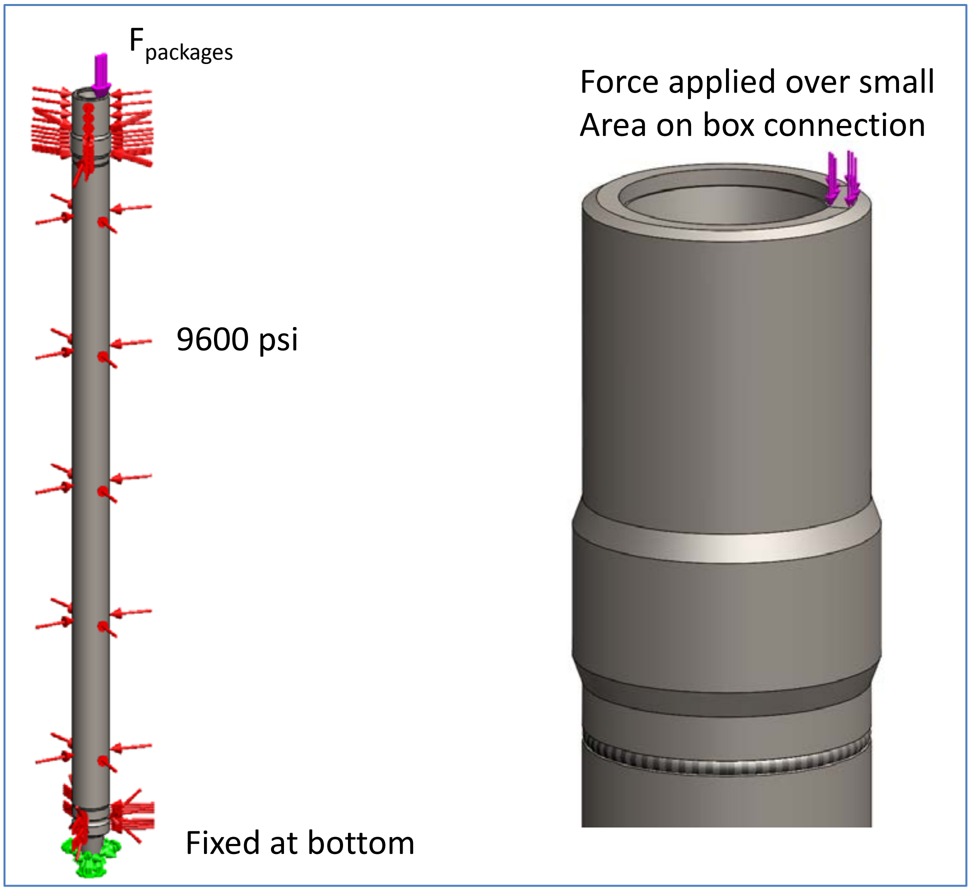


Figure 5-8. Waste package loading conditions.

Stress contours due to impact force levels for both for the reference and small (slim) package are shown in Figures 5-9 and 5-10, 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.

The conclusion from this study (used in the risk analysis of Appendix A) 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.

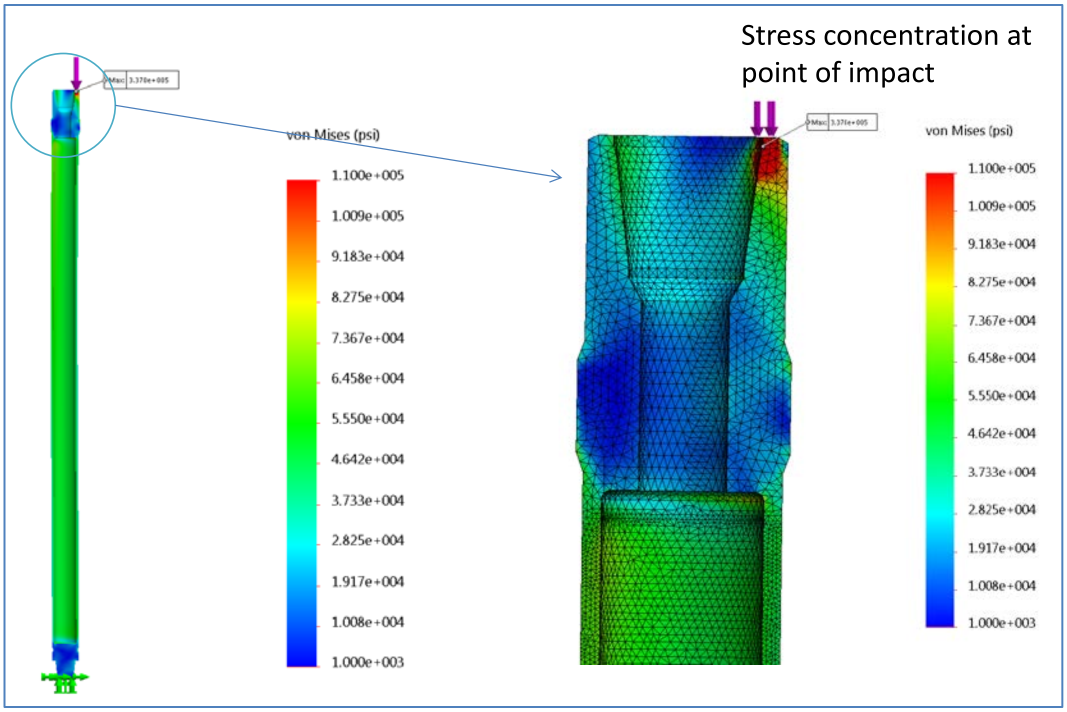


Figure 5-9. Calculated stress from impact of a single reference-sized waste package falling at terminal velocity.

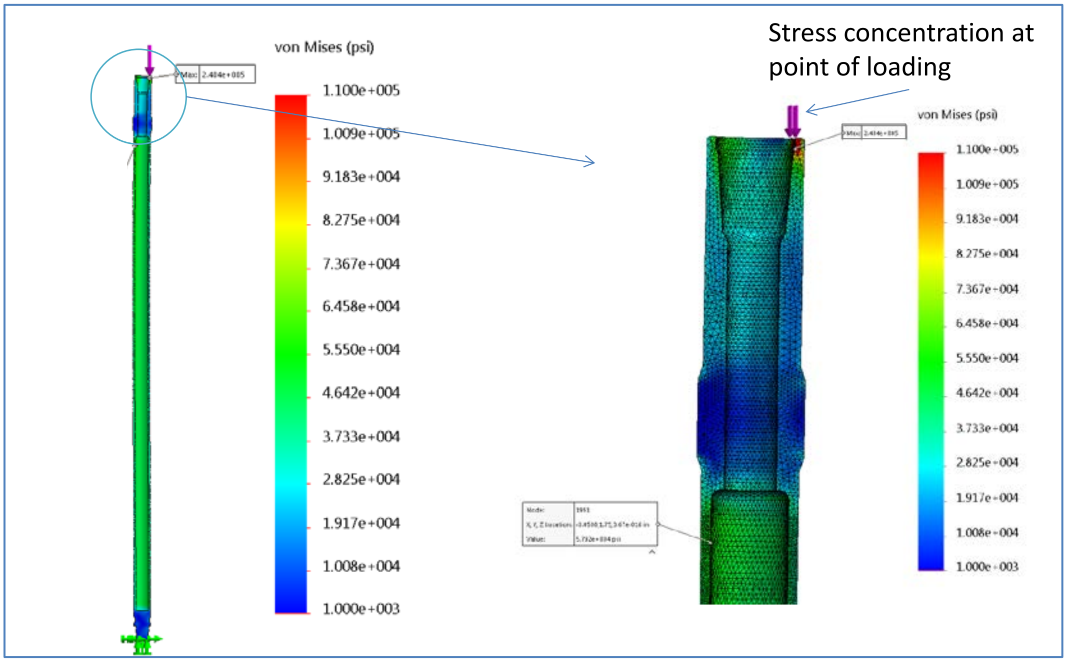


Figure 5-10. Calculated stress from impact of a single small size (slim) waste package falling at terminal velocity.

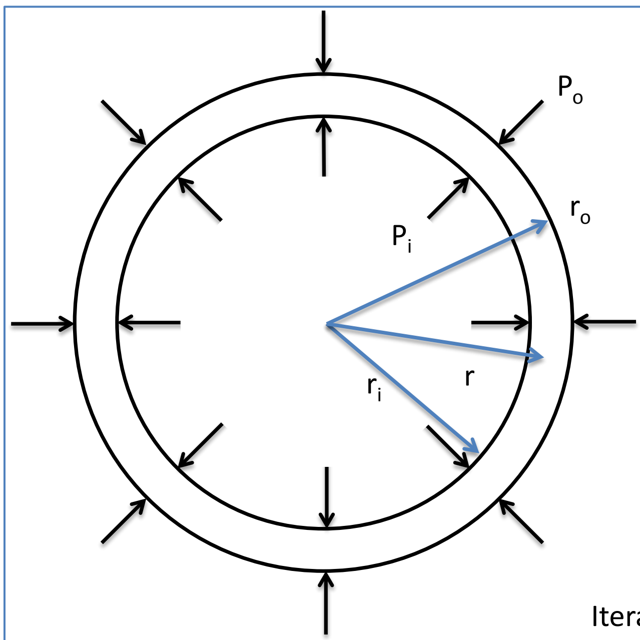
5.1.6 Fluid-Filled Waste Package

The factor of safety 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)



$$\sigma_t = \frac{P_i r_i^2 - P_o r_o^2 - r_i^2 r_o^2 \frac{(P_o - P_i)}{r^2}}{r_o^2 - r_i^2} \qquad \varepsilon_t = \frac{1}{E}\left[\sigma_t - \nu(\sigma_r + \sigma_l)\right] + \alpha\Delta T$$

$$\sigma_r = \frac{P_i r_i^2 - P_o r_o^2 + r_i^2 r_o^2 \frac{(P_o - P_i)}{r^2}}{r_o^2 - r_i^2} \qquad \varepsilon_r = \frac{1}{E}\left[\sigma_r - \nu(\sigma_t + \sigma_l)\right] + \alpha\Delta T$$

$$\sigma_l = \frac{P_i r_i^2 - P_o r_o^2}{r_o^2 - r_i^2} \qquad \varepsilon_l = \frac{1}{E}\left[\sigma_l - \nu(\sigma_t + \sigma_r)\right] + \alpha\Delta T$$

$$dP = -K\left(\frac{dV}{V_0} + \beta\Delta T\right)$$

Fluid Pressure Due Constrained Volume

Iterate to solve for final deformation and pressure

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

Figure 5-11. Internal fluid pressure illustration.

Figure 5-11 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.

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 5-12). The converged solution for pressure and temperature changes is shown in Figure 5-13.

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 5-13) and could provide additional margin of safety (assuming corrosion and other interactions between the filling fluid, packaging, and waste forms are limited).

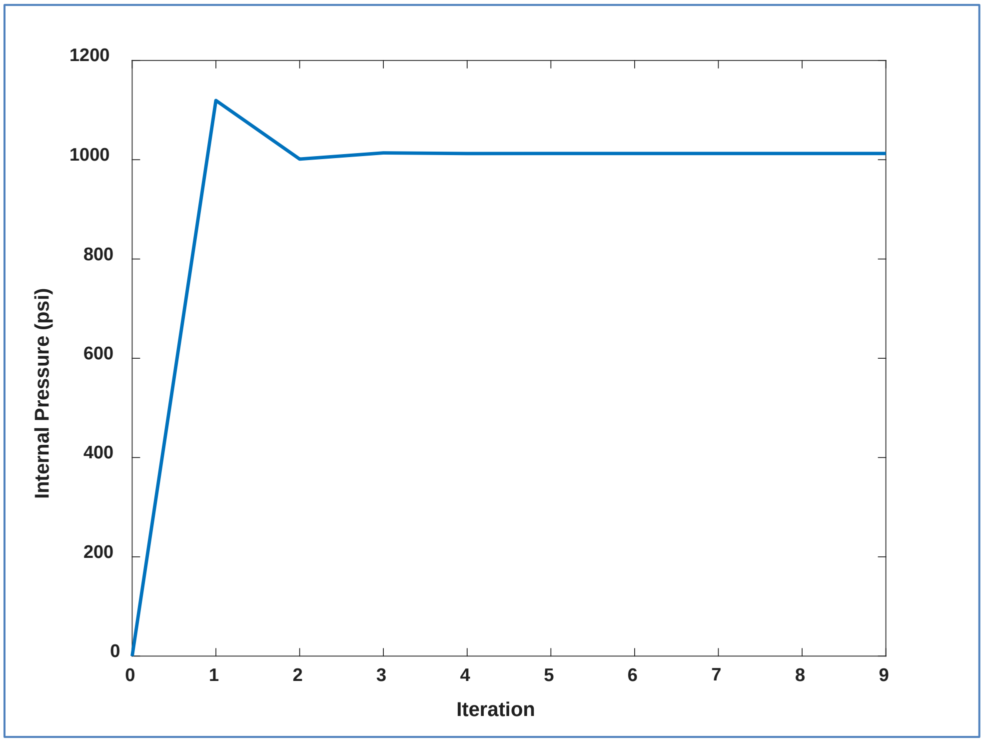


Figure 5-12. Internal fluid pressure iteration for *ΔT = 0*.

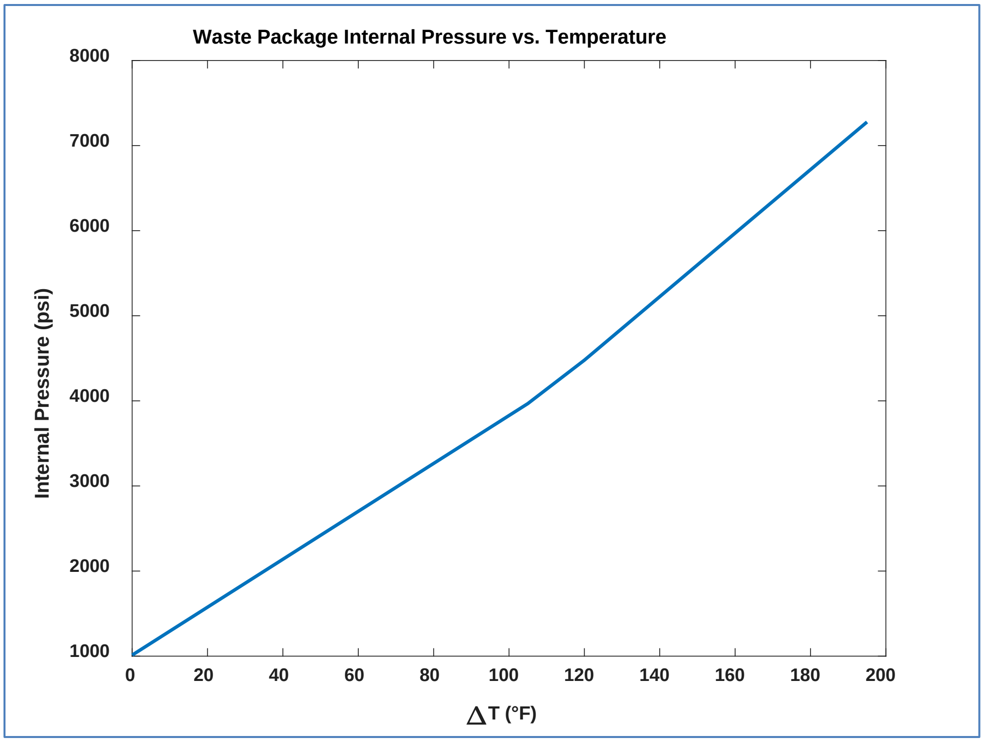


Figure 5-13. Internal fluid pressure vs. temperature and 9,600 psi external pressure.

5.2 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 2-2) 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 (Figures 5-14 and 5-15). 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 5-2. In this table, the maximum OD is the diameter of the external upset for threads.

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

Table 5-2. Waste package dimensions for thermal analyses.

Nominal OD (in)	Nominal ID (in)	Max External OD (in)	Min Internal 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).				

5.2.1 Numerical Model

SolidWorks Flow Simulation CFD® 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 5-14.

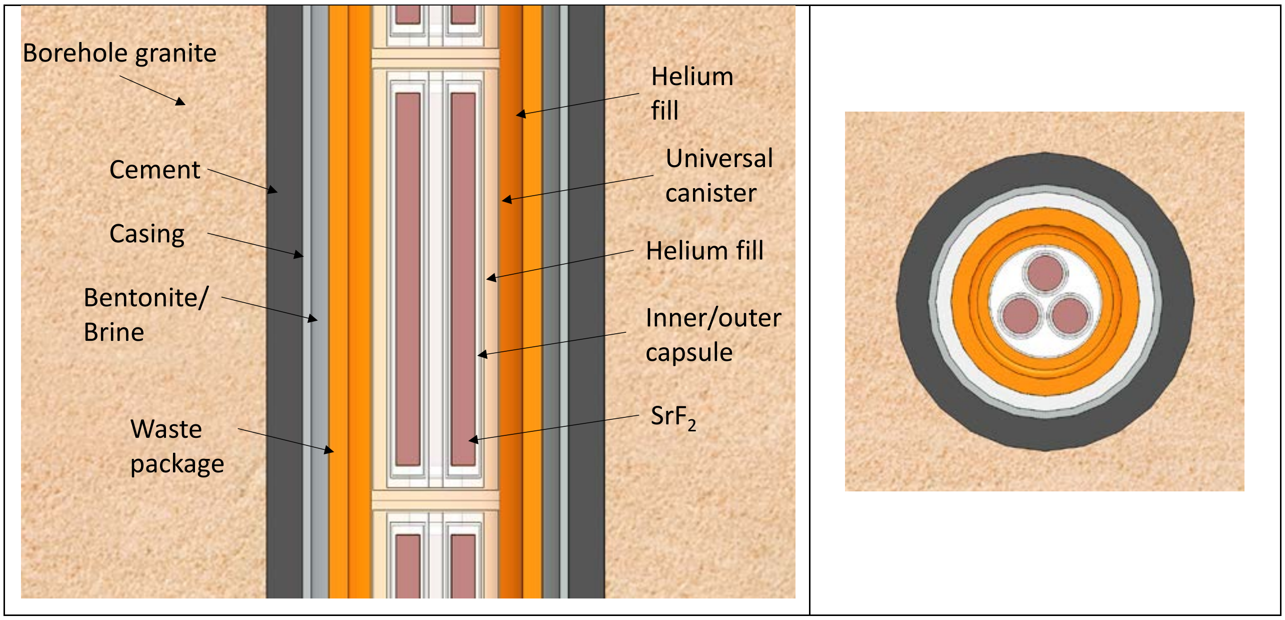


Figure 5-14. Waste package configuration within borehole, for finite element thermal model.

5.2.2 Materials

Material properties used in the analysis are shown in Table 5-3. Borehole and casing dimensions were consistent with Table 2-2, 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.

5.2.3 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.

Table 5-3. 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

5.2.4 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 5-4) that were selected using a blending algorithm that levelized 3-pack thermal output over all 601 SrF_2 capsules. Heat outputs are for 2050 (Section 2.4). The distribution of the heat sources is shown below in Figure 5-15. The heat output decays with time using the decay constant of ^{90}Sr (and decay energy including daughters).

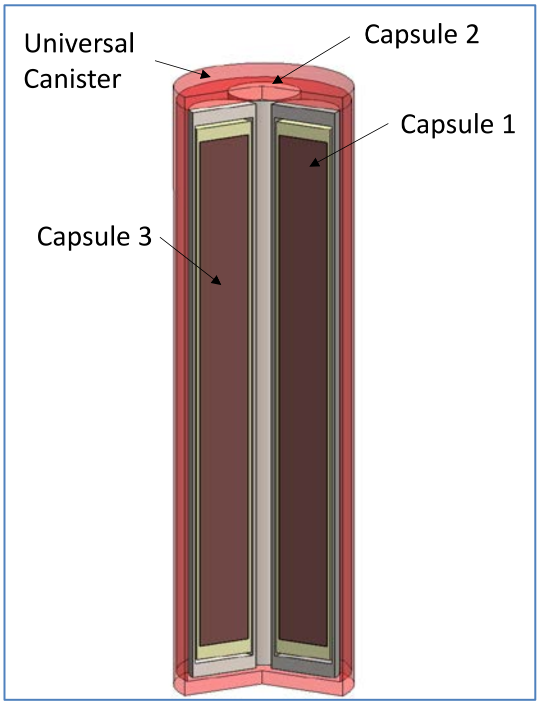


Figure 5-15. Universal canister with three capsules.

Table 5-4. SrF_2 Blended hottest 3-pack configurations (heat output in year 2050).

3-Pack ID	Thermal Power Output			
	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 5-16). 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 5-17. A higher grid refinement level was used in the borehole and the package, decreasing away from the borehole.

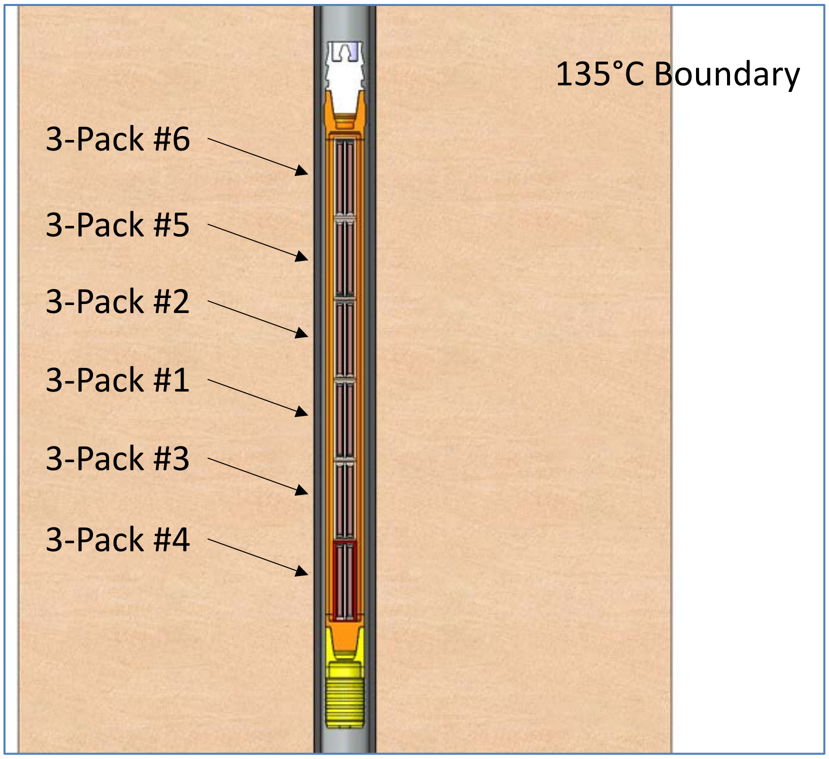


Figure 5-16. Capsule and 3-pack configuration within the waste package.

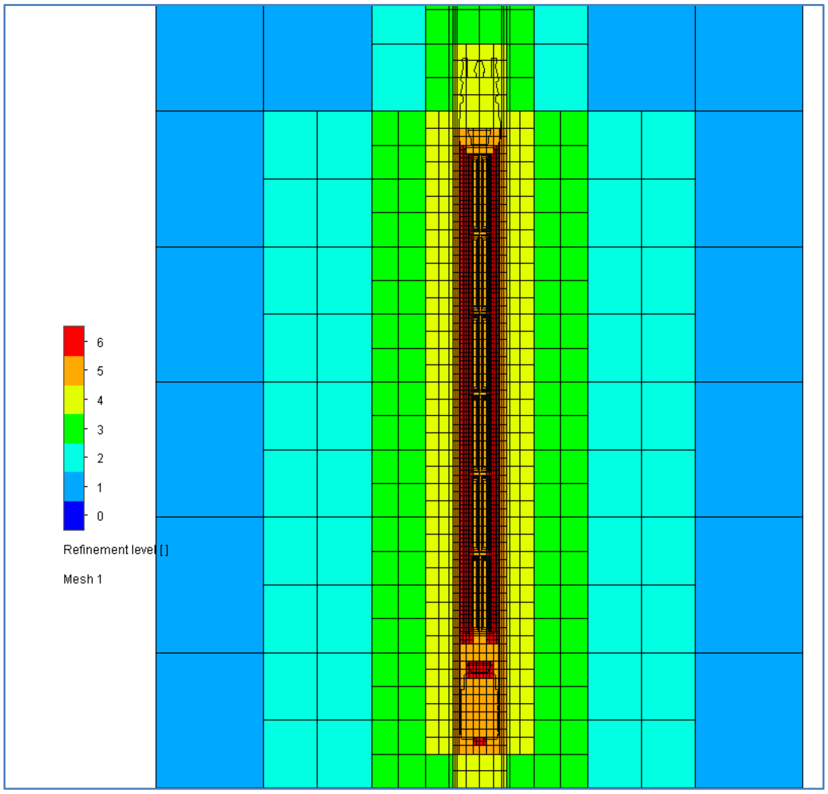


Figure 5-17. Model grid for 3-dimensional thermal simulation of SrF_2 capsule disposal.

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 (labeled 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.

5.2.5 Results

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

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 5-18 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.

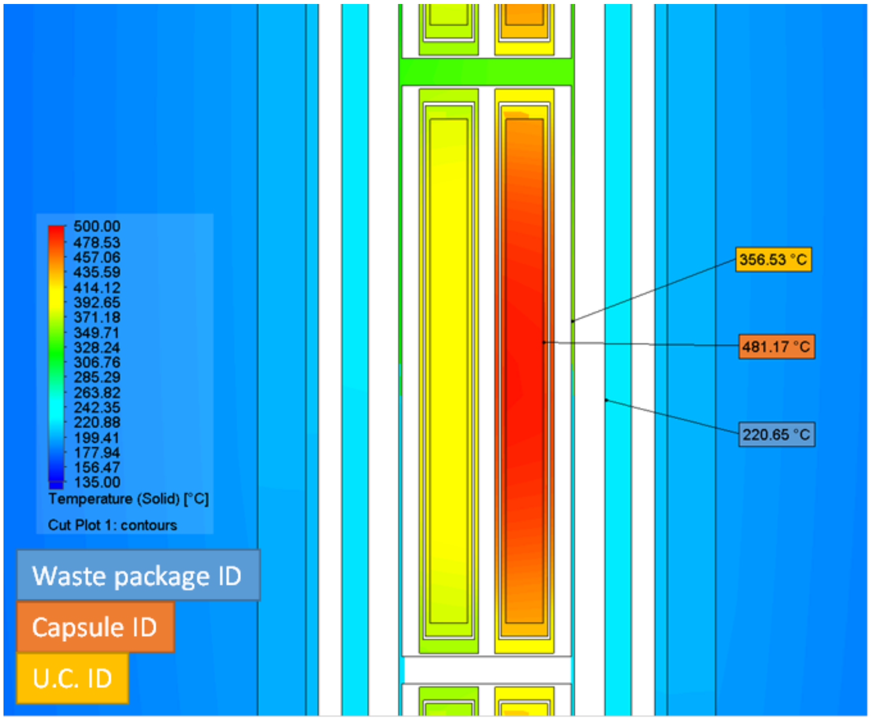


Figure 5-18. Steady-state waste package temperature distribution (brine in casing).

Figure 5-19 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.

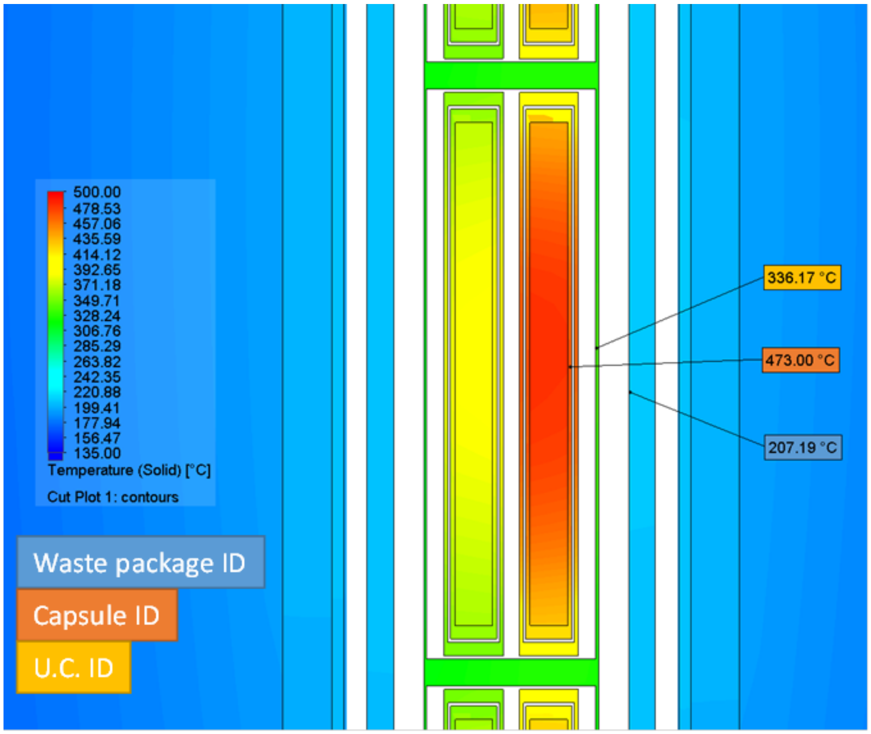


Figure 5-19. Steady-state waste package temperature distribution (sealed in bentonite)

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

Table 5-5. 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

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 5-20. Peak temperatures at 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.

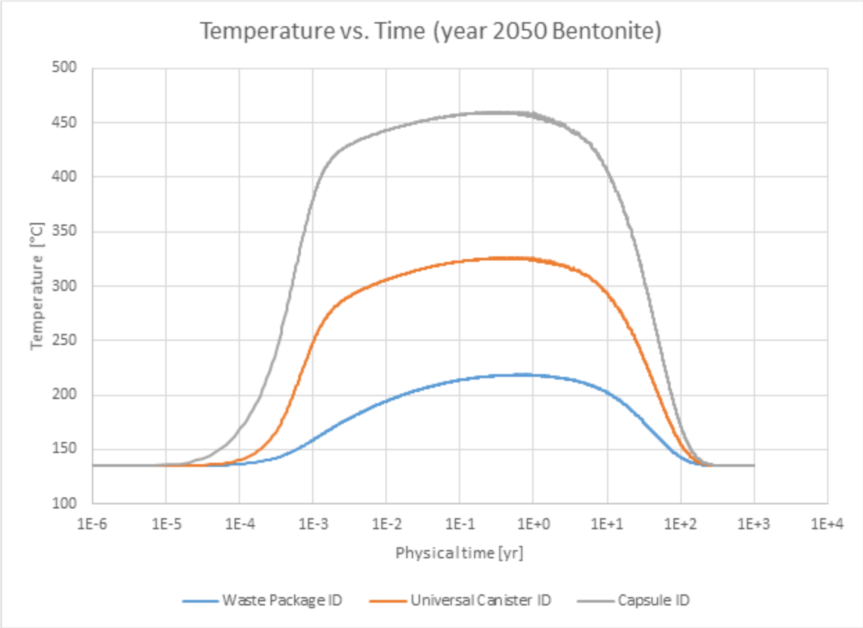


Figure 5-20. Transient temperature response of waste package sealed in bentonite (log time)

A linear time scale plot of the temperature rise is shown in Figure 5-21. The rise time (90% of maximum temperature) for the WP and inner contents is approximately 0.011 yr (4 days).

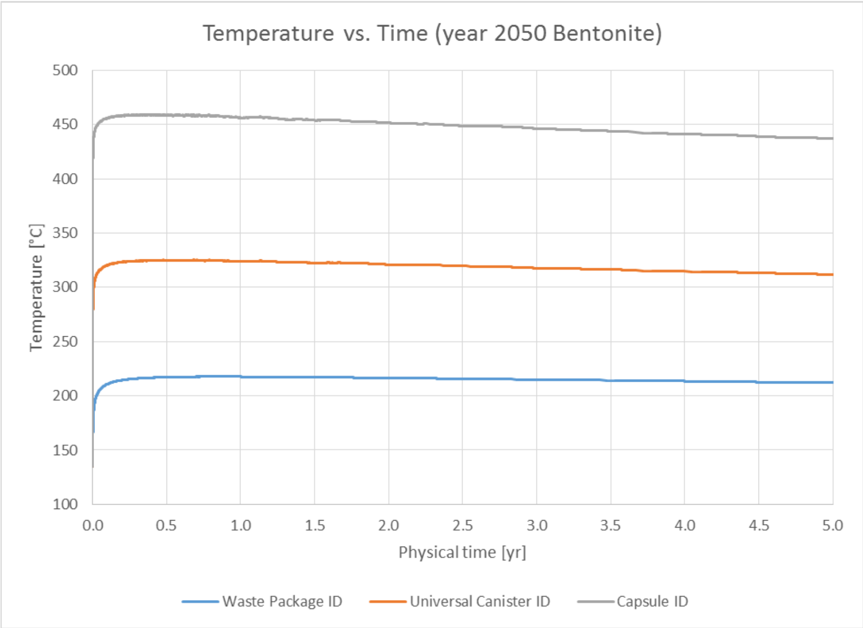


Figure 5-21. Transient temperature response of waste package sealed in bentonite (linear time)

A simulation was also conducted assuming a brine-filled borehole. The results are shown in Figures 5-22 and 5-23. 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.

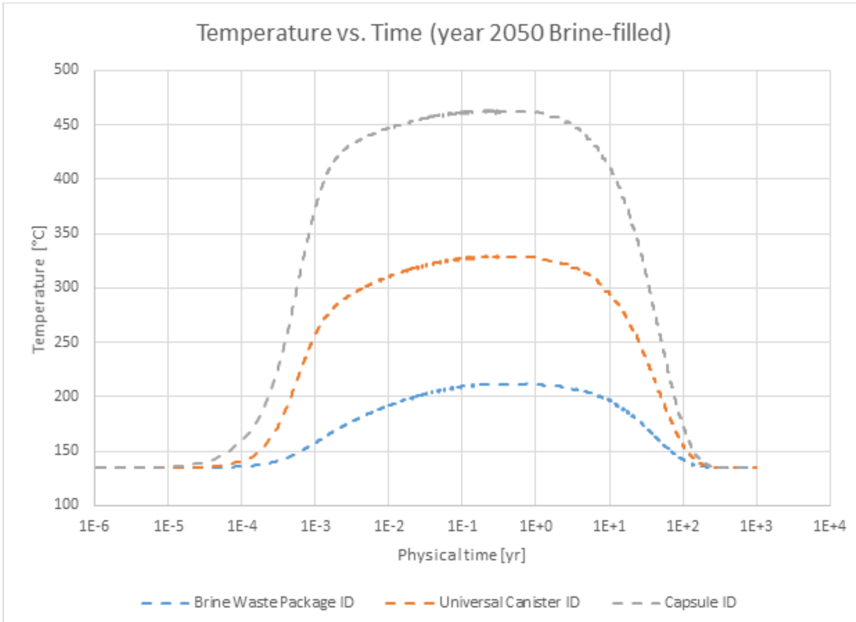


Figure 5-22. Transient temperature response of waste package in brine (log time scale)

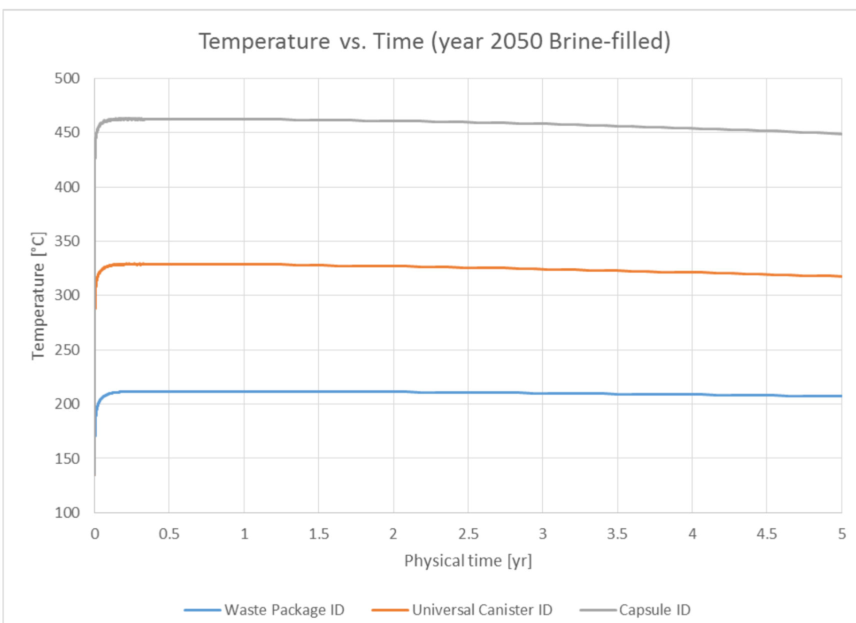


Figure 5-23. Transient temperature response of waste package in brine (linear time scale)

5.3 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.

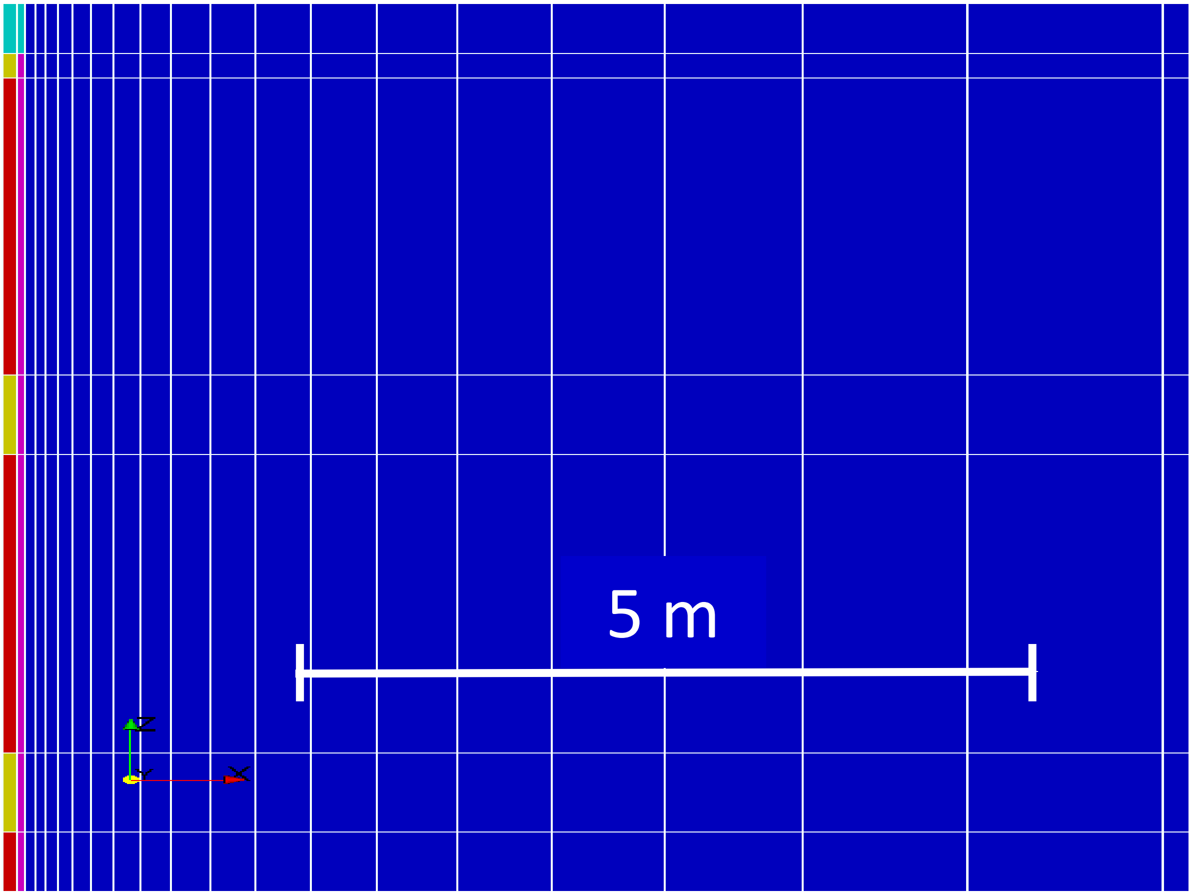
For this analysis emplacement is assumed to occur in 2050 (Section 2.4), at which time the entire heat output of all 1,935 capsules will be 114 kW (calculated from 2007 values in Arnold et al. 2014). Thermal loading is of interest for two main reasons: 1) temperature at the WP wall in excess of 250°C 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 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.

5.3.1 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 5-24) 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 40^{th}, 80^{th}, and 108^{th} 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 5-6) 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 disturbed rock zone is indistinguishable by color; it occupies the first three cell widths to the right of the annulus.

Figure 5-24. Portion of the model domain showing materials in the disposal zone.

Table 5-6. 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[2]	0.747	*NA*

Notes:
1. See Table 2-2 of this report, and Arnold et al. (2014, Table 3-4)
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 5-7). 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 5-7. 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.

5.3.2 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.

Temperature

Waste package temperature is bounded by the reported temperature of the WP, and of the borehole annulus (Figures 5-25 through 5-28). 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 7^{th} WP)
- At the deepest SrF_2 WP (z = 1364.82 m, the 75^{th} WP)
- At the uppermost WP (z = 1531.9 m, the 108^{th} WP)
- Within the bentonite seal just above the top cement plug (z = 1546.58 m)

Temperature histories are plotted for the first three of these elevations (Figures 5-25 through 5-28) at four locations:

- Within the WP

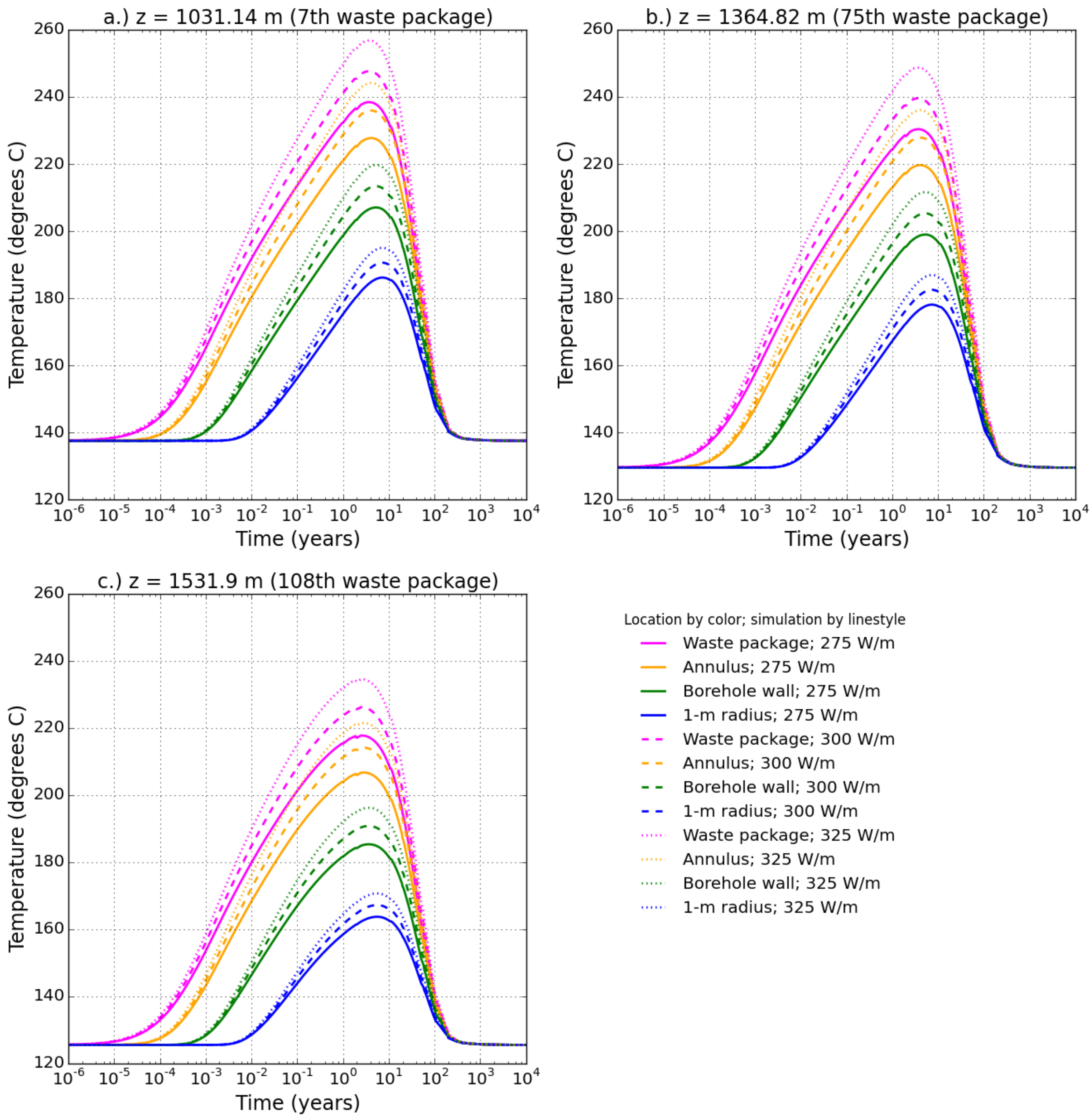
- Within the annulus
- Within the first cell of the DRZ (labeled "borehole wall")
- Within the undisturbed granite at 1-m radius

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 (Figures 5-25 and 5-27). For example in the cement simulations (Figure 5-25) 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.

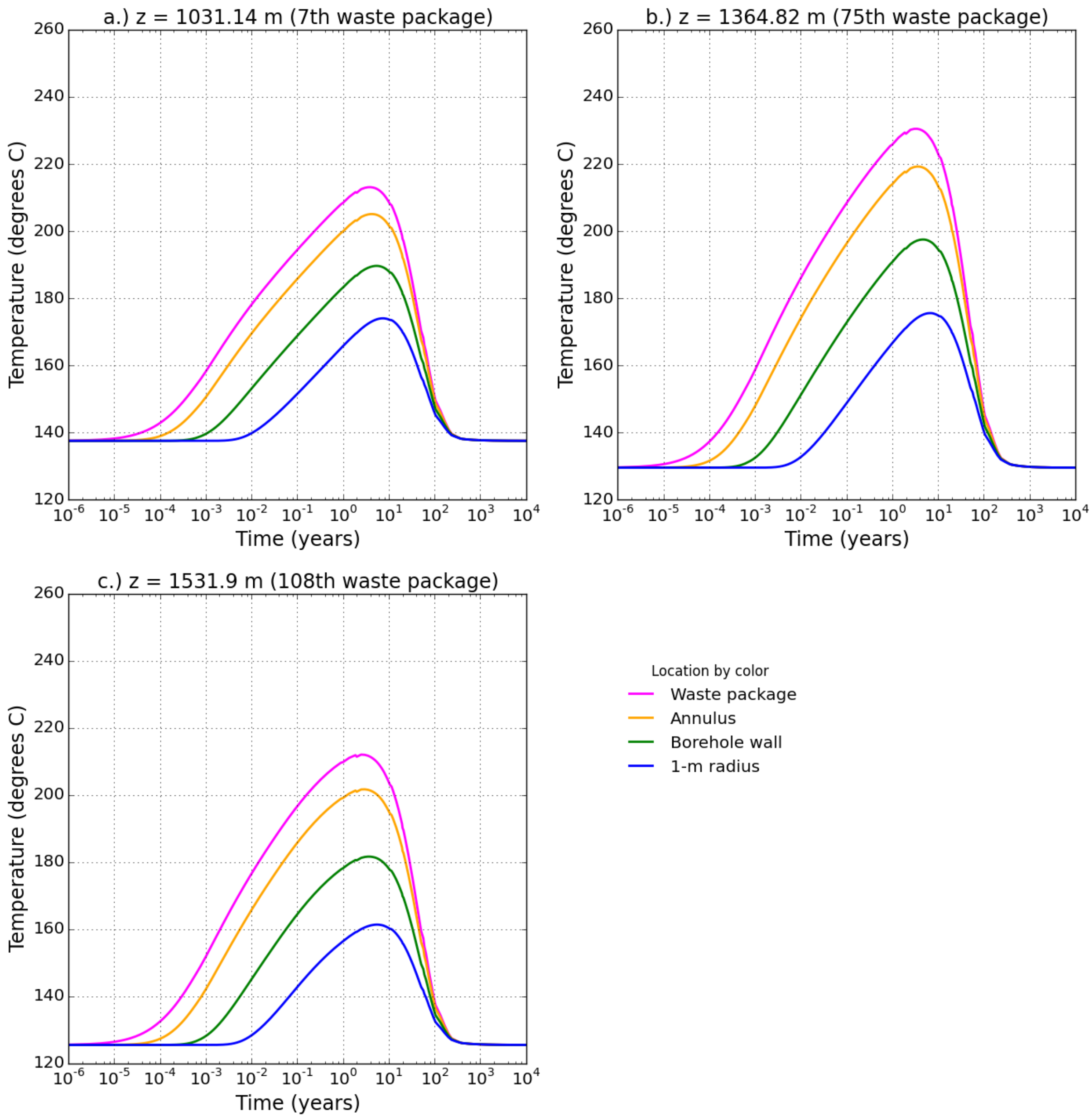
Calculated temperature rise is greater with brine in the borehole annulus than cement (Figures 5-27 through 5-28). Higher temperatures occur because brine has lower thermal conductivity, even though the simulations produce fluid fluxes in the near field that are orders of magnitude greater than in cement (Figures 5-25 and 5-26). 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) (Figures 5-25 and 5-27). 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.



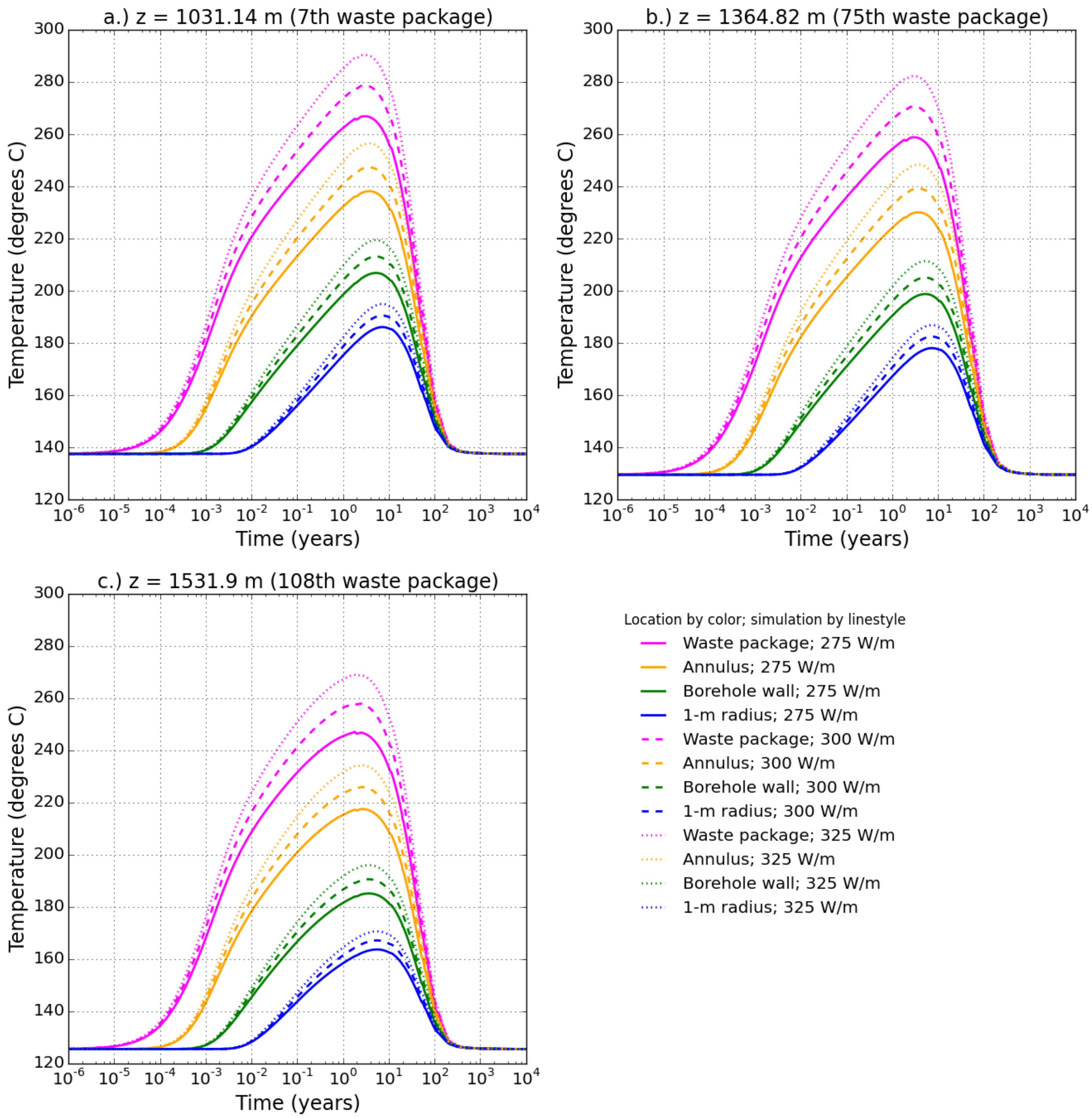
Note: the 7th package is 7th from the base of the EZ, the 75th is the deepest SrF_2 package, and the 108th is the uppermost package.

Figure 5-25. Temperature histories for the line load simulations with cement in the borehole annulus, for three elevations, four locations, and three power levels as indicated.



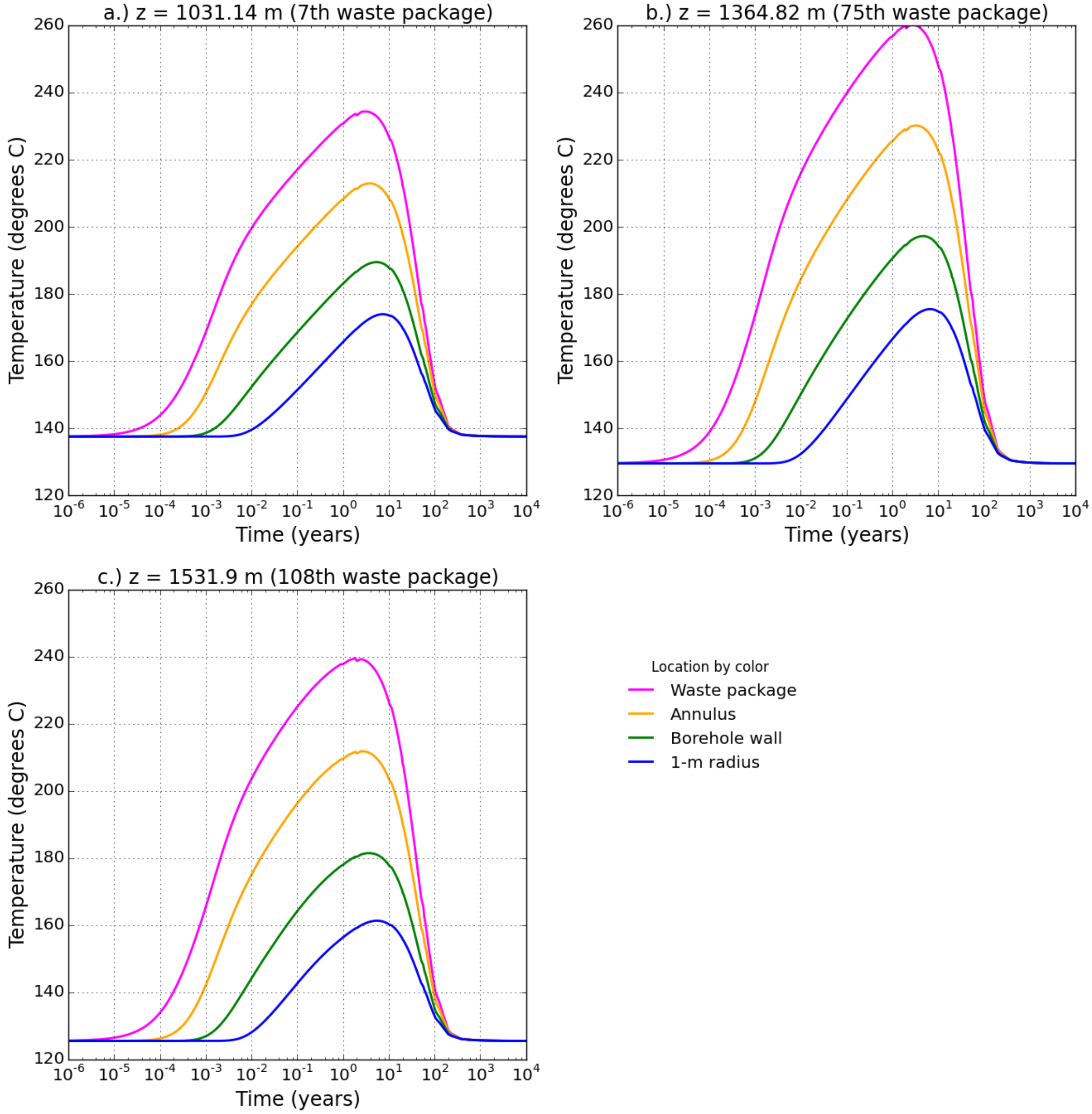
Note: the 7th package is 7th from the base of the EZ, the 75th is the deepest SrF_2 package, and the 108th is the uppermost package.

Figure 5-26. Temperature histories for the 2050 simulations with cement in the borehole annulus, for three elevations and four locations as indicated.



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

Figure 5-27. Temperature histories for the line load simulations with brine in the borehole annulus, for three elevations, four locations, and three power levels as indicated.

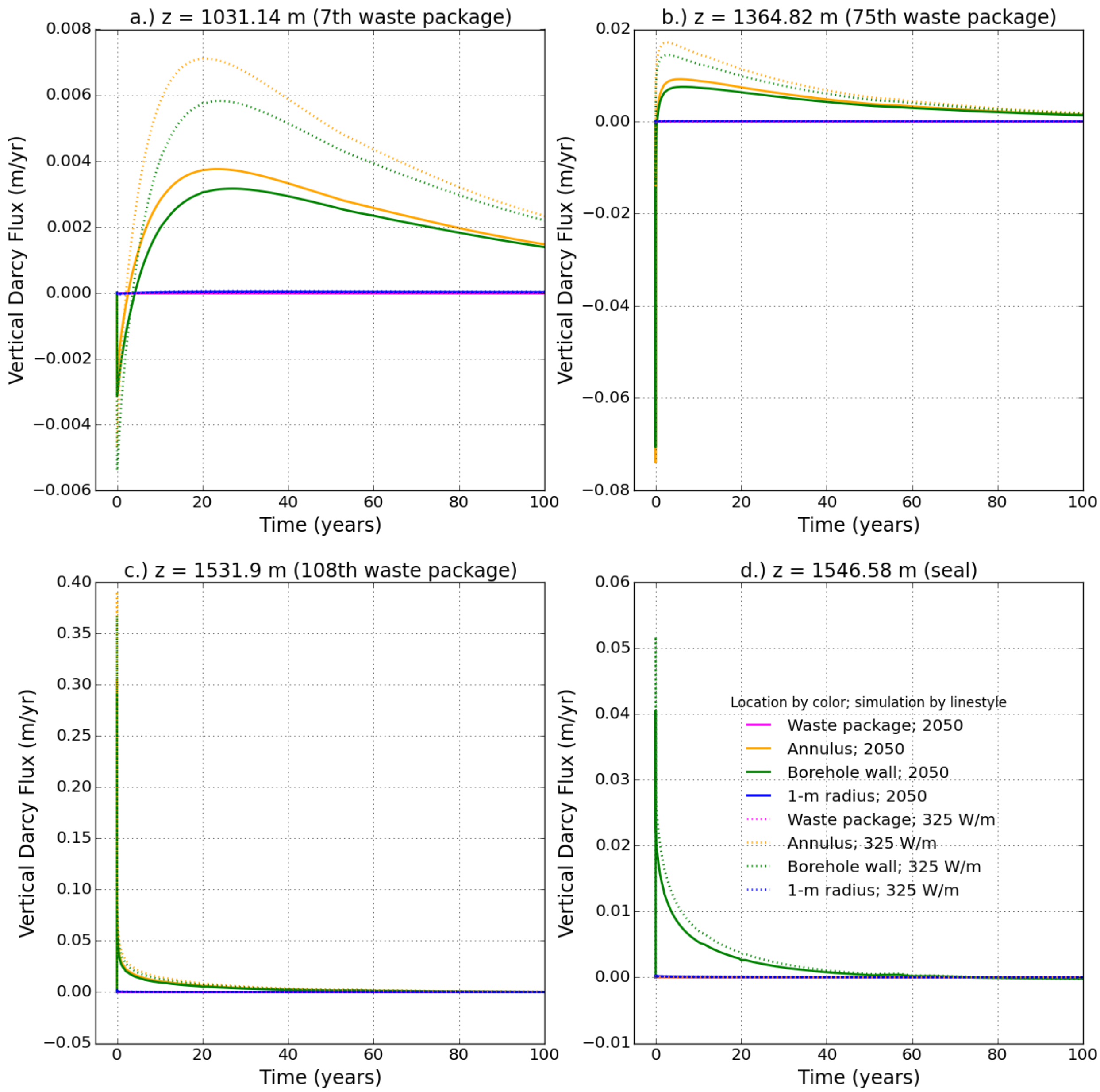


Note: the 7th package is 7th from the base of the EZ, the 75th is the deepest SrF_2 package, and the 108th is the uppermost package.

Figure 5-28. Temperature histories for the 2050 simulations with brine in the borehole annulus, for three elevations and four locations as indicated.

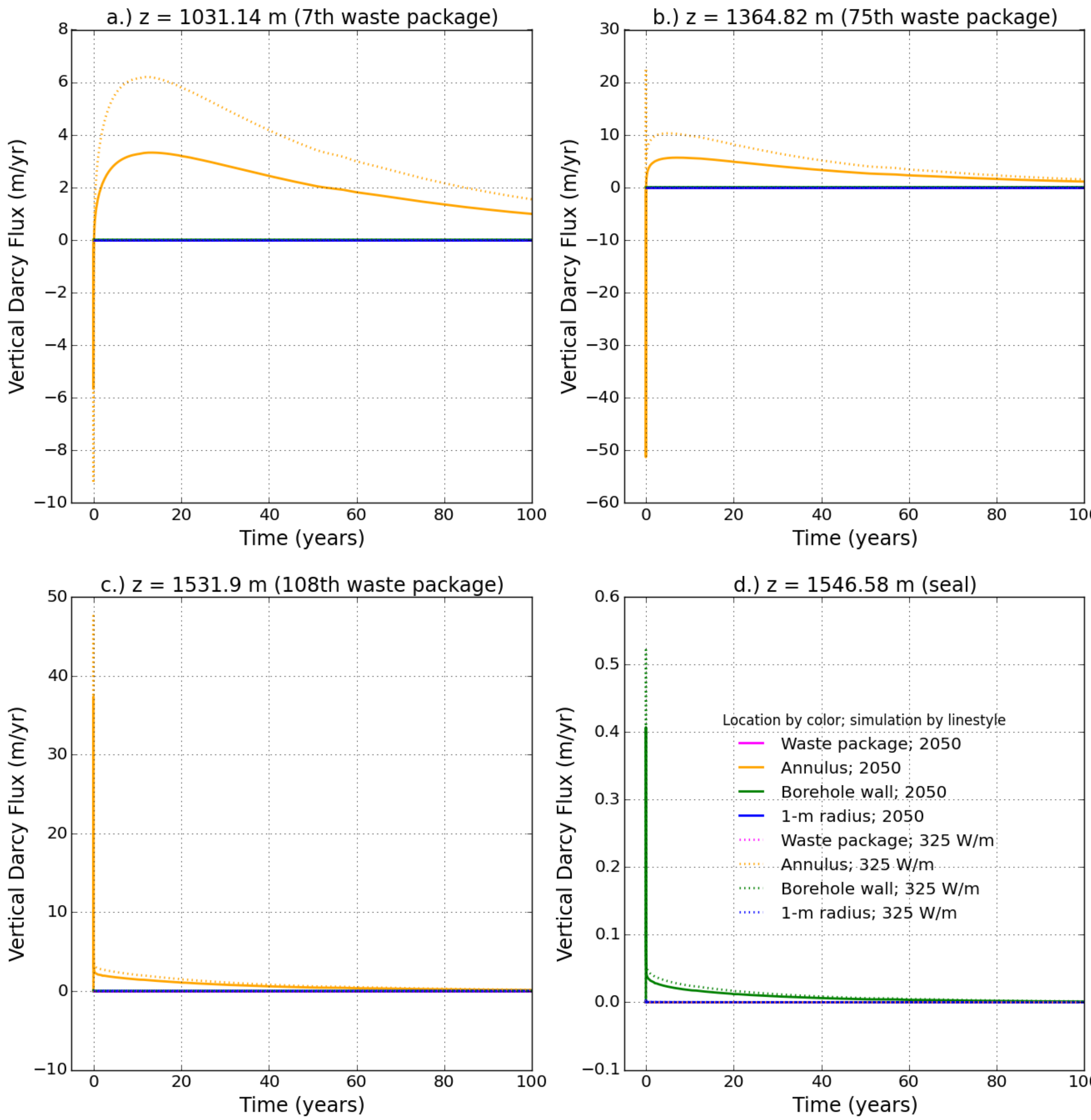
Fluid Flux

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 5-29 (cement in annulus) and Figure 5-30 (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 5-29. Vertical fluid flux versus time with cement in the borehole annulus, for four elevations, four locations, and two 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 5-30. Vertical fluid flux versus time with brine in the borehole annulus, for four elevations (including the base of the seal zone), four locations, and two thermal loading conditions as indicated.

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.

5.4 Terminal Sinking Velocity

With a guidance casing running from the surface to TD, and the borehole filled with an emplacement fluid, it could be possible to safely allow packages to sink freely into disposal position. Also, with wireline emplacement there is a small probability of an off-normal event that releases a package to sink freely (Appendix A). In either case, package terminal sinking velocity is a key aspect of emplacement safety.

Bates (2011) analyzed terminal sinking velocity for a package with 5.0 m length and 0.34 m diameter, and mass of 2,000 kg. The gap between the package and the well casing was 2.35 cm. These dimensions are similar to the reference large package discussed in Sections 2.3, 2.4, and 3.2. The calculated terminal velocity was 2.37 m/sec (at surface temperature) and 2.6 m/sec (at 120°C, representing bottom-hole temperature). Bates (2011) also estimated terminal velocity in an open body of fluid (assuming vertical orientation) to be 11.51 m/sec. The Reynolds number for this velocity range and assumed properties is 1.1×10^5 to 5.4×10^5.

Reynolds numbers in this range indicate that the flow regime involved with packages sinking in casing is turbulent. Flow resistance is dominated by form drag (i.e., acceleration of the fluid around the package) with a smaller contribution from viscous friction in the annulus between the package and the casing. The upward speed of flow in this annulus can be several times greater than the downward speed of the package.

The Bates (2011) estimate was for unperforated casing, whereby fluid displaced by downward package movement flows upward through the gap between the package and the casing. In this study, an approximate analytical solution was developed for an open condition in which part of the water displaced by the package is lost due to leakage through perforations. This solution is appropriate for use as an upper bound estimate of sinking velocity.

Turbulence is highly 3-dimensional, and the applicability of analytical solutions could be limited and needs to be examined using numerical simulation. The main objectives of the current study were to develop a numerical computational fluid dynamic (CFD) model for comparative analysis, and to update package dimensions and emplacement fluid properties in the evaluation. Consistent with the current reference design for DBD (Section 3.2) the package has 18.5 ft length, 11-inch diameter, and mass of 4,620 lb (buoyancy is accounted for in the analysis). The gap between the package and casing is 13/16 inches, corresponding to the ID of 13-3/8 inch casing and the 11-inch OD of the reference size package. (Although casing drift diameter is used in Section 2.3, fluid flow will occur throughout the gap.)

Two options are evaluated for the casing: unperforated and perforated with circular holes distributed vertically. Part of the displacement flow will discharge through the perforations into the annulus between the borehole wall and the casing, where it is assumed to disperse axially and/or radially. The outflow increases the terminal velocity of the sinking package, to an extent that will depend on the diameter and spacing of the perforations, and the length of the perforated interval.

5.4.1 Fluid Dynamics Model

ANSYS Fluent 16.2 CFD code (ANSYS 2015) was selected because it has a broad range of mathematical models for simulating turbulent flow and capabilities to represent moving boundaries, moving reference frames, and dynamic mesh generation. *Fluent* also has a database of fluid properties.

The steady-state modeling approach is indirect; the package remains in place and the emplacement fluid and casing move with specified velocity. The terminal velocity is calculated by changing the relative velocity of the wall and package until the total forces acting on the package are equal to its weight. This approach is computationally efficient, supports axisymmetric analysis, and allows the use of the same (static) mesh. An alternative, transient modeling approach would involve dynamic adjustments to account for new package position at each time step, with significantly more computational effort and complexity. Such an approach could be needed to simulate transient behavior such as complex package movement involving the six degrees of freedom of movement (i.e., translation and rotation about three axes). Measurement of actual package motion in the DBFT demonstration will help determine whether an alternative modeling approach is needed to describe terminal sinking velocity.

The next step was to select an appropriate turbulence model. The k-ω models were recommended for highly turbulent flow with significant wall or boundary effects. The presence of walls gives rise to turbulent momentum with the steepest variation in the near-wall regions, which is represented by the k-ω models. Adequate near-wall modeling is important because prediction of frictional drag and pressure drops depends on the local shear at solid boundaries.

Fluent has three k-ω models:

- Standard
- Baseline (BSL)
- Shear-stress transport (SST)

The standard model (Wilcox k-ω model) is an empirical one based on transport equations for the turbulence kinetic energy (k) and the specific dissipation rate (ω) (Wilcox, 1998):

$$\frac{\partial}{\partial t}(pk) + \frac{\partial}{\partial x_i}(pku_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \qquad (5\text{-}8)$$

$$\frac{\partial}{\partial t}(p\omega) + \frac{\partial}{\partial x_i}(p\omega u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + S_\omega \qquad (5\text{-}9)$$

where x_i and x_j are spatial coordinates, and u is velocity. G_k represents the generation of turbulence kinetic energy due to mean velocity gradients, G_ω represents the generation of ω, and Γ_k and Γ_ω represent the effective diffusivity of k and ω, respectively. Y_k and Y_ω represent the dissipation of k and ω due to turbulence, and S_k and S_ω are source terms. One of the weak points of the Wilcox model is the sensitivity of the solutions to values for k and ω outside the shear layer (ANSYS 2015).

The baseline (BSL) k-ω model (Menter 1994) was developed to blend the robust and accurate formulation of the k-ω model in the near-wall region with the free-stream independence of the k-ω model in the far field. The standard k-ω model and the transformed k-ω model are both multiplied by a blending function and both models are added together. The blending function is unity in the near-wall region, which activates the standard k-ω model, and zero away from the surface, which activates the transformed k-ω model. The transport equations are similar to Eq. 5-8 and Eq. 5-9, except the cross-diffusion term is added to Eq. 5-9.

The SST k-ω model includes all the refinements of the BSL k-ω model and also accounts for transport of the turbulence shear stress in the definition of the turbulent viscosity (ANSYS 2015). These features make the SST k-ω model more accurate and reliable for a wider class of flows than the standard and the BSL k-ω models. The SST k-ω model was selected for modeling the terminal velocity problem.

Modeling Setup and Parameters

Figure 5-31 represents how the conceptual model of package sinking was translated into the numerical model. The numerical model is 2-dimensional axisymmetric with domain radius equal to 0.16 m corresponding to the casing ID. The package with radius of 0.14 m and length of 5.64 m is centered. Fluid flow next to the package is restricted to the gap between the package and the casing. Fluid flow below and above the package is restricted by the casing. The constant fluid velocity is specified at the bottom boundary, so that fluid moves upward to represent downward movement of the package. The casing is moving upward with the same velocity as the fluid at the boundary. The upper boundary is simulated as a pressure outlet.

Note that the weight of the package is not a direct input into the model. The total forces acting on the package are calculated for the different velocity values and compared to the package weight to determine if the terminal velocity is reached.

Also shown in Figure 5-31 is a close-up of the model mesh. All the regions close to the package and casing walls have fine discretization to represent boundary layers. A total of 25 boundary inflation layers were defined while generating this mesh.

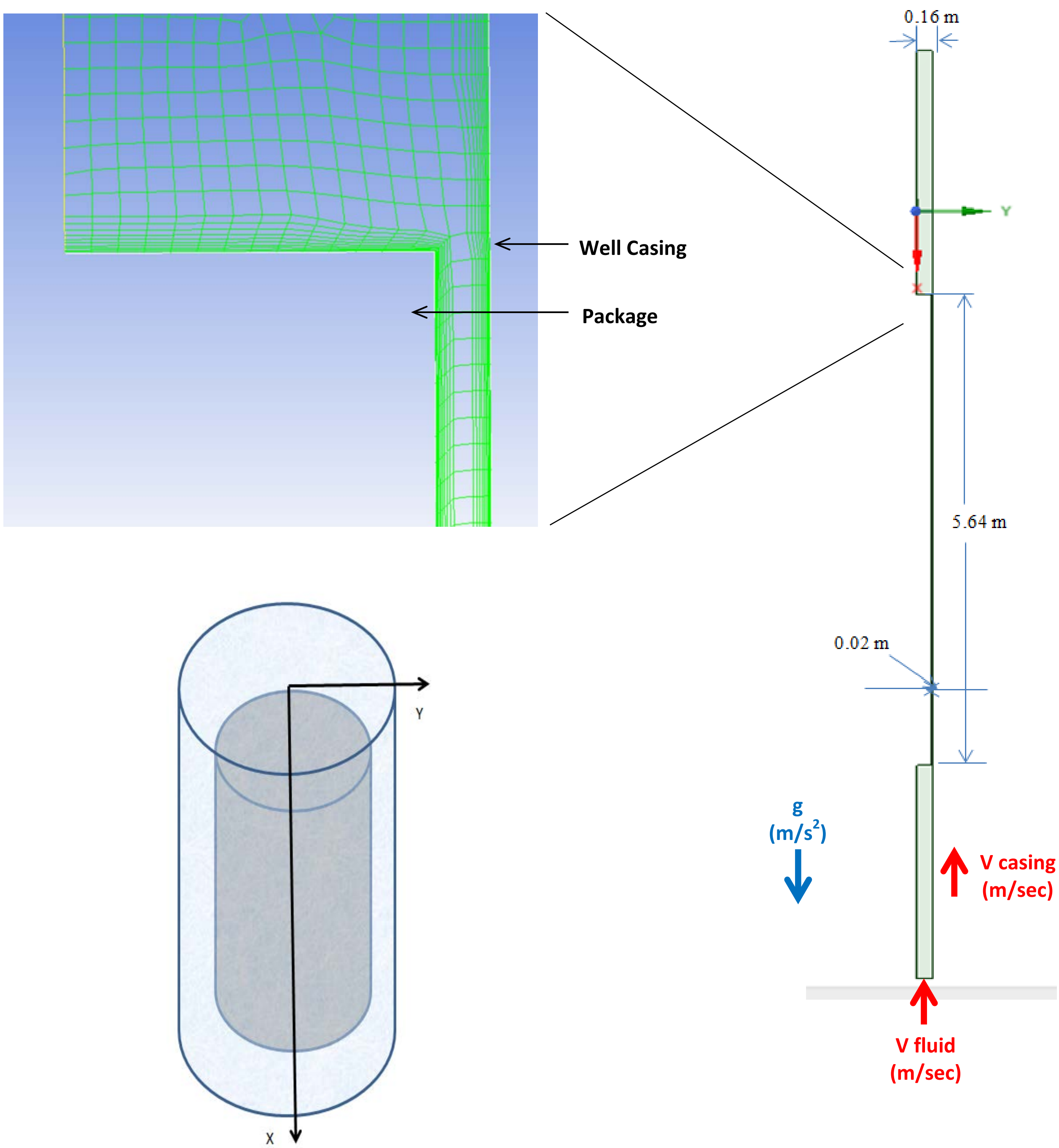


Figure 5-31. CFD modeling setup.

The model shown in Figure 5-31 was modified to simulate different gap widths. A gap of 7.6 cm was used to represent the condition in which the effects of casing are negligible and fluid flow is controlled by the gap between the package and the borehole wall. This is the limiting case for analysis of perforations (Section 5.4.3). Gaps of 4, 6, and 9 cm were considered in comparing numerical and analytical solutions (Section 5.4.4).

As it was discussed above, the SST k-ω model was selected as the turbulence model. The default *Fluent* parameters for this model are:

- Specific dissipation rate (ω): 1/s
- Turbulent intensity: 5%
- Turbulent viscosity ratio: 10

The applicability of these parameters was examined by calculating key turbulence properties using relationships in Wilcox (2006) and Andersson et al. (2012).

The turbulence intensity (I) can be calculated from Reynolds number (Re) as:

$$I = 0.16Re^{-1/8} \tag{5-10}$$

Eddy frequency (ω) is defined as:

$$\omega = \frac{k^{1/2}}{l}, l = 0.07x_{char} \tag{5-11}$$

where x_{char} is characteristic length.

Turbulence kinetic energy (k) can be calculated as:

$$k = \frac{3}{2}(u_{char}I)^2 \tag{5-12}$$

where u_{char} is characteristic velocity.

The turbulent viscosity can be calculated as:

$$v_t = \frac{C_\mu k^2}{\varepsilon}, C_\mu = 0.09 \tag{5-13}$$

where ε is eddy dissipation defined as:

$$\varepsilon = \frac{k^{1/2}}{l}, C_\mu = 0.09 \tag{5-14}$$

The turbulent viscosity ratio is $\frac{v_t}{v_f}$, where v_f is fluid viscosity.

The calculations were done for water at 20°C, 40°C, 80°C, and 120°C assuming fluid velocity of 2.0 m/sec (Tables 5-8 and 5-9). The calculated specific dissipation rate and turbulent intensity values are close to the *Fluent* default values. Each calculation was iterated once, updating the turbulent viscosity (starting with a default value then changing the inputs according to the results).

Possible emplacement fluids include water and brines. The fluid properties needed for the model are the density and dynamic viscosity. Because these properties change with temperature and pressure, a few calculations were done to represent the temperature and pressure range applicable to the borehole condition (20°C to 120°C, and 0 to 65 MPa hydrostatic pressure). These fluid properties are summarized in Table 5-8.

Two brines were considered: 300 g/L sodium chloride (NaCl) to represent naturally occurring high-salinity brine, and 40% sodium bromide (NaBr). Sodium bromide was selected because it is often used as a single-salt brine or in combination with sodium chloride to form workover and completion fluids with densities up to 1,527 kg/m^3. This brine is meant to represent a possible high-density fluid. Note that temperature effects on brine density are much greater than pressure effects.

The following formula was used to estimate brine density (ρ_T) as a function of temperature (T):

$$\rho_T = \rho_0(1 + \beta \cdot (T_0 - T) \qquad (5\text{-}15)$$

where ρ_0 is the brine density reported at temperature T_0 (°F) and β is the coefficient of thermal extension. Density values are usually reported for T of 60° or 70°F.

Table 5-8. Properties of emplacement fluids analyzed (after GEO 2016).

Temperature (°C)	Water		NaCl		NaBr	
	Density (ρ_T, kg/m^3)	Dynamic Viscosity (ν_f, kg/m-s)	Density (ρ_T, kg/m^3)	Dynamic Viscosity (ν_f, kg/m-s)	Density (ρ_T, kg/m^3)	Dynamic Viscosity (ν_f, kg/m-s)
20	998.2	1.00E-03	1231.7	1.55E-03	1498.0	3.00E-03
40	992.2	6.58E-04	1220.5	1.05E-03	1484.4	2.00E-03
80	971.8	3.64E-04	1197.9	6.90E-04	1455.6	1.00E-03
120	961.1	2.43E-04	1175.3	4.00E-04	1426.8	9.00E-04

5.4.2 Terminal Velocity in Unperforated Casing

Terminal Velocity in Water

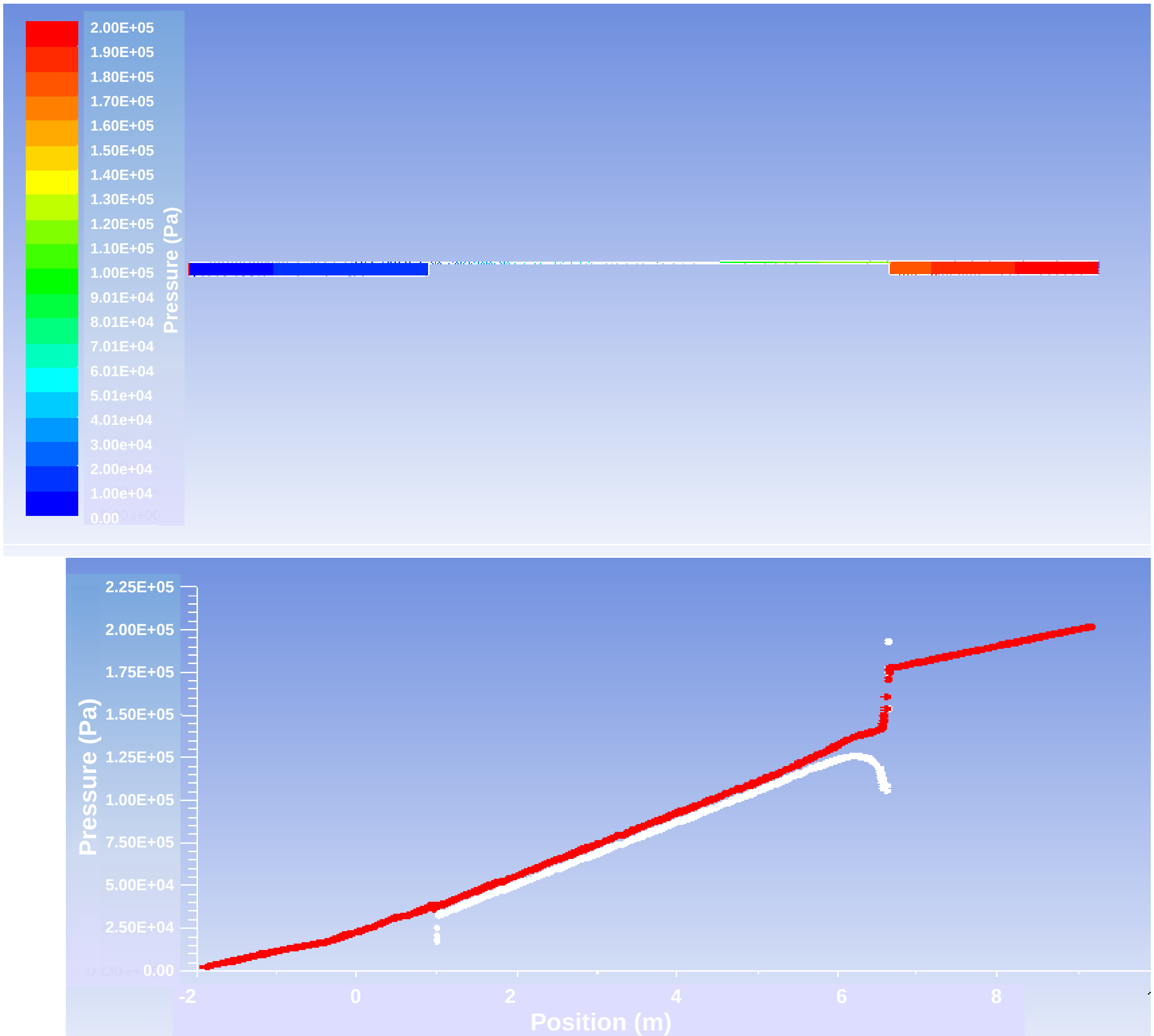
The package terminal velocity in water-filled casing was calculated for four temperatures and corresponding properties shown in Table 5-8. The results of these calculations are summarized in Table 5-9, along with the pressure drag and viscous drag forces expressed as percent of the total force acting on the package, and the maximum Reynolds number in the model domain.

The terminal velocity ranges from 1.95 m/sec (at 20°C) to 2.13 m/sec (at 120°C). The range obtained from the analytical solution for the slightly different package design (Bates 2011) was from 2.37 m/sec (at 20°C) to 2.6 m/sec (at 120°C). In both cases (numerical and analytical) the terminal velocity slightly increases (by about 10%) at increased temperature.

The main force acting on the package is the pressure drag (around 95%). The viscous drag is 4.9% at 20°C, and drops to 4.4% at 120°C (for which the viscosity decreases by a factor of 4.2). Lower viscosity with increasing temperature causes greater turbulence. The maximum Reynolds number in the model domain ranges from 1.7×10^5 (at 20°C) to 7.2×10^5 (at 120°C).

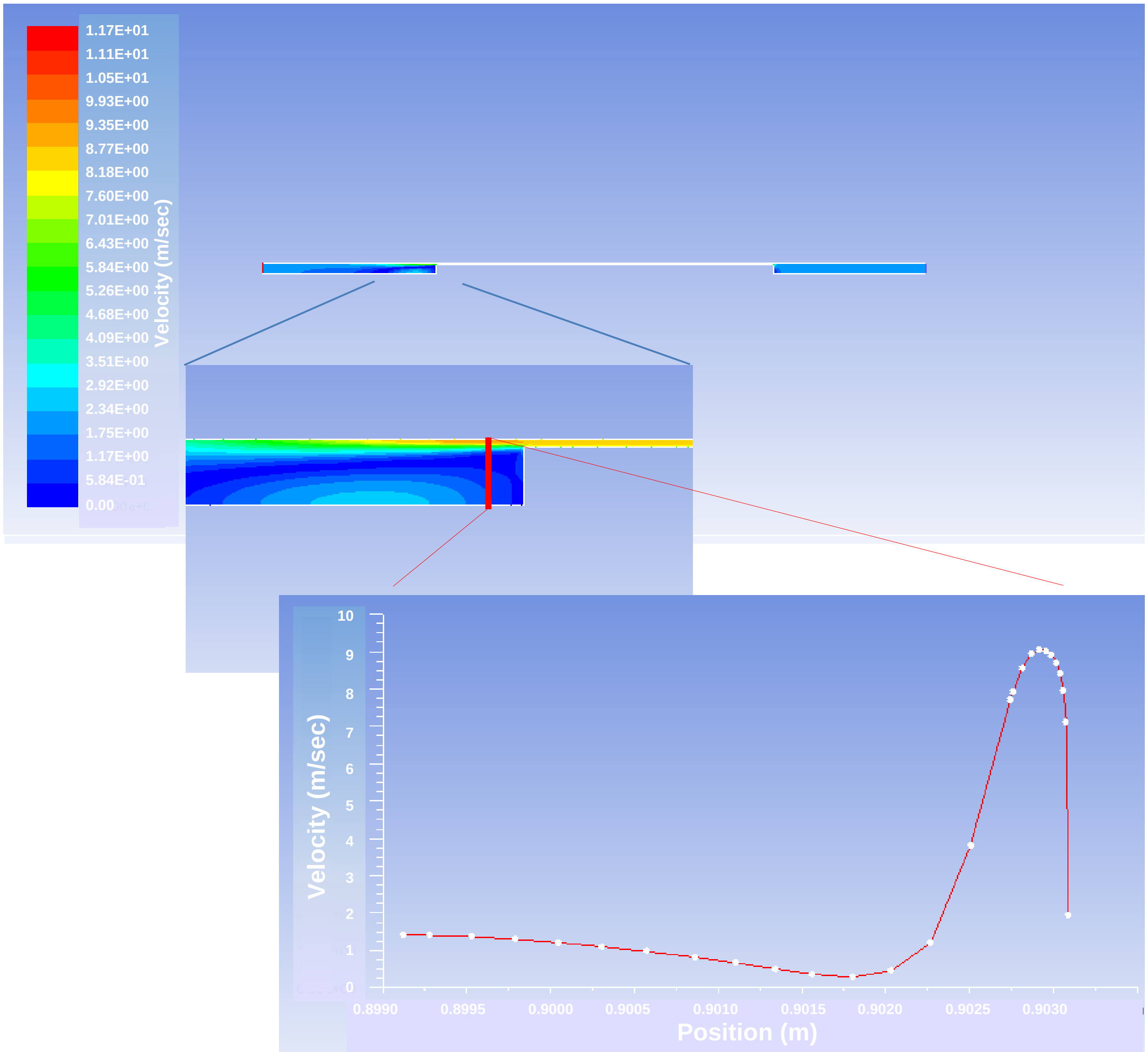
Figure 5-32 shows the total pressure contours and the total pressure profile along the vertical axis at 20°C (total pressure includes hydrostatic). The total pressure distribution is relatively insensitive to temperature because the terminal velocity depends mostly on form drag (and density). The sinking package generates pressure increase of about 90,000 Pa at steady state. The total pressure above the package is hydrostatic, while that below the package is hydrostatic plus the 90,000 Pa increase.

Figure 5-33 shows contours of velocity in the *r-z* plane, and a radial profile of axial velocity, in the wake of the moving package (above the package). The velocity ranges from 0 to 9 m/sec. The highest velocities are in the middle of the gap between the package and the casing. The complex distribution of the velocities above the package is due to turbulence in the wake. Figure 5-34 shows the distribution of the Reynolds number in the model domain. The highest Reynolds numbers are in the region of turbulence above the package, in the middle of the casing.



Note: The upper figure shows the model grid with pressure (Pa) plotted in color, while the lower figure is the axial profile of pressure (Pa) along the casing surface (red symbols) and the surface of the package and borehole centerline (white symbols).

Figure 5-32. Distribution of the fluid pressure (Pa) in the model domain with water as emplacement fluid at 20°C.



Note: The upper figure shows the model grid with velocity (m/sec) plotted in color, while the lower figure is the cross-section of fluid velocity (m/sec) across the gap at the location indicated.

Figure 5-33. Distribution of fluid velocity (m/sec) in the wake of a moving package, with water as emplacement fluid at 20°C, showing contours of velocity in the *r*-*z* plane (upper), and a radial profile of axial velocity (lower).

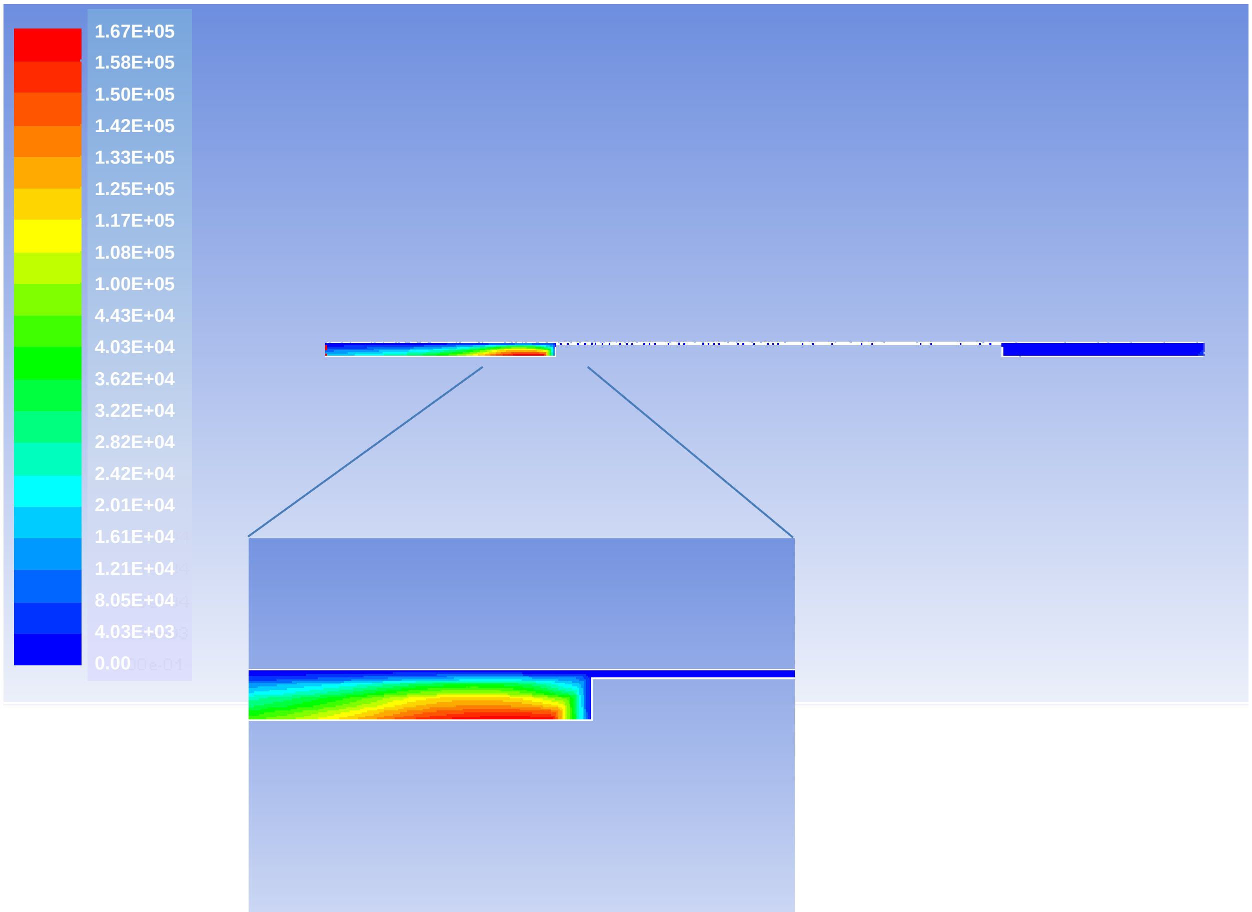


Figure 5-34. Distribution of Reynolds number in the model domain with water as emplacement fluid at 20°C.

Terminal Velocities in Sodium Chloride and Sodium Bromide Brines

Terminal velocity in water and brine was calculated for four temperatures using the corresponding properties (Table 5-8). The results are summarized in Table 5-9 and shown in Figure 5-35. The terminal velocity in the sodium chloride brine ranges from 1.61 to 1.79 m/sec, while that in the higher density sodium bromide brine ranges from 1.30 to 1.46 m/sec. Terminal velocity in brines is smaller than in water, with similar temperature dependence. Viscosity has only a minor effect on sinking velocity, and the effect of viscosity (viscous drag force) is inversely related to fluid density. Turbulence in the brines is less than in the water.

Figures 5-36 through 5-38 show the distribution of the total pressure, velocities, and Reynolds number in the model domain for sodium bromide brine at 20°C. The sinking package generates a pressure increase of about 65,000 Pa which is smaller than the pressure increase in water (90,000 Pa).

Table 5-9. Results from terminal velocity calculations.

Fluid	Terminal Velocity (m/sec)	Temperature (°C)	Pressure Drag	Viscous Drag	Maximum Reynolds Number
Water	1.95	20	95.1%	4.9%	1.67E+05
	1.99	40	95.3%	4.7%	2.57E+05
	2.073	80	95.5%	4.5%	4.74E+05
	2.13	120	95.6%	4.4%	7.22E+05
NaCl	1.61	20	95.5%	4.5%	1.11E+05
	1.66	40	95.7%	4.3%	1.66E+05
	1.71	80	95.8%	4.2%	2.56E+05
	1.79	120	95.9%	4.1%	4.51E+05
NaBr	1.3	20	96.0%	4.0%	5.58E+04
	1.35	40	96.1%	3.9%	8.61E+04
	1.42	80	96.2%	3.8%	1.77E+05
	1.46	120	96.2%	3.8%	1.99E+05

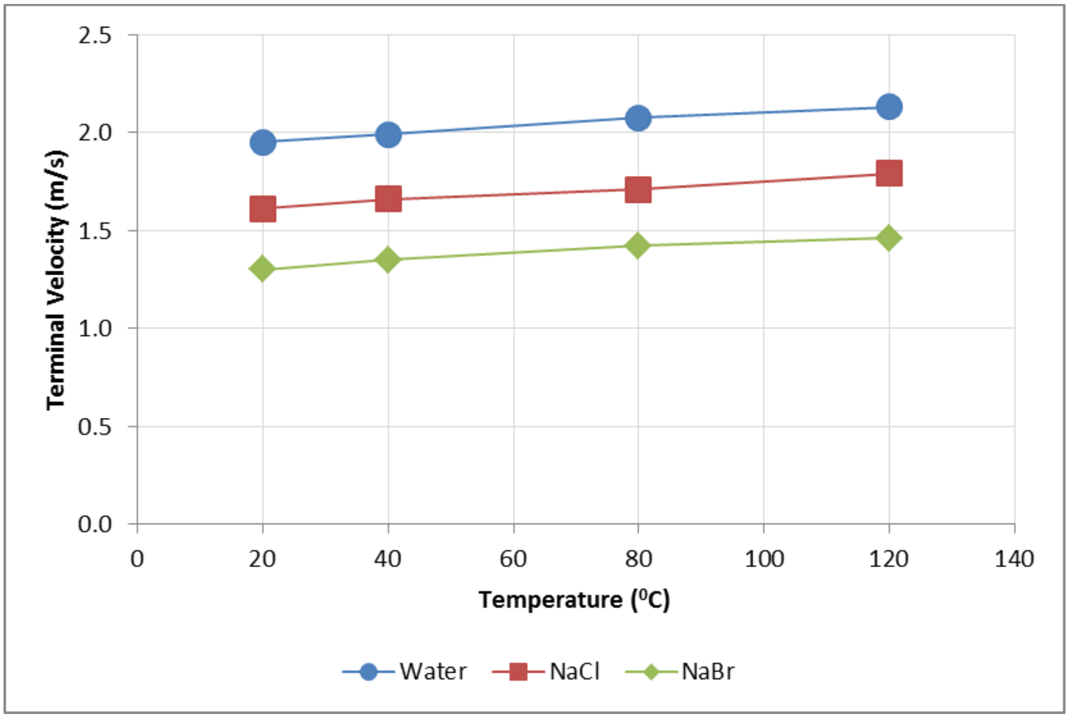
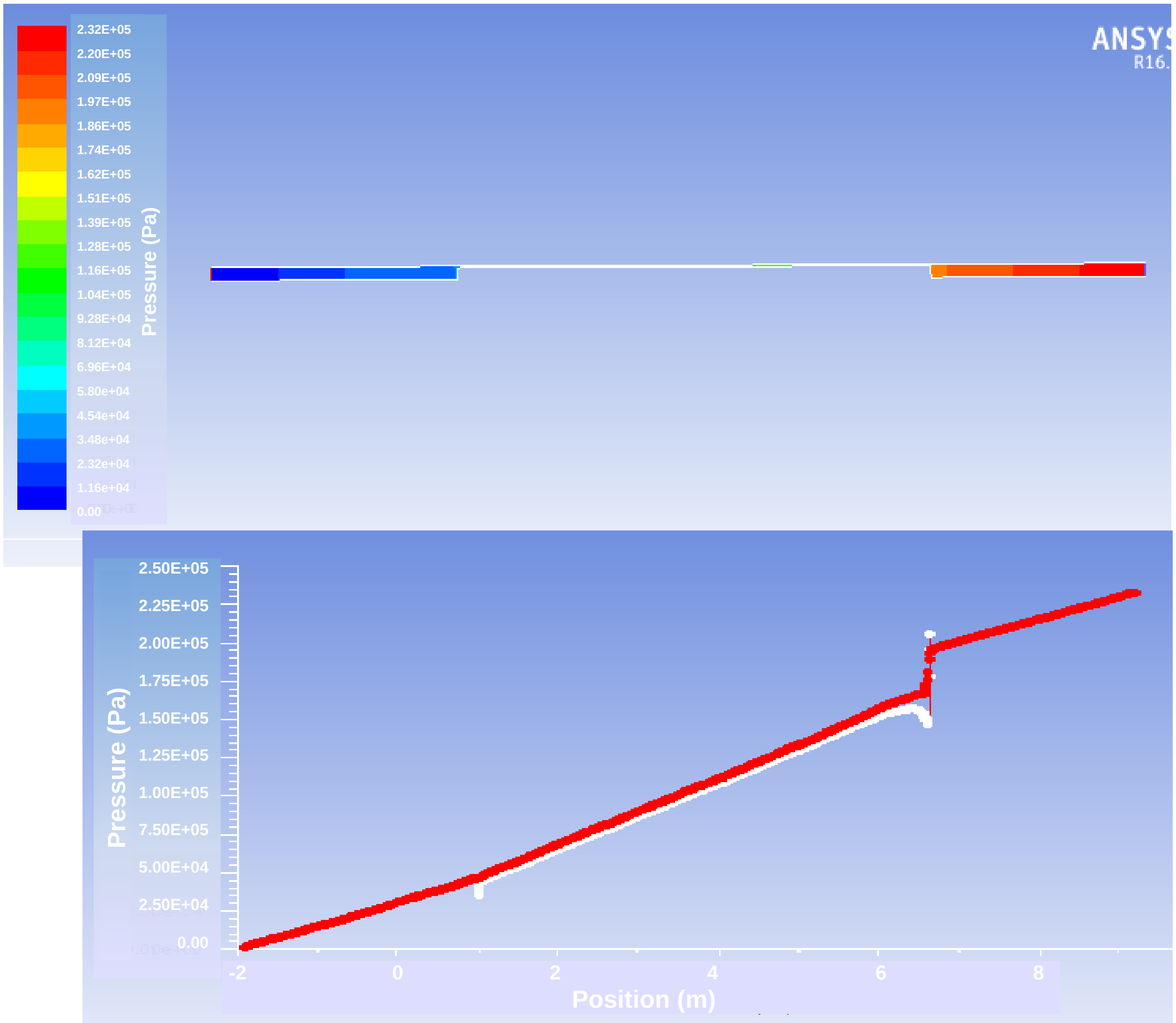
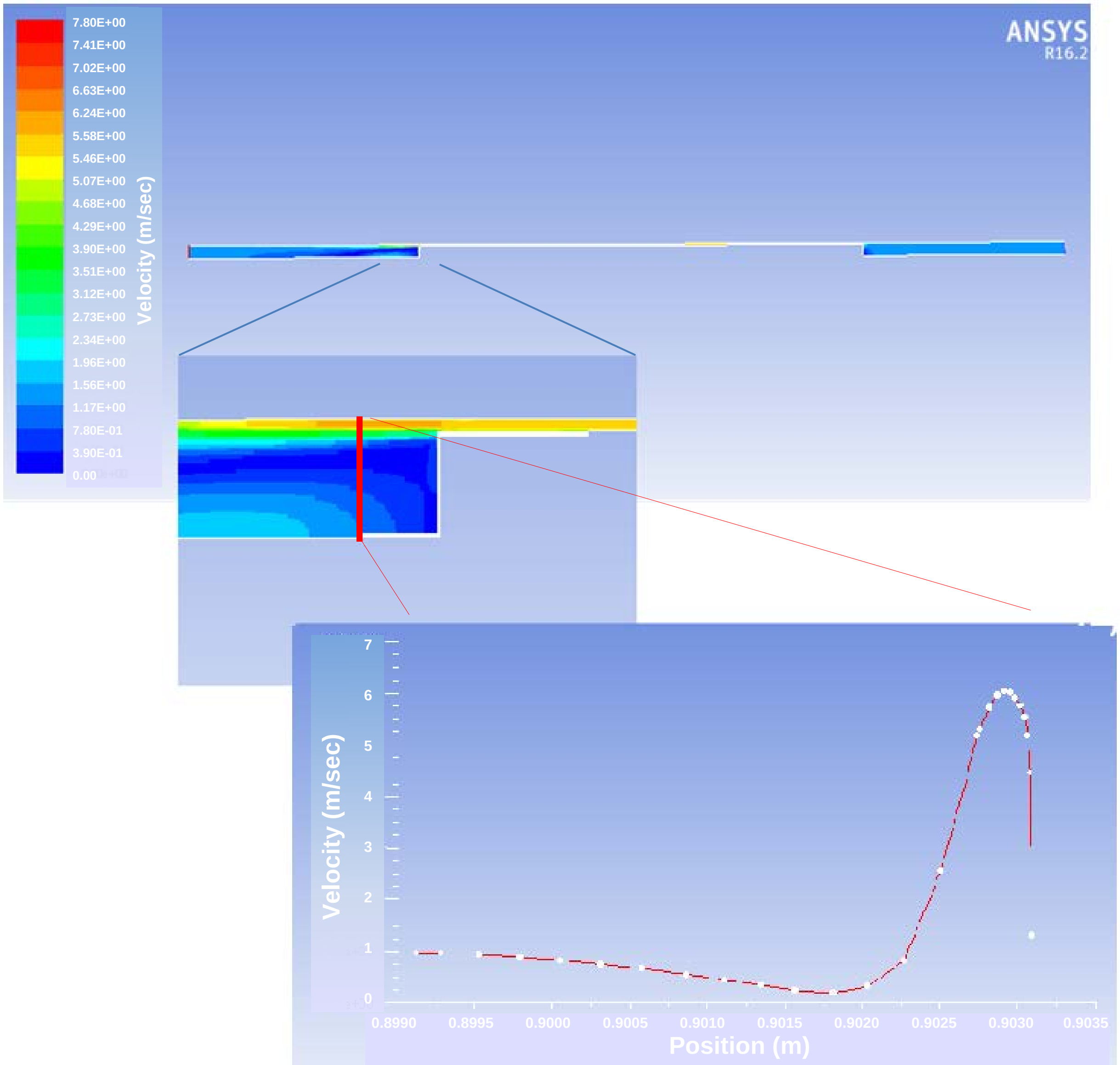


Figure 5-35. Terminal velocity as a function of the emplacement fluid temperature.



Note: The upper figure shows the model grid with pressure (Pa) plotted in color, while the lower figure is the axial profile of pressure (Pa) along the casing surface (red symbols) and the surface of the package and borehole centerline (white symbols).

Figure 5-36. Distribution of the total pressure (Pa) in the model domain with NaBr brine as emplacement fluid at 20°C.



Note: The upper figure shows the model grid with velocity (m/sec) plotted in color, while the lower figure is the cross-section of fluid velocity (m/sec) across the gap at the location indicated.

Figure 5-37. Distribution of axial fluid velocity (m/sec) in the wake of a moving package, with NaBr brine as emplacement fluid at 20°C, showing contours of velocity in the *r-z* plane (upper), and a radial profile of axial velocity (lower).

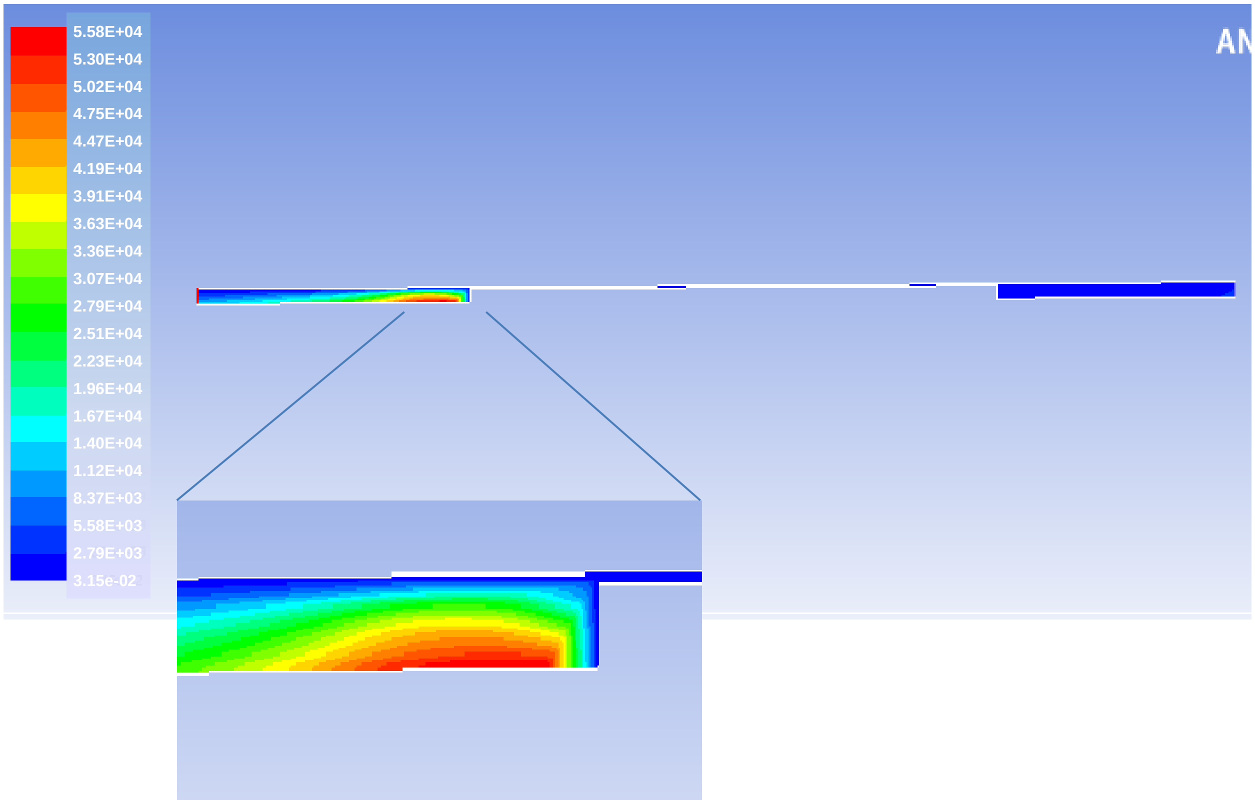


Figure 5-38. Distribution of Reynolds number in the model domain above the package with NaBr brine as emplacement fluid at 20°C.

5.4.3 Bounding Estimate of Terminal Velocity in Perforated Casing

Lower and upper bounds for the terminal velocity can be estimated from the numerical CFD models. The lower limit corresponds to unperforated casing (see Section 5.4.2). The upper limit corresponds to casing that is perforated to the extent at which its presence can be ignored. In this case, the gap is the distance between the package and the borehole wall, which is 7.6 cm for the reference design. A CFD model similar to the one described in Section 5.4.2 was developed to simulate this gap, with the result that the bounding terminal velocity was 7.0 m/sec.

Perforations will cause outflow from the casing into the borehole annulus, and the resulting range of terminal velocity is between 1.95 and 7.0 m/sec. The actual value will depend on the total discharge through perforations.

This bounding estimate is based on first estimating the outflow into the well annulus and then estimating the terminal velocity for the given outflow.

Estimating Outflow into the Well Annulus

Orifice plate theory was used to estimate the outflow from a single perforation, modeled as a round hole. The flow Q_i through one hole can be calculated as:

$$Q_i = K * A_0 * \sqrt{\frac{2\Delta P}{\rho_f}} \tag{5-16}$$

where ΔP is the difference in pressure between the casing and borehole annulus, A_0 is the perforation area, ρ_f is the fluid density, and K is the flow coefficient. This approximation probably overestimates leakage flow because it does not account for flow restriction in the annulus.

The dynamic pressure increase ahead of a sinking WP was calculated to be 90,000 Pa in water (Section 5.4.2). The perforation area is $2\pi r_0^2$ where r_0 is the hole radius. The coefficient K can be obtained from a plot (Roberson and Crowe 1990, Figure 13.12) as a function of known quantities Re/K and $2r_0/D$, where D is the casing diameter, and Re/K is calculated as:

$$Re/K = \frac{2r_0}{\nu}\sqrt{\frac{2\Delta P}{\rho_f}} \tag{5-17}$$

where ν is kinematic viscosity.

For hole diameters of 0.5 cm, 1 cm, 2 cm, and 5 cm, Re/K varies from 6.7×10^4 to 6.7×10^5 and $2r_0/D$ varies from 0.0156 to 0.156. For these ranges K is constant and approximately equal to 0.6 (Roberson and Crowe 1990).

Parameter K was also calculated using the following expression (Reader-Harris/Gallagher equation):

$$K = 0.596 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521\left(\frac{10^6\beta}{Re}\right)^{0.7} +$$

$$(0.0188 + 0.0063A)\beta^{3.5}\left(\frac{10^6}{Re}\right)^{0.3} + (0.043 + 0.08e^{-10L1} - 0.123e^{-7L1}) \times$$

$$(1 - 0.11A)\frac{\beta^4}{1-\beta^4} - 0.031(M_2 - 0.8{M_2}^{1.1})\beta^{1.3}$$

$$with\ M_2 = \frac{2L2}{1-\beta}, A = (\frac{19000\beta}{Re})^{0.8}, L1 = L2 = \frac{0.0254}{D}, and\ Re = \frac{4Q_m}{\pi\mu D} \tag{5-18}$$

where β=2r_0/D, Q_m is the mass flow, and μ is dynamic viscosity. Q_m can be calculated from the terminal velocity, flow area, and fluid density.

For the range of the parameters discussed above, coefficient K calculated from Eq. 5-18 is constant and equal to 0.596, which is consistent with the graphical estimate.

The pressure increase generated by the sinking package (ΔP_0) can be applied to the last perforation in the casing. Flow Q_0 through this perforation can be calculated with Eq. 5-16. This flow will result in the pressure drop (ΔP_1) between the last and next to the last holes:

$$\Delta P_1 = \Delta P_0 - \frac{\rho_f v_0^2}{2},\ v_0 = \frac{4Q_0}{\pi(D_b^2 - D_s^2)} \tag{5-19}$$

where v_0 is the velocity in the well annulus, D_b is the borehole diameter, and D_s is the casing diameter (D_b-D_s is the annulus hydraulic diameter).

Eq. 5-19 is valid if the distance between the holes is larger than the hydraulic diameter of the annulus. This condition is met for the spacing between the holes greater than 1 m (hydraulic diameter 0.11 m).

The cumulative flow in the annulus at the level of the second perforation from the bottom is equal to the sum of Q_0 and the flow through the second perforation from the bottom, Q_1, calculated from Eq. 5-16 using ΔP_1 from Eq. 5-19. This flow will result in the pressure drop (ΔP_2) between the second and third hole from the bottom of the borehole. This is schematically shown in Figure 5-39. The flow through the perforations into the borehole annulus continues until the pressure drop between the adjacent perforations (m and m-1) is zero. This location can be found by solving Eq. 5-16 and Eq. 5-19. The cumulative flow at this location (Q_0+Q_1+Q_2+ … +Q_{m-1}) is equal to the total outflow from the casing into the borehole annulus.

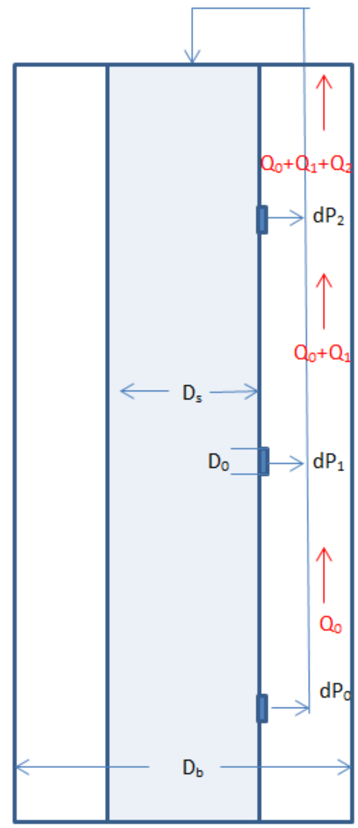


Figure 5-39. Conceptual representation of flow through the borehole annulus.

Estimating Terminal Velocity with Outflow into the Well Annulus

The analytical expression from Bates (2011) for terminal velocity (V_c) assuming closed boundary (unperforated) conditions is:

$$\mathrm{v}_c = \sqrt{\frac{2gl(\frac{\rho_c}{\rho_f}-1)}{[f\left(\frac{1}{D_h}+\frac{1}{D_c}\right)+K_f\}(v_{ratio}+1)^2}}\ and\ \mathrm{v}_{ratio} = \frac{{D_c}^2}{D_h(2D_c+D_h)} \tag{5-20}$$

where D_c is the diameter of package, D_h is hydraulic diameter equal to 2 times the gap between the package and casing, g is gravitational acceleration, l is the package height, ρ_c is the package density, f is friction coefficient, and K_f is form coefficient.

The friction coefficient f can be estimated by iteratively solving implicit equation (Bates 2011):

$$\sqrt{\frac{1}{f}} = 0.862\ ln\left(Re\sqrt{f}\right) * 0.588\ and\ Re^* = \frac{\rho_f l \mathrm{v}_c}{\mu} \tag{5-21}$$

where μ is dynamic viscosity. The closed boundary condition assumes that the water displaced by the package moves entirely upward through the gap. This condition can be described as:

$$\mathrm{v}_f \frac{\pi}{4}\left[(D_c+D_h)^2 - {D_c}^2\right] = \mathrm{v}_c(\frac{\pi}{4}{D_c}^2) \tag{5-22}$$

where v_f is the fluid velocity in the gap.

Equation 5-20 can be modified as follows to account for the constant outflow (Q) into the borehole annulus:

$$v_f \frac{\pi}{4}\left[(D_c + D_h)^2 - {D_c}^2\right] = v_c\left(\frac{\pi}{4}{D_c}^2\right) - Q \tag{5-23}$$

To use this simplified approach, Q should be smaller than the displacement flow through the casing.

The expression for the terminal velocity (v_c') based on Eq. 5-22 is:

$$v_c' = \frac{v_{f*}\left(D^2 - {D_c}^2\right) + Q}{(D^2 - D_c^2)}\ and\ v_{f*} = \sqrt{\frac{2gl\left(\frac{\rho_f}{\rho_f} - 1\right)}{f\left(\frac{1}{D_h} + \frac{1}{D_c}\right) + K_f}} \tag{5-24}$$

The increase in the terminal velocity in the perforated casing is then v_c'/v_c. For example, if Q is equal to half of the flow through the casing assuming a closed boundary, then v_c'/v_c is equal to 1.79.

The estimate of increase in the terminal velocity due to outflow into the well annulus can then be used to adjust the terminal velocity calculated from the numerical model. The terminal velocity calculated from the numerical model with 2-cm gap is 2.0 m/sec (40°C). If outflow into the borehole annulus is half of the displacement flow, the adjusted terminal velocity is 2.0 × 1.79 = 3.58 m/sec.

5.4.4 Casing Perforation Design

The parameters of the casing perforation design are:

- Perforation diameter
- Spacing of perforations
- Total number of perforations (length of perforated interval × # perforations/length)

The casing perforation design should take into account the maximum acceptable increase in the terminal velocity due to leakage through perforations. The analysis below is based on a target limiting terminal velocity of 3.0 m/sec. The increase in terminal velocity is compared to the terminal velocity in unperforated casing with water at 40°C, which is 2.0 m/sec (Table 5-9).

Three different perforation diameters were considered: 1 cm, 2cm, and 5 cm. Eq. 5-15 and Eq. 5-19 were iteratively used to calculate the number of holes that contribute to the outflow into the borehole annulus. The pressure drop in the annulus for these 3 cases is shown in Figure 5-40. The number of holes required to reach zero pressure drop is 22 (5 cm diameter), 76 (2 cm diameter), and 192 (1 cm diameter).

The total outflow from the perforated casing into the borehole annulus is shown in Figure 5-41. The total outflow through the 22 5-cm perforations is significantly greater than the total outflow through 192 1-cm perforations. This results in the higher terminal velocity shown in Figure 5-42.

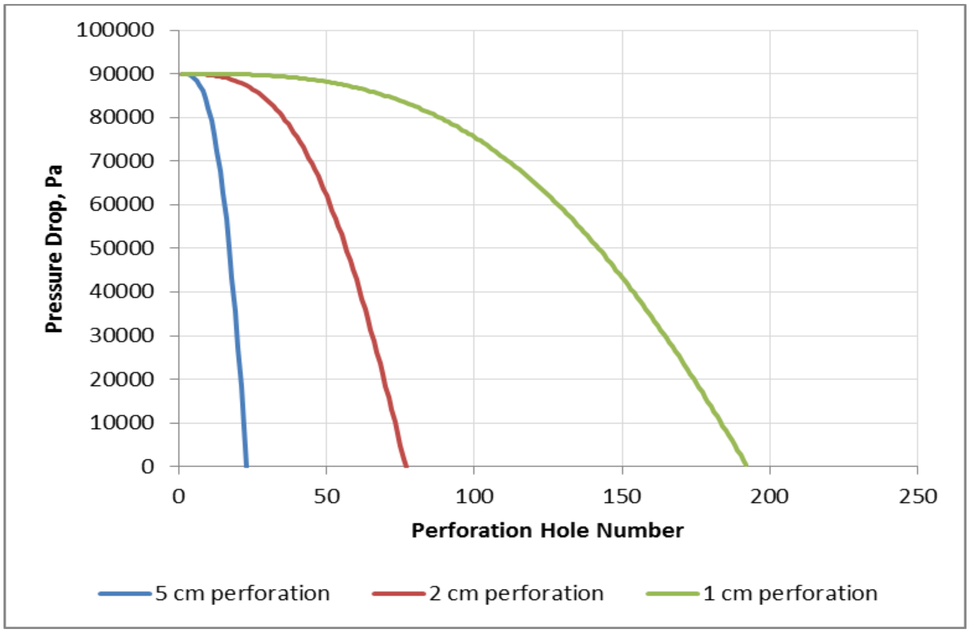


Figure 5-40. Pressure drop in the borehole annulus due to the flow from perforated casing.

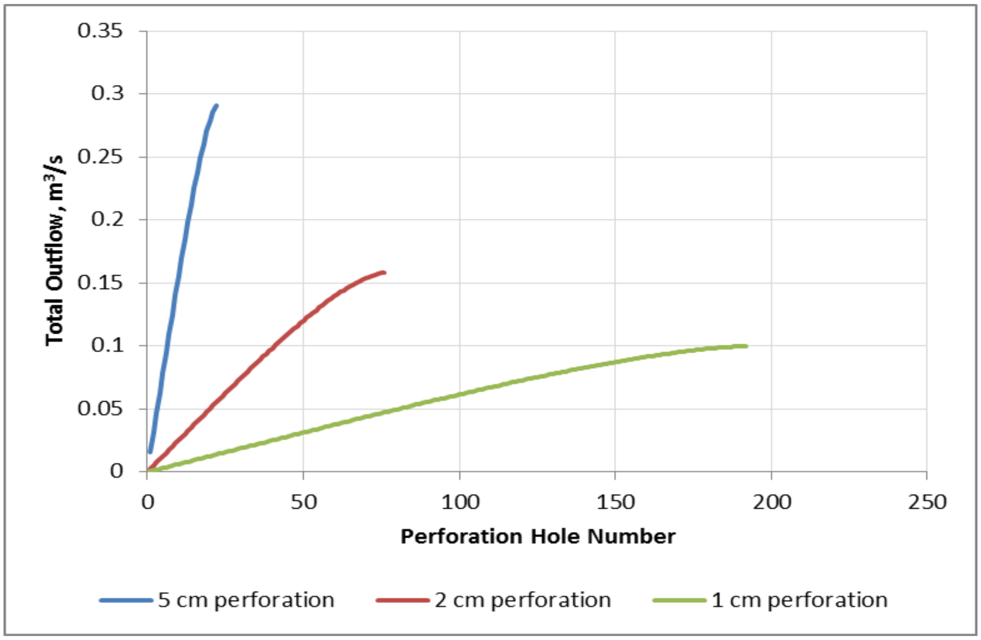


Figure 5-41. Total outflow into the borehole annulus as a function of the number of perforations.

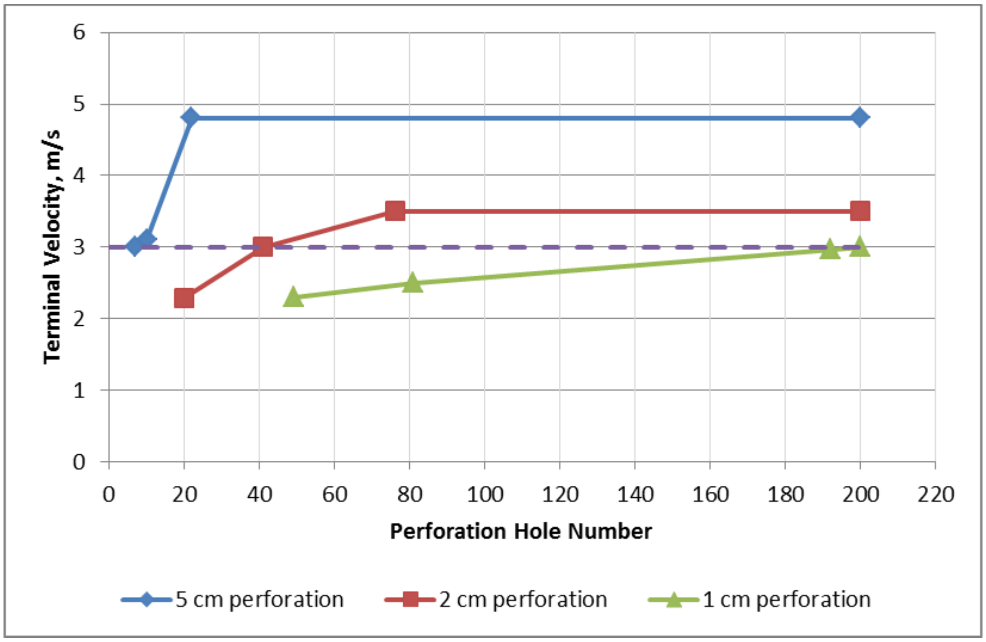


Figure 5-42. Terminal velocity as a function of the number of perforations.

The terminal velocities shown in Figure 5-42 were calculated by multiplying the terminal velocity in the unperforated casing (2 m/sec) by v_c'/v_c ratio calculated from Eq. 5-20 and 5-24 using the total outflow shown in Figure 5-41.

As indicated by Figure 5-42, to limit terminal velocity to 3 m/sec, no more than seven 5-cm perforations should be constructed in the 2 km long guidance casing. The terminal velocity rapidly increases with the number of holes until it reaches 4.8 m/sec at 22 perforations. Additional perforations (more than 22) are predicted to have no impact on the terminal velocity.

For 2-cm perforations, the number should be fewer than 41 (in the 2 km-long guidance casing) to limit terminal velocity to 3.0 m/sec. The terminal velocity increases with the number of holes until it reaches 3.5 m/sec corresponding to 76 perforations. Additional perforations (more than 76) are predicted to have no impact on the terminal velocity.

For 1-cm perforations, the terminal velocity is below 3 m/sec regardless of the number of perforations.

It should be noted that the excessive terminal velocity (e.g., greater than 3.0 m/sec) could be mitigated by leaving a part of the casing unperforated. Because the terminal velocity is reached in a very short time (a few seconds), 30 m of unperforated casing could be sufficient to decelerate a package to the terminal velocity corresponding to unperforated casing conditions.

5.4.5 Comparison with Analytical Solution

A slightly different package was considered by Bates (2011):

- Cylindrical package dimensions: 0.17 m radius and 5.0 m length
- Package mass: 2,000 kg
- Radial gap between the package and casing: 0.0235 m

Terminal velocity in unperforated casing was calculated using an analytical solution (Eq. 5-20), with the result that terminal velocity in water at 20°C would be 2.37 m/sec.

For model comparison, the numerical model described in Section 5.4.2 was reposed using the same inputs, with the result that terminal velocity was calculated to be 1.6 m/sec.

The difference between the analytical and numerical solutions can be explained by the difference in the velocity ratio (v_{ratio} in Eq. 5-20) which is the ratio of the fluid velocity in the gap between the package and casing, to the terminal package velocity. The analytical solution assumes that the velocity ratio is a simple function of the package diameter and the gap size (Eq. 5-20), which is 3.38 for the Bates (2011) analysis.

The numerical solution calculates the velocities in the model domain using the turbulent model (Eq. 5-8 and Eq. 5-9). The maximum fluid velocity in the domain is 10.5 m/sec. The velocity profile calculated for the gap between the package and casing 1 m below the top of the package is shown in Figure 5-43. The maximum fluid velocity in the gap is 7.6 m/sec, with a velocity ratio of 4.75.

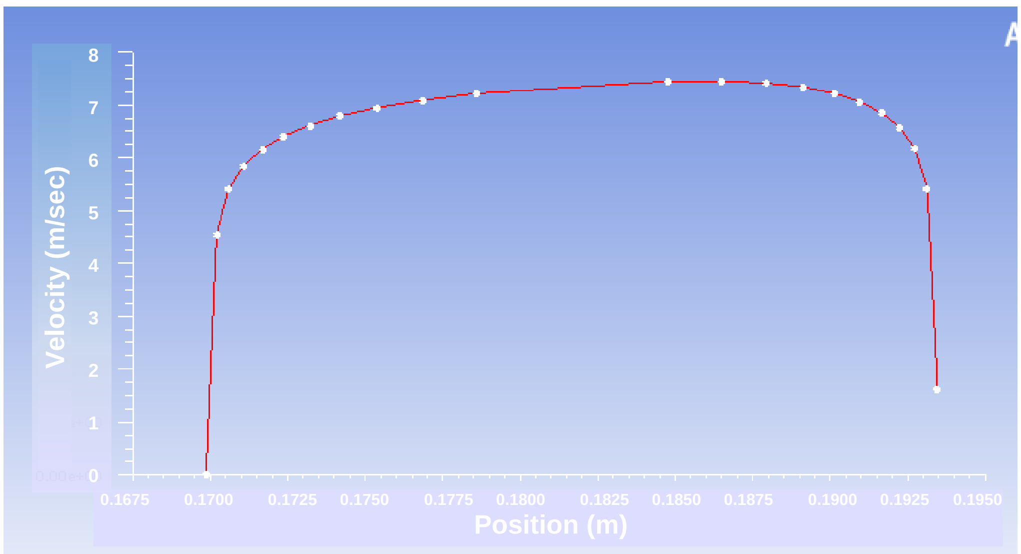


Figure 5-43. Velocity profile (m/sec) in the gap 1 m below the package top.

Using the velocity ratio from the numerical solution in Eq. 5-20 results in terminal velocity of 1.7 m/sec, which is similar to the one calculated with the numerical model. It can be concluded that the analytical model underestimates the velocity ratio in the gap. The other parameters in Eq. 5-20 have significantly less impact on the terminal velocity. This is consistent with the conclusion that pressure drag is the main force acting on the package (Table 5-9).

Figure 5-44 illustrates the relationship between the velocity ratio and the terminal velocity calculated using Eq. 5-20 for the friction coefficient equal to the original value used by Bates (2011) and values 3 times larger and 3 times smaller. The impacts due to different friction coefficients are very small. The impacts from the velocity ratio are significant, especially for the lower velocity ratio.

Figure 5-45 compares the terminal velocities calculated for the different gaps using the numerical model described in Section 5.4.3 and the analytical model (Eq. 5-20). The larger the gap, the closer the analytical solution is to the numerical solution.

5.4.6 Conclusions

Terminal velocity was analyzed using a numerical CFD model, for the reference package size, in unperforated casing filled with water and two brines (NaCl and NaBr), for four temperatures (20°C, 40°C, 80°C, and 120°C). The Fluent SST turbulence model was used in these simulations. Flow around the sinking package is turbulent with Reynolds number ranging from 5.6×10^4 to 7.3×10^5. Turbulence increases with temperature and decreases with density.

The calculated terminal sinking velocity varies with the fluid and temperature:

- Water: 1.95 (at 20°C) to 2.13 m/sec (at 120°C)
- Sodium chloride brine: 1.61 (at 20°C) to 1.79 m/sec (at 120°C)
- Sodium bromide brine: 1.30 (at 20°C) to 1.46 m/sec (at 120°C)

The main force acting on the package is the pressure drag (about 95%). Because the viscous frictional force is relatively small, decrease in viscosity with temperature has negligible effect on the terminal velocity. The terminal velocity increases slightly (by about 10%) at bottom-hole conditions mainly due to lower density.

Because the viscous drag is only 4%-5% of the total force, adding viscosifier additives to the emplacement fluid would have only a minor impact on package terminal velocity.

The reference design has a small gap (less than 2 cm) between the package and the casing. In this condition, the terminal velocity calculated with the numerical model is smaller than the analytical solution. The terminal velocity in the analytical solution is higher because a simple relation used in the solution underestimates the velocity of fluid in the gap. The larger the gap, the closer are the analytical solution and the numerical solution.

An increase in terminal velocity due to casing perforations was estimated from the modified analytical solution. The modified solution includes the total flow that discharges from the casing into the borehole annulus. The total flow is a function of the discharge through the perforations and the pressure loss due to the upward flow in the annulus. This total flow was iteratively calculated for perforation diameters of 1 cm, 2 cm, and 5 cm and used in evaluating the corresponding terminal velocities. Note that this bounding approach has potential for (conservatively) overestimating the increase in terminal velocity due to perforations.

Terminal velocities in perforated casing were calculated in water at 40°C; calculated velocities in brines will be smaller. Importantly, the predicted terminal velocities for unperforated casing (Table 5-9) are low (generally less than 2 m/sec) allowing margin for increases in velocity with perforations.

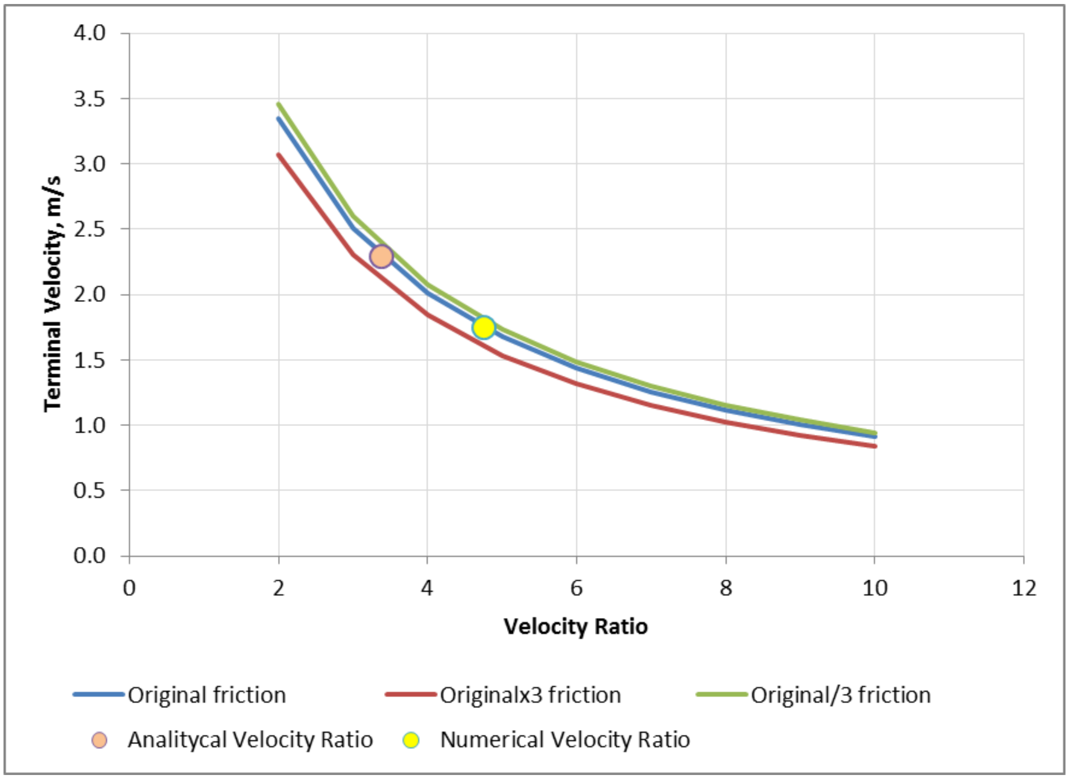


Figure 5-44. Terminal velocity as a function of the velocity ratio.

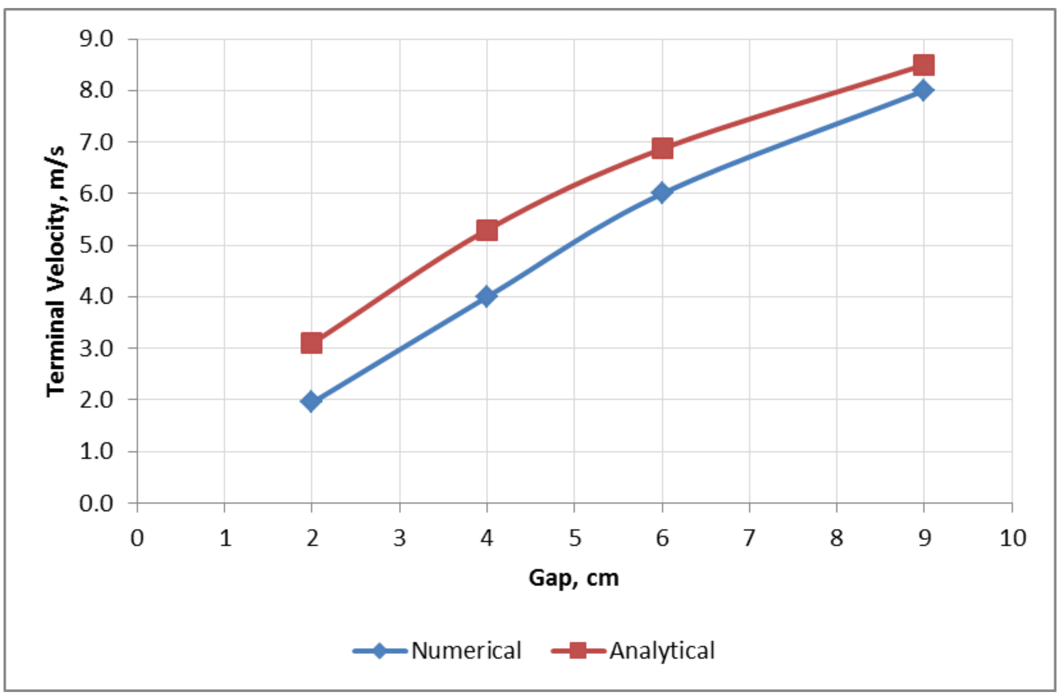


Figure 5-45. Terminal velocity as a function of gap between the package and casing.

For 1-cm perforations, the terminal velocity would be less than the target maximum velocity of 3 m/sec regardless of the number.

For 2-cm perforations, the terminal velocity would be less than 3 m/sec with approximately 40 or fewer perforations, which translates to perforation spacing of 50 m in the EZ (2 km). The maximum terminal velocity would be approximately 3.5 m/sec.

For 5-cm perforations, the terminal velocity would be less than 3 m/sec with seven or fewer perforations, which translates into perforation spacing of approximately 280 m in the EZ. The maximum terminal velocity would be approximately 4.8 m/sec.

The estimated upper limit for terminal velocity in perforated casing is 7 m/sec. This is based on using a gap of 7.6 cm between the package and borehole wall, and produces the result that the casing has little effect on the terminal velocity.

The numerical CFD model does not simulate the six degrees of freedom of package movement. There is a possibility that eccentric packages that slide down one side of the casing, could reach greater terminal velocity especially for large gaps. Also, because it is a steady-state model, it does not predict the time required to reach the terminal velocity, which must be estimated as a low multiple of the time needed to reach the same velocity in free fall (e.g., in air). More accuracy can be obtained with significantly greater computational effort.

5.5 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 5-46) (Noss et al. 2000).

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) based on the discussion above (Section 5.4).

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:

$$\frac{1}{2}MV^2 = \frac{\pi D^2}{4} f_{cr} s \qquad (5\text{-}25)$$

so that

$$s = \frac{2MV^2}{\pi D^2 f_{cr}} \tag{5-26}$$

and deceleration rate is

$$a = \frac{V^s}{2s} = \frac{\pi D^2 f_{cr}}{4M} \tag{5-27}$$

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.

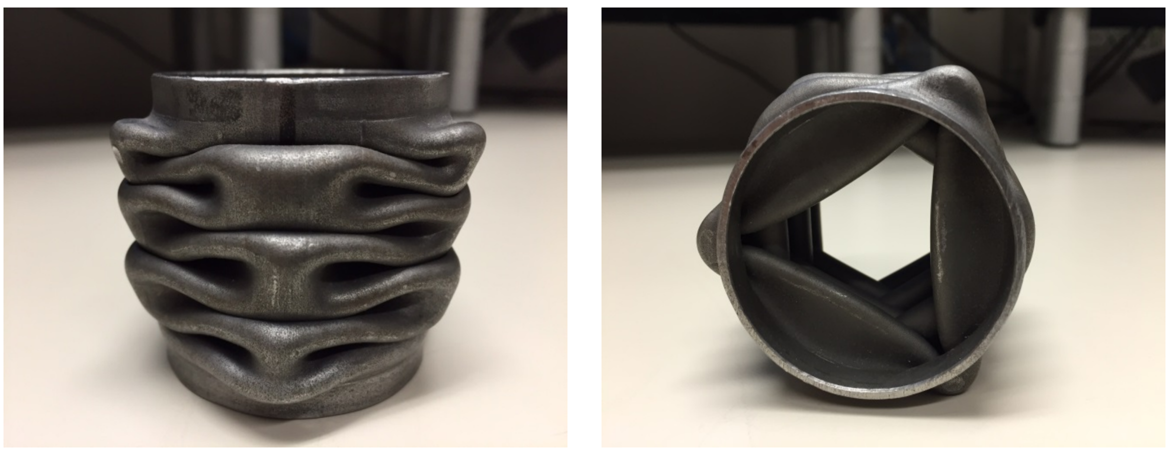


Figure 5-46. Tubular crush box impact limiter, after crushing (provided by Brad Day, SNL).

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).

5.6 Shielding Calculations

The DBFT work scope includes demonstration of handling methods suitable for WPs containing the CsCl or SrF_2 capsules currently in storage at Hanford Waste Encapsulation and Storage Facility. For this shielding analysis it is assumed that the NAC LWT® (or equivalent) Type-B cask would be used to ship packaged Cs/Sr capsules to a disposal site. The LWT cask is currently authorized for transportation of SNF as described in the Certificate of Compliance 71-9225 (NRC 2015). The LWT cask cavity is 178 inches long and 13.4 inches in diameter.

This section provides an evaluation of shielding requirements for a transportation cask or transfer cask, loaded with a package containing Cs/Sr capsules, in order to decrease dose rate below 2.5 mrem/hr assuming capsule radioactivity as of 2016.

The shielding requirements at the borehole location were evaluated using the following assumptions:

- The capsules would be placed inside a package with the outer dimensions compatible with the LWT cask cavity dimensions.
- Each package would contain eight layers of capsules, each layer containing three capsules. The eight layers assumed here are more than the six assumed for thermal calculations in Sections 5.2 and 5.3, because the shielding calculations were based on a slightly different concept for capsule storage and transport (and dose at the ends of the package would be nearly the same for eight and six layers).
- Package materials other than capsule materials can be neglected because no information is currently available. For shielding evaluations, this is a conservative assumption.

Shielding evaluations were performed for the CsCl capsules because they produce greater external dose rates than SrF_2 capsules. The Cs capsules produce gamma rays and bremsstrahlung radiation from beta decay of ^{137}Cs ($t_{1/2}$ = 30.17 years) to ^{137m}Ba ($t_{1/2}$ = 2.5 min), which decays by isomeric transition emitting a 0.662-MeV gamma ray. The decay of ^{90}Sr in the SrF_2 sources produces beta and bremsstrahlung radiation (i.e., short-range radiation).

Cs Capsule Characteristics

Capsule radioactivity varies, e.g., between 2.51×10^4 and 3.42×10^4 Ci as of January 1, 2016. There are three types of Cs capsules with same outer and inner lengths and different wall thicknesses, as shown in Table 5-10. This evaluation used the Type 1 capsules (Price et al. 2015) which is slightly conservative for shielding design.

The design-basis CsCl waste form is melt-cast. CsCl content ranges from 1,286 to 3,247 g resulting in average density within the internal volume of 1.36±0.05 to 3.45±0.11 g/cc at room temperature (Roetman and Randklev 1996). The actual density of capsule contents will vary depending on the initial impurity content and on the formation of barium compounds during radioactive decay. The theoretical density of CsCl is 3.97 g/cc (NASA 1968) and the average void space of capsules is 65% (Jackson 1976). This evaluation assumed 2.7 kg of CsCl (Roetman and Randklev 1996) with a mass density of 2.65 g/cc as the source material. This mass density, which characterizes melt CsCl waste form, maximizes the dose rate at the top of the capsule.

Table 5-10. Materials and dimensions for the CsCl capsules.

Capsule Type	Containment Boundary	Material	Wall Thickness (in./cm)	Outer Diameter (in./cm)	Total Length (in./cm)	Cap Thickness (in./cm)
1	Inner	SS316L	0.095/0.2413	2.250/5.715	19.724/50.09896	0.4/1.016
2			0.103/0.26162	2.250/5.715		
3			0.136/0.34544	2.255/5.7277		
1	Outer	SS316L	0.109/0.27686	2.625/6.6675	20.775/52.7685	0.4/1.016
2			0.119/0.30226	2.645/6.7183		
3			0.136/0.34544	2.657/6.74878		

The photon energy distribution and source strength (Roetman and Randklev 1996) are presented in Table 5-11.

Table 5-11. CsCl radiation source characteristics.

Energy (MeV)	Photons/sec for 37.65 kCi Cs-137	Normalized Energy Spectrum
1.50E-02	3.182E+13	2.342E-02
2.50E-02	1.547E+13	1.138E-02
3.50E-02	1.042E+14	7.668E-02
4.50E-02	4.919E+12	3.620E-03
5.50E-02	3.708E+12	2.729E-03
6.50E-02	2.547E+12	1.874E-03
7.50E-02	1.990E+12	1.465E-03
8.50E-02	1.434E+12	1.055E-03
9.50E-02	1.096E+12	8.066E-04
1.50E-01	3.636E+12	2.676E-03
2.50E-01	7.220E+11	5.313E-04
3.50E-01	1.841E+11	1.355E-04
4.75E-01	7.770E+10	5.718E-05
6.50E-01	1.187E+15	8.736E-01
8.25E-01	2.689E+09	1.979E-06
1.00E+00	2.362E+08	1.738E-07
Total for 37.65 kCi	1.359E+15	
Total for 1 kCi	3.609E+13	

Model

A horizontal cross-section view and a vertical cross-section view of the model used in the shielding calculations are shown in Figures 5-47 and 5-48, respectively. The shielding shown in these figures is not included in the thermal analyses in Sections 5.2 and 5.3 because the shielding is part of the transportation cask or transfer cask, not the WP, and will not be disposed of with the waste.

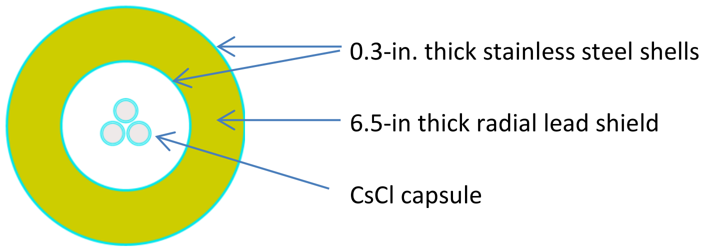


Figure 5-47. Horizontal cross-section view of the model.

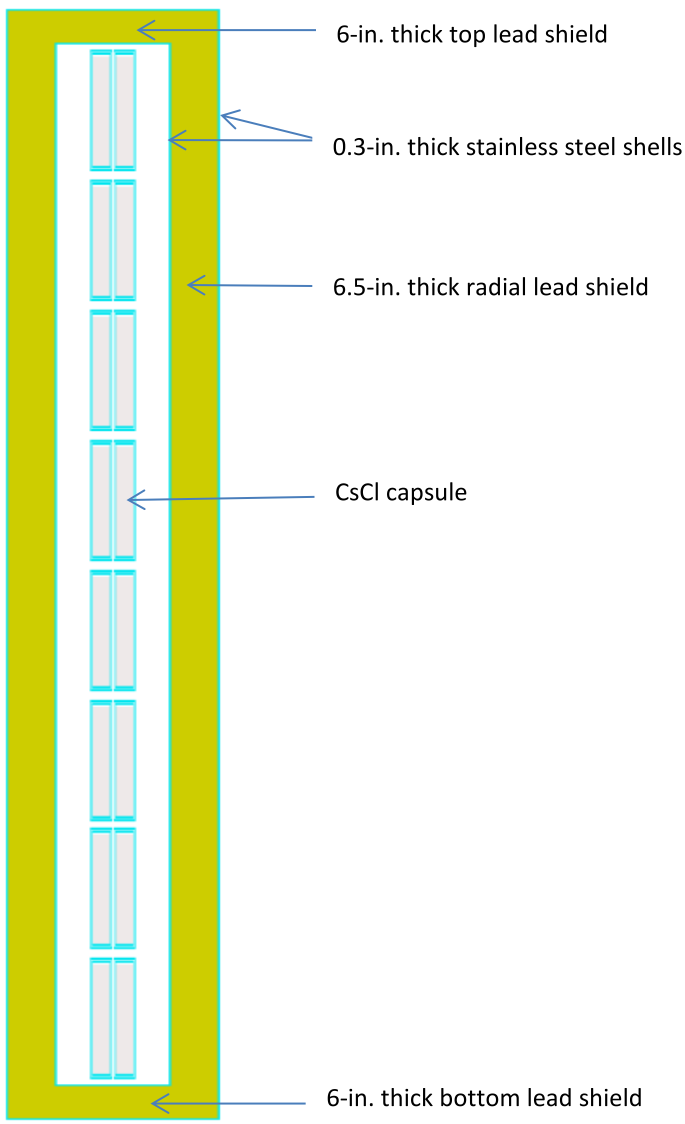


Figure 5-48. Vertical cross-section view of the model (height not to scale).

Method

The dose rate values documented in this report were obtained with MAVRIC in the pre-release version 6.2 of the SCALE computer code system (Rearden and Jessee 2016). MAVRIC is the SCALE Monte Carlo transport shielding sequence with automated variance reduction capabilities. The ANSI/ANS 6.1.1-1977 neutron and photon flux-to-dose-rate conversion factors (ANS 1977) are used in the dose rate calculations. These flux-to-dose-rate conversion factors are typically used in shielding safety analyses documented in safety analysis reports.

Results

Shielding requirements were evaluated based on the maximum activity of any CsCl capsule, of 3.42×10^4 Ci as of January 1, 2016. Three different materials, lead, stainless steel, and tungsten alloy, were analyzed. The shielding material thicknesses required to obtain a dose rate less than 2.5 mrem/h at the shield outer surface are listed in Table 5-12. The dose rate variations as a function of shield thickness for stainless steel, lead, and tungsten alloy are illustrated in Figures 5-49 through 5-51, respectively.

The capsules would be transported inside a WP. However, the waste package/universal canister materials, which would further decrease dose rate, were neglected since a package design is not available at this time. As a result of this approximation, the thickness values presented in Table 5-12 are conservative.

Table 5-12. Thicknesses required for different shielding materials.

Shielding Material		Mass Density (g/cc)	Radial Shield Thickness	Top Shield Thickness	Bottom Shield Thickness
Lead [a]	(cm)	11.3	16.5	15.2	15.2
	(in)		6.5”	6”	6”
Stainless steel	(cm)	7.99	35.6	33.7	33.7
	(in)		14”	13.25”	13.25”
Tungsten alloy [b]	(cm)	17	13.3	12.7	12.7
	(in)		5.25”	5”	5”

[a] Lead encased in 0.3-in. thick stainless steel plates.
[b] Tungsten alloy composition consists of 90 wt% W, 6 wt% Ni, and 4 wt% Co.

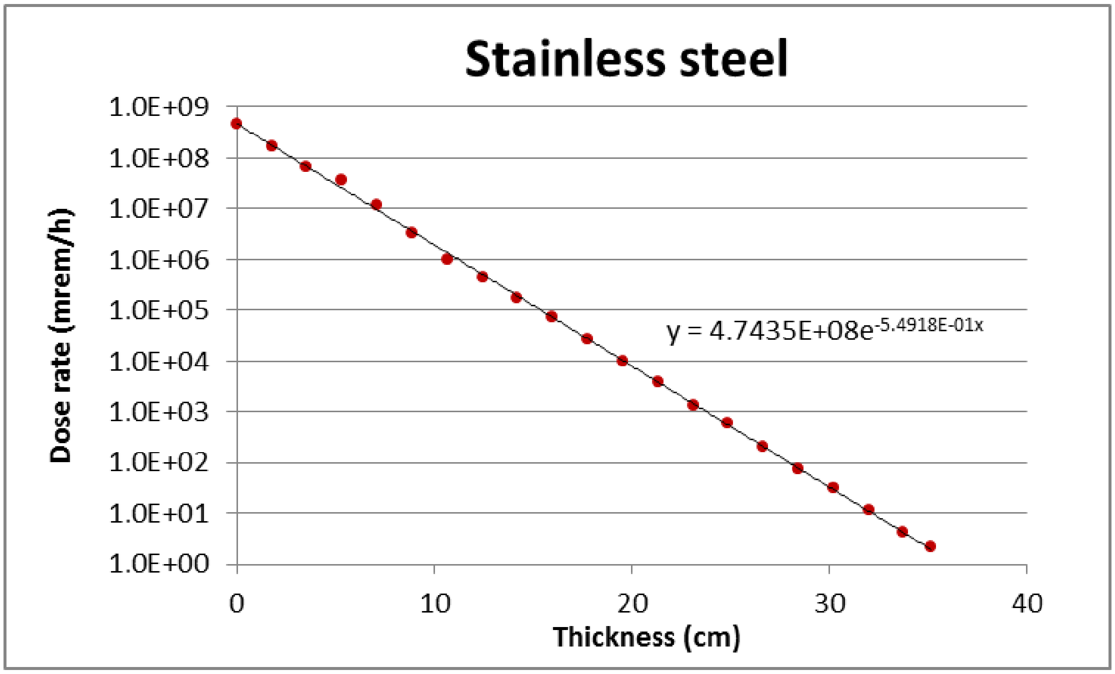


Figure 5-49. Dose rate variation as a function of stainless steel shield thickness.

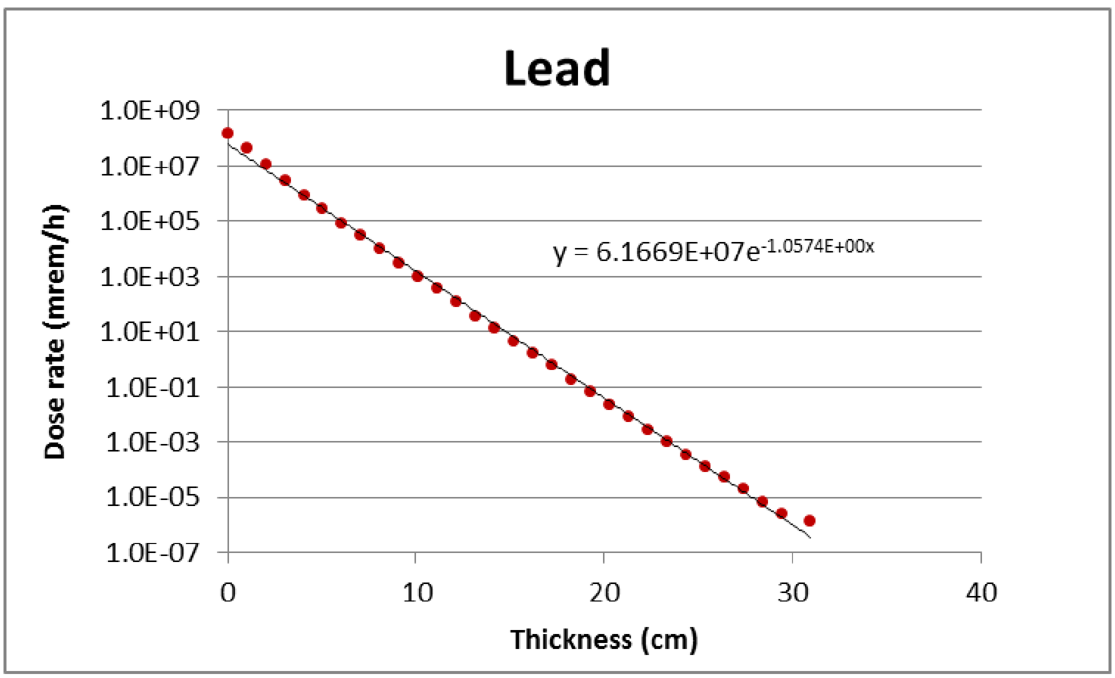


Figure 5-50. Dose rate variation as a function of lead shield thickness.

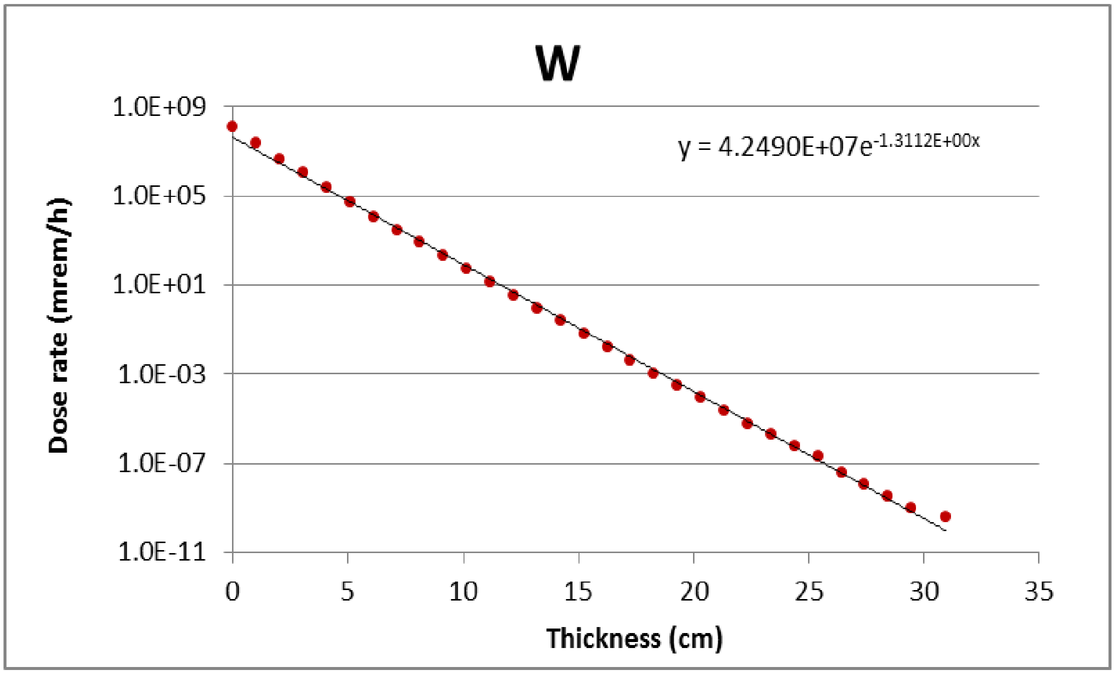


Figure 5-51. Dose rate variation as a function of tungsten alloy thickness.

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6. Discussion and Recommendations

This report documents a conceptual design for the DBFT engineering demonstration, including test packages (not containing waste), downhole instrumentation, a surface handling and transfer system, and a system for emplacing and retrieving of those packages in the FTB. The selections are based on a review of available technologies (Section 2). These systems and components would first be tested in an ITF, then deployed for the field demonstration in a deep borehole to demonstrate the technical feasibility of the deep borehole disposal concept (Section 4).

A conceptual design such as that presented here is one that is shown by limited analysis to be technically feasible and likely to meet requirements. Conceptual design development is part of a process that proceeds in three stages: 1) conceptual design including feasibility studies; 2) preliminary design that includes technical and cost information necessary for final design; and 3) final design sufficient for fabrication or construction. The DBFT engineering demonstration will follow such an evolution.

6.1 Disposal Concept Development

For the DBFT to have demonstration value, it must be based on conceptualization of a DBD system for specific waste forms. This document therefore describes a reference DBD concept (Section 3) to guide selection of options for the DBFT. One major selection is the emplacement mode, i.e., whether packages are emplaced using a wireline or a string of drill pipe (with a drill rig), or using one of several other possible approaches (Section 2.9). The selection of wireline emplacement is supported by the cost/risk analysis described in Appendices A through C.

DBD Safety Case and Conditions

The DBD safety case is summarized in Sections 2.1 and 2.2, which present an overview of the preclosure and postclosure risks that were considered in developing the current reference design concept. Preclosure risks are associated with worker safety, accidents, 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.

Requirements and Assumptions

Sections 2.3 and 2.4 present design requirements and controlled assumptions for both DBD and the DBFT. The requirements represent the engineering challenges associated with future waste handling, transport, transfer, emplacement, and retrieval. They include administrative requirements, functional and operating requirements for handling and emplacement/retrieval equipment, performance criteria, WP design and emplacement requirements, borehole construction requirements, and sealing requirements. Assumptions are identified if they could impact engineering design. The requirements are presented as parallel sets for waste disposal and the DBFT. Requirements that have been identified but not yet fully defined are identified as "TBD" and are tabulated in Appendix D.

Waste Packaging Options

Two basic packaging concepts are presented: 1) flask-type WP for bulk waste, and 2) internal semi-flush type package for canistered waste. The pros and cons of each concept are summarized in Table 6-1. Both types are analyzed in Section 5.1. Suitable materials, connection types, and fabrication services for both are available from vendor offerings to the oil and gas industry.

Table 6-1. Waste package concept pros and cons (AREVA 2016).

Waste Package Concept	Pros	Cons
Flask-Type Concept	• Uses conventional API threads • Joints suited for repeated assembly/disassembly (e.g., more flexibility for rework during package preparation) • Provides a flush exterior surface • Relative ease of manufacturing • A final sealing weld on the fill plug may be possible after waste loading, without post-weld heat treatment, because of the massive end plug • Both top and bottom end plugs would be welded to the tubular section and heat treated prior to waste loading • Fill port could be readily threaded and configured with a metal-metal seal (non-welded final closure)	• API threads require pipe dope • Fill port has reduced diameter and is suited mainly for granular wastes • Welds in the axial load path • Threaded fill plug would require a seal or weld (e.g., welded cover plate or backup threaded connection) for containment
Internal Semi-Flush Concept	• Large opening diameter can accommodate pre-canistered waste • No welds in the axial load path (casing connections will bear axial loads) • Casing connections provide high-performance metal-metal seals for external pressure	• Could require a custom mill run based on material selection • Casing wall thickness may not be sufficient for a threaded fill plug • Fill plug closure design may not allow welding after waste loading • External surface may have shoulders at the casing connections due to external upset in larger sizes, depending on how forging is used in the fabrication process

Disposal Borehole Construction Options

Several options for borehole construction that are important to satisfying requirements for demonstrating emplacement and retrieval in the DBFT were discussed (Section 2.7). This includes directional drilling, diameter/casing plan options, wellhead equipment (such as BOPs), EZ completion options, and sealing/plugging options. Options for completing the EZ vary with respect to how cement is emplaced to anchor the guidance casing to rock and to support the weight of stacks of WPs. These options also address the extent to which the guidance casing is perforated, the type of cementing used, the need to manage thermal expansion of guidance casing and emplacement fluid, and the rate of hydrogen generation from corrosion of the casing.

Emplacement Options

Emplacement method options are summarized in Section 2.9. Wireline emplacement is selected in Section 3.4 and Appendix A as the preferred option for the DBFT engineering demonstration, based on consideration of safety and costs associated with DBD.

6.2 Reference Disposal Concept

The current reference disposal concept is presented in Section 3. It is based on previous work (Arnold et al. 2011; Patrick 1986) but with modifications proposed. The reference disposal concept is intended to guide planning and design of the DBFT engineering demonstration.

Borehole Drilling and Construction

Borehole drilling and construction for the DBFT will be based on currently available technology that can be accomplished at reasonable cost. The goal is to achieve 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). This is described in Section 3.1.

The major changes from the previous reference disposal concept are the type of emplacement fluid, and the method of EZ completion. The previous disposal concept proposed using an oil-based mud for the emplacement fluid, but the current reference concept proposes aqueous brine to better match formation fluid composition. The current disposal concept varies from the previous disposal concept by recommending that cement interval plugs be emplaced by squeeze cementing. The casing would not be slotted, but would have small perforations to manage fluid thermal expansion and gas generation. The effect of this perforation scheme on the terminal sinking velocity of a package dropped in the borehole is analyzed in Section 5.4.

Waste Packages

Waste packages for wireline emplacement would have threaded connections at each end to attach the wireline latch and an impact limiter. These threaded connections would also serve as backup for the fill plug seals within for which the primary function is waste containment. The WP and its attachments would maintain containment integrity under hydrostatic loading plus loads from emplacement and stacking of packages in the borehole. Both the flask-type and internal semi-flush type package concepts would be suitable for DBD, depending on the waste form and whether it has already been canistered.

Numerical stress analysis of the waste packaging concepts (Section 5.1) has generated important insights including

- Compressive stress is greatest, so that yielding will first occur, on the inner surface of the tubular section, for every package concept analyzed. This is controlled by the ratio of OD to wall thickness (D/t), which should have a value less than 12.42 to eliminate buckling (Section 5.1.5).
- 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 (based on hydrostatic pressure).
- For disposal volume efficiency, i.e., to maximize internal volume available for waste, medium-carbon steels with higher yield strength are recommended (Table 2-4).

Dimensions for small, medium and large WPs, based on the Tenaris-Hydril® line of high-strength steel tubing are presented in Table 3-2. For a maximum downhole pressure of 9,560 psi (Table 2-4), and steels that retain 90% of yield strength at the maximum estimated ambient bottom-hole temperature (Section 2.6), the minimum external pressure rating (at ambient surface temperature) to meet FoS = 2.0 would be 21,250 psi. This specification is met for the configurations presented in Table 3-2, as determined from: 1) numerical stress analysis of the tubular and end sections for both the flask-type and internal semi-flush type packages (Section 5.1); and 2) manufacturer's pressure ratings for the casing threads that would be used for attachments on top and bottom. For heat-generating waste at even higher temperature, either a higher grade of casing (e.g., Q125 instead of P110 grade), greater wall thickness, or shallower target depth of disposal application would be needed. Selection of materials for the WP will need to consider containment lifetime of WPs in the expected downhole environment (e.g., hot brine under high pressure).

Transfer Cask and Wellhead Equipment

Section 3.3 describes the equipment recommended for package receipt, handling, emplacement, recovery, and related operations. This conceptual design assumes that the NAC LWT® Type B transportation cask would be used to transport WPs to a disposal site. A double-ended cask is needed to lower packages into a borehole, and a purpose-designed transfer cask is proposed. This approach avoids potential difficulty with licensing a double-ended cask for transportation, and 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, while preserving the ability to control and contain wellbore pressure with the transfer cask attached. The transfer cask would have removable plugs on both ends, and would receive the WP from the transportation cask in a horizontal position. A side latch mechanism (internal to the cask) would hold the WP in place until just prior to lowering in the borehole on a wireline. The wellhead configuration would include a rotating shield plate, and equipment operated remotely within a wellhead shield (including the wellhead with annular BOP, locking wellhead flange, and a mechanism for removing and replacing the lower shield plug). 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 BOP.

Emplacement Method

As described in Sections 2.9.2 and 3.3, the reference disposal concept would use a wireline to emplace WPs one at a time. Commercially available wireline cable systems, logging and sampling tools, and remotely operated release mechanisms, are available (Section 3.4). The cost-risk engineering study used to select the emplacement mode (Appendix A) provided important insights on the reliability of emplacement. The likelihood for any off-normal event that could cause a WP to breach in the borehole, releasing radioactivity, is estimated to be less than 0.002% per borehole with 400 WPs, for wireline emplacement (Table 3-3). This type of reliability is possible with use of an impact limiter on every WP, to mitigate consequences if a package is accidentally released in the borehole and drops to the bottom or onto the top of the most recently emplaced WP.

Normal and Off-Normal Emplacement Operations

For the emplacement mode selection study, equipment failures and human errors were considered that could result in off-normal outcomes. Off-normal events were identified using hazard analysis (SNL 2015) leading to five types of off-normal outcomes involving packages in the borehole. 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.

Another class of off-normal events with potentially significant consequences that was not considered in the emplacement mode selection study, is dropping WPs (or casks containing packages) in air at the surface. Evaluation of hazards from such events may be undertaken during design for the DBFT engineering demonstration, if appropriate.

Disposal System Architecture

System architecture for the disposal borehole, and for waste packaging, handling and emplacement/retrieval, is presented in Tables 3-4 and 3-5. This architecture is intended as a starting point for future design development, functional analysis, project management, and risk analysis activities. It does not include all aspects of borehole drilling and construction, or field site infrastructure, but it does include disposal borehole configuration prior to the start of emplacement. It is presented for the disposal system, with the expectation that the DBFT will fit within the same architecture, possibly with omission of non-essential features.

6.3 Recommendations for the DBFT Demonstration

The scope of the DBFT engineering demonstration is summarized as follows.

DBFT Borehole Drilling and Construction

For the FTB, the emplacement fluid selected will be similar to formation brine, with uniform composition over the full length of the FTB. A conceptual guidance casing perforation scheme for testing predictions of terminal sinking velocity for dropped packages, is described in Section 4.1.

Waste Packages

Test packages used in the engineering demonstration will meet requirements given in Section 2.3.10 and summarized in Table 2.3. Impact limiters and wireline latch fittings will be developed and used on all test packages. Two or more test packages will be fabricated and leak tested. One or more of these will be subjected to drop testing and external pressure testing, with additional leak testing to verify condition, before deployment in the DBFT field demonstration.

In addition, the DBFT will develop the design for a test instrumentation package with a closure that can be opened and resealed in the field (e.g., bolted and not welded), and an instrument module (6-axis acceleration including rotations, plus pressure and temperature) for deployment in the instrumentation package. The instrument module will be used to study the dynamics of motion for a package that has been dropped; the results of this study will support WP design and future preclosure safety assessments. One or more test instrumentation packages and instrument modules will be fabricated and subjected to appropriate testing to verify performance prior to deployment in the DBFT demonstration.

Package Handling and Transfer

All features of the transfer cask and related equipment described in Sections 3.3 and 4.3 will be demonstrated. This includes equipment to be used for package receipt, handling, transfer to the transfer cask, interfacing with the wellhead, and emplacement/retrieval to/from the borehole. In addition to the major features of the system such as cradles, transfer shield, carousel, and shielded wellhead pit, the scope also includes minor features such as trunnions, rigging, shield plugs and related equipment, cask side latches, horizontal transfer equipment, plug handling equipment in the pit, package kneeling jacks, and so on. Many of these details are briefly described in Section 3.3, but all of them will be defined during the DBFT engineering design process.

Emplacement and Retrieval

All features of the wireline system and related equipment for package emplacement and retrieval (Sections 3.4 and 4.4) will be demonstrated. This includes commercially available components such as the wireline cable and winch, cable head, tool string, sheaves, tool string containment tube (i.e., “lubricator” section), and grease tubes. The electromechanical mechanism for releasing packages downhole may be modified from commercial equipment (Sections 2.9 and 3.3.7).

The handling and emplacement equipment used in the DBFT can be simplified, if appropriate to focus available resources on those aspects of emplacement operations that are most risk significant. For example, among the risk insights presented in Appendix A, wireline overtension is particularly risk-significant for wireline emplacement.

An important objective for the DBFT field demonstration is to test the function of impact limiters. They must prevent test package breach on impact (for the free drop test), and also not hang up on the casing or become jammed in the casing after crushing.

DBFT Integrated Test and Field Demonstration

Before the engineering demonstration at the DBFT field site is conducted, an integrated test of the engineered components will be performed. The purpose of the integrated test is to identify and resolve any equipment operability or interface issues at a location with access to shop facilities. Test packages and components of the transfer/emplacement system, including a mockup borehole, crane, and wireline setup, will be brought to the ITF. The integrated test will be the last opportunity for adjustment, modification, and maintenance prior to demonstration at the DBFT field site. It also is an opportunity to check the condition of rented equipment such as the wireline cable, winch, and downhole tools.

6.4 Summary of Engineering Analyses

Several engineering analyses were performed in support of the conceptual design (Section 5), as summarized below.

Waste Package Stress Analysis

Stress analyses were performed for four WP options, two with a nominal OD of 10.75 inches and two with a nominal OD of 5 inches (Section 5.1). These sizes correspond to WPs that could be emplaced in boreholes with the diameters of the FTB and CB, respectively. For each analysis, an external pressure of 9,600 psi was applied over the exterior surfaces and an axial tension force representing the buoyant weight of a string of packages was applied through the top threaded connection.

The stress analyses indicate that to obtain the required FoS of 2.0 at downhole temperature (approximately 10% reduction of yield strength at 170°C) higher yield strength typical of medium-carbon steel would be needed (e.g., P110 and Q125, Table 3-2). These steels are commonly used for oilfield applications. They do require post-welding heat treatment for stress relief and tempering, and the treatment temperatures generally exceed limits for waste forms, so a requirement to avoid heat treatment after loading packages with waste could be important in package closure design. Heat-generating waste could produce WP peak temperature up to 250°C in the borehole environment, with further decrease in yield strength. Either a higher grade of steel (e.g., Q125 instead of P110), greater wall thickness, or shallower target depth of disposal application would be needed.

Thermal Analysis for Heat-Generating Waste

A high-fidelity thermal analysis that included internal details of package construction was conducted to investigate peak temperatures, particularly of the waste form and the WP wall (Section 5.2). The main concern is with package containment integrity prior to permanent closure of the disposal borehole. A medium-size internal semi-flush package suitable for disposal of Cs/Sr capsules from Hanford was selected for analysis of capsules in bundles of three, stacked six high (18 capsules per package). The analysis used actual thermal output of the hottest capsules containing $^{90}SrF_2$, emplaced in calendar year 2050. The annular space between the guidance casing and the borehole wall was filled with cement, and the WPs were embedded in either hydrated bentonite, or brine. For the bentonite case, the maximum temperature at the inner surface of the WP wall was about 220°C (85°C rise), while for the brine case, it was about 210°C (75°C rise). These results show that disposal is possible with this packaging configuration and disposal timeframe, while limiting peak temperature of the WP to 250°C.

Coupled Heat and Fluid Flow

Simulations of coupled heat and fluid flow in a fluid saturated system were conducted using PFLOTRAN, an open-source massively parallel flow and transport model (Section 5.3). An entire array of WPs containing 1,936 Cs/Sr capsules in a single borehole was simulated. Eight cases are presented, varying WP heat output and the type of material filling the casing and the annulus behind the casing. The peak temperature results are consistent with those from Section 5.2. The fluid flow 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.

Terminal Sinking Velocity

Sinking behavior of packages dropping freely in a reference size borehole (similar to the FTB) with unperforated guidance casing, was analyzed using CFD and compared to previously published analytical and experimental results (Section 5.4). With a package diameter of 11 inches, radial gap of 0.79 inches, and package weight of 4,400 lb, terminal (steady state) velocities in the range 1.3 to 2.1 m/sec were calculated depending on fluid density and viscosity (with both properties temperature dependent). The fluids simulated were pure water, NaCl brine, and NaBr brine (with greater density). Importantly, flow resistance is caused mostly by form drag (95% of total drag force) which is sensitive to fluid density but relatively insensitive to viscosity. Viscous drag associated with the amplified upward velocity of fluid in the annulus around the package, was about 5% of the total drag force. This is advantageous for disposal operations because fluid viscosity could be more difficult to control than density in practice.

The simulation results were extended to estimate the effects from perforations in the uncemented guidance casing, on terminal sinking velocity (Section 5.4.3). The main concern is increased sinking velocity from bypass flow around the sinking package, through the annulus behind the casing. The results indicate that terminal velocity is sensitive to both the diameter of perforations and the total number, especially the number ahead of (below) a sinking package. The total number of perforations could be important because the elevated pressure ahead of a sinking package would be transmitted rapidly throughout the entire wellbore (i.e., the pressure wave would travel much faster than the package). Bypass flow through all perforations ahead of a sinking package could significantly increase sinking velocity, and therefore limit the number of perforations. For example, according to the analysis, to limit terminal velocity to 3 m/sec a maximum of seven 2-inch perforations would be allowed over the entire 2-km EZ. Testing such predictions is an important aspect of the DBFT engineering demonstration.

Impact Limiters

Impact limiters would be an important part of the operational safety strategy for wireline emplacement of WPs, as noted above. Analysis of impact limiter performance (Section 5.5) indicates that an impact limiter that is 28 cm long could arrest a WP sinking at 2.5 m/sec, with average deceleration rate of 2.3 g. Shorter impact limiters could be possible, with greater deceleration rate, because the WPs would be robust. Section 5.5 offers an example of impact limiters with tubular configuration, made from resistant material that could function at downhole pressure and temperature, while filled with emplacement fluid. The analysis also shows that impact limiters designed to arrest single packages would be fully crushed one by one during emplacement as additional packages were stacked.

Energy Needed for Package Breach

The energy needed to breach a WP in the event of a WP drop was also analyzed (Section 5.6). Results indicate that drops of more than one package moving at terminal velocity could produce significant yielding in a target package. The occurrence of yielding was adopted as a surrogate for large deformations likely to cause package breach. These results were used in the emplacement mode study to discriminate between consequences from dropping a single package, vs. dropping a string of packages threaded together possibly with a string of drill pipe attached (Appendix A).

Shielding

A shielding analysis was performed to estimate the shielding needed for a transfer cask to handle WPs loaded with Cs/Sr capsules as discussed above (Section 5.7). Packages loaded with Cs capsules were analyzed because they emit penetrating gamma radiation. The results indicate that worker dose rates could be maintained at less than 2.5 mrem/hr with shielding comparable to what is used on the existing LWT transportation cask. For a stainless steel transfer cask the top and bottom shield plugs would be 13.25 inches thick, and the cask wall would be 14 inches thick. These results were calculated using Cs capsule activity in 2016, so a reduction in dose (or substantial reduction in thicknesses) could be realized if disposal operations take place much later (e.g., calendar 2050 as assumed for thermal analysis).

6.5 Further Recommendations

The most important recommendations of this study concern the conduct of the DBFT engineering demonstration: 1) emplacement zone completion and 2) WP transfer and wellhead equipment. With respect to emplacement zone completion, it is recommended that the emplacement fluid be brine, which for a disposal borehole would have ionic composition similar to formation fluid to promote return of the natural salinity gradient after borehole closure. The casing in the EZ would have small perforations (Section 4.1). Full-scale investigation of terminal velocity behavior in perforated casing is needed for model development and validation.

With respect to WP transfer and wellhead equipment, an application-specific concept is proposed to move packages from a transportation cask to the borehole. In this concept the transfer cask, wellhead and related equipment become part of the pressure envelope for well control, capable of managing a borehole pressure "kick" without resort to BOPs that could damage packages or wireline tools, or sever the wireline. The need to maintain well control was assumed for concept development. Specific requirements for DBFT demonstration in the FTB (or other borehole) need to be determined for design to progress, such as whether a BOP is needed and what type, and pressure ratings for well control capability.

Special emphasis is also recommended on major design elements of the DBFT demonstration including:

- Design and testing of both flask-type and internal semi-flush test packages would maximize the extent of experience gained, and address packaging requirements for a full range of possible waste forms.
- Design of WP fill port closures, such that they do not require heat treatment to achieve necessary strength and containment (Sections 2.6 and 3.2). Final sealing welds on fill plugs are discussed in Sections 2.6 and 3.2, but may not be possible given other requirements. Alternatives include metal-metal seals, which could be sufficient but require additional fabrication (e.g., special threads).
- Modification of an existing remotely operated electromechanical release mechanism for release of packages on the bottom, and retrieval from the bottom (Section 3.3). The mechanism should also be capable of releasing a package under full load for the free-drop test planned as part of the DBFT demonstration.
- Design of impact limiters to achieve needed performance without contributing to getting packages stuck on trips in (not snagging) or after impact (Sections 2.6, 3.2, and 5.5).
- Developing a test instrumentation package and instrument module (Section 4).
- Design of surface handling and transfer equipment to demonstrate shielding and other safety measures, and to meet well pressure control requirements.

Other system enhancements for a DBD system are discussed and listed in Section 3.7, and are recommended to be addressed in the DBFT to the extent practical.

References for Section 6

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Appendix A. Emplacement Mode Design Concept Selection Cost-Risk Study

This appendix describes a study done to support the selection of an engineering concept for emplacement of WPs for DBD. The same emplacement concept is then planned to be tested in the DBFT. The appendix describes the methodology used for evaluating and comparing two alternative concepts (Section A.1), model inputs (Sections A.2 through A.4), initial results (Section A.5), and sensitivity analyses (Section A.6).

A.1 Approach and Methodology

Probabilistic risk analysis (PRA) and multi-attribute utility analysis (MUA) (Clemen 1997; Keeney and Raiffa 1976) provide the methods used in this evaluation. These approaches promote a transparent, rational, and defensible analysis that is easy to explain and communicate. MUA methods in particular have been used by the DOE and other entities in the public and private sectors for decades to provide logically consistent analysis of options that are intended to achieve more than one objective where no single option dominates the others on all of those objectives (e.g., Merkhofer and Keeney 1987; SNL 1991; Younker et al. 1992; BSC 2003).

A.1.1 Study Steps

Multi-attribute utility analysis is straightforward in concept. Three steps are typically followed to frame the analysis: 1) identify a set of objectives that an “ideal” alternative would achieve; 2) define a set of performance measures that provide a clear definition of each objective; and 3) identify or define alternatives that should be considered. Although most studies, including this one, start with alternatives already defined, careful attention to the identification of fundamental objectives and how initial alternatives perform often lead to improvements to those alternatives, or even to the identification of new alternatives (Hammond et al. 1999).

Once alternatives, objectives, and performance measures have been clearly defined, each alternative is evaluated using the performance measures. Then, if necessary, the performance of each alternative and the objectives are combined using a value model to create a single metric that can be used to compare the alternatives and make a recommendation. If a value model is necessary to select a preferred option, there are additional steps required to assess decision-maker preferences, the relative importance of achieving each objective, and the tradeoffs they are willing to make among those objectives.

For this evaluation, it was not necessary to include a formal combination of outcomes with decision-maker specified tradeoffs in order to come to a conclusion (i.e., a value model). Rather, a probabilistically weighted cost was developed for each alternative, and compared with other metrics such as the probability of radiological releases, to support a decision basis.

The final step is to use the result of the evaluation to make a recommendation for which alternative will best meet the objectives that were considered in the evaluation. Figure A-1 illustrates the steps in an MUA as they were applied for this Engineering Design study.

The overall process includes feedback between the first five steps illustrated; indeed, a key benefit of the approach is that it allows and promotes design modifications that enable each alternative to better meet decision-maker objectives. In particular, Sections A.1.3 and 3.7, and Appendix B describe some of the engineering concept modifications identified during this study.

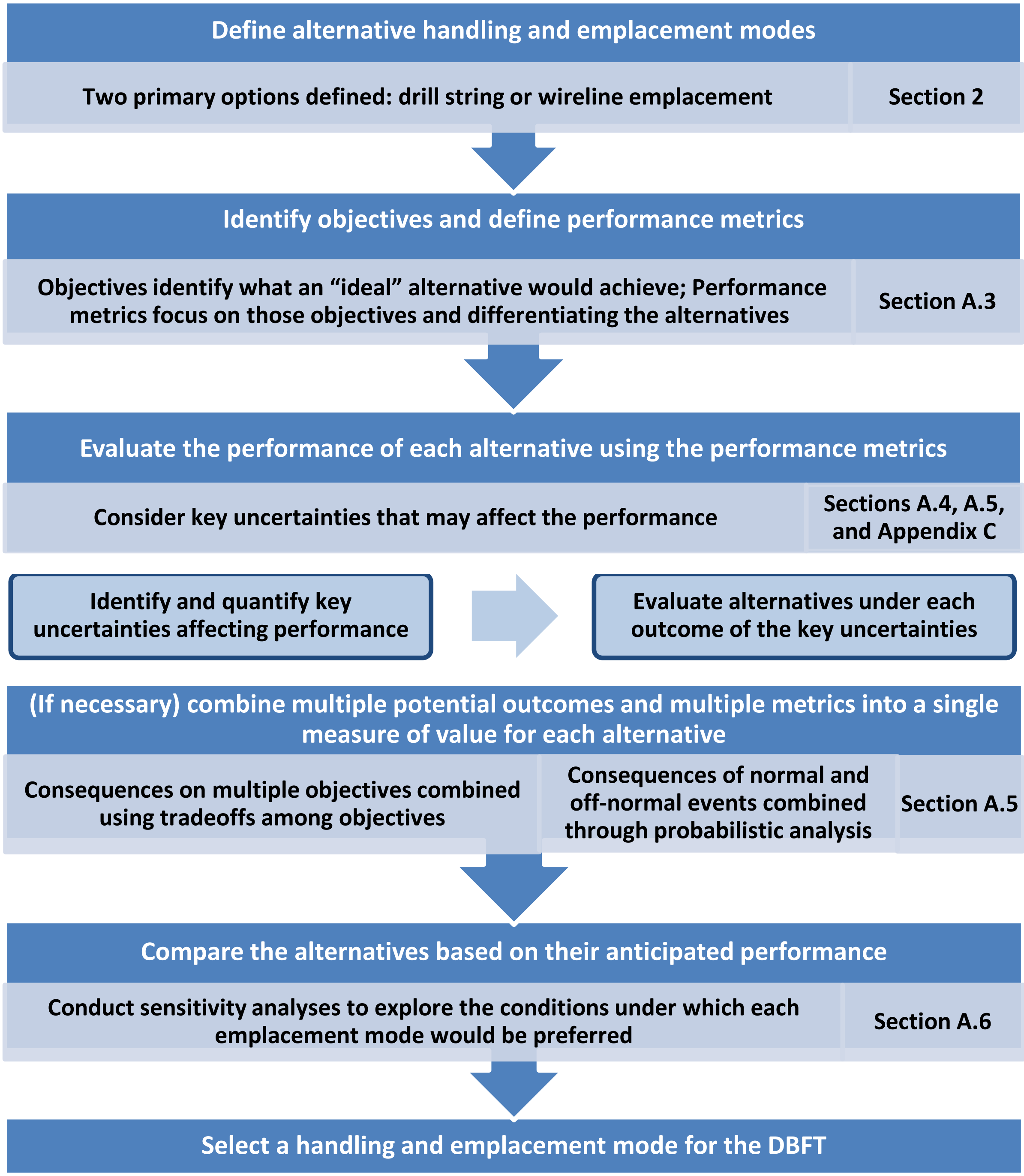


Figure A-1. Steps in the engineering design selection study.

A.1.2 Uncertainty in Performance

In addition to logical analysis of alternatives considering multiple objectives, this study also required explicit consideration and logical treatment of uncertainties. Again, decision analysis and related tools provide approaches for logical decision making under uncertainty (Morgan and Henrion 1990). The most rigorous approaches involve identification of each critical uncertainty, assessment of the probability of every possible outcome of each uncertainty, and then an assessment of the performance of each alternative under each of those possible outcomes using all relevant objectives and performance measures. Section A.4 and Appendix B describe how various uncertainties were addressed in this analysis, using sensitivity analysis and the principles of decision analysis and probabilistic risk analysis (PRA).

A.1.3 Expert Panel Input

Preliminary estimates for many of the steps and inputs outlined in Figure A-1 were developed by project staff, including detailed engineering background (Hardin 2015; Su and Hardin 2015); descriptions of the alternatives to be compared (Cochran and Hardin 2015); objectives, metrics, and analysis assumptions (Jenni and Hardin 2015); hazard analysis (Sevougian 2015); and preliminary cost estimates for both normal and off-normal operations (Appendix C). Many of these initial data were subsequently modified and the final data are provided in this report.

To bring a broader perspective to the analysis and to engage expertise in drilling and wireline operations to help quantify the risks of each mode, a panel of experts was convened to review and update these preliminary inputs. Panel members are listed in Table A-1, and were chosen to represent a cross-section of experts in drilling and wireline operations, nuclear equipment and operations, risk and reliability analysis, and other related areas. All panel members received the preliminary documents described above, and participated in a short introductory conference call describing those materials and the purpose and agenda for an expert workshop. They then met for three days in a facilitated workshop to walk through all aspects of the analysis. During the workshop panel, members provided critical review and updates for all the preliminary inputs including:

- Description of the two alternative emplacement modes. During this process the panelists identified a number of modifications to the initial designs for each mode that significantly reduced the risks associated with emplacement. These concept modifications are listed in Section 3.7, and several were incorporated in the descriptions of the emplacement modes in Section 2.9 and elsewhere.
- Hazard analysis to identify what can “go wrong” during emplacement. The panel reviewed and updated this analysis, including identifying and categorizing basic events in the fault trees into roughly order-of-magnitude groupings based on estimated probability of occurrence; those inputs are reviewed in Section A.4 and Appendix B.
- Steps that could be taken if a WP becomes stuck in the borehole during emplacement (“fishing”), and the probabilities for different fishing outcomes. Those inputs are reviewed in Section A.5.
- The potential for radiological exposures, occupational safety, costs, and delay of operations for each identified outcome. Those inputs are also reviewed in Section A.5

Table A-1. Expert panel and supporting resources.

Name	Role	Representing	Location
Doug Blankenship	Panelist	Sandia National Laboratories	Albuquerque, NM
Sven Bader	Panelist	Areva Federal Services	Charlotte, NC
Scott Bear	Panelist	Areva Federal Services	Seattle, WA
John Finger	Panelist	Sandia National Laboratories (consultant)	Albuquerque, NM
Courtney Herrick	Panelist	Sandia National Laboratories	Carlsbad, NM
Mark MacGlashan	Panelist	Sandia National Laboratories (consultant)	Long Beach, CA
Frank Spane	Panelist	Pacific Northwest National Laboratory	Richland, WA
Nelson Tusberg	Panelist	Leitner-Poma Ltd.	Grand Junction, CO
Andrew Clark	Analyst	Sandia National Laboratories	Albuquerque, NM
John Cochran	Engineering Support	Sandia National Laboratories	Albuquerque, NM
Paul Eslinger	Engineering Support	Pacific Northwest National Laboratory	Richland, WA
Ernest Hardin	Project Lead	Sandia National Laboratories	Albuquerque, NM
Karen Jenni	Facilitator and Analyst	Insight Decisions, LLC (consultant)	Denver, CO
Steve Pye	Engineering Support	Sandia National Laboratories (consultant)	San Juan, WA
Jiann Su	Engineering Support	Sandia National Laboratories	Albuquerque, NM
Allen Croff	Observer	U.S. Nuclear Waste Technical Review Board	Arlington, VA
Eric Wang	Observer	China Nuclear Power Engineering Co.	Beijing, China

A.2 Emplacement Mode Design Aspects Evaluated

Many aspects of the DBD concept have been sufficiently well-defined that no comparative evaluation of options is necessary (see Section 3). However, the emplacement methods described in Section 2.9 are viable, and the study described here was undertaken to support a selection for the reference DBD concept and for the DBFT.

The analysis focused exclusively on the potential differences between the alternatives, specifically those that might be discriminating. Key assumptions and findings included:

1) Issues other than the emplacement mode are irrelevant to this study (e.g., this study does not address issues such as comparing deep borehole disposal to other disposal methods).
2) Many aspects of the disposal process are identical between the alternatives and thus need not be evaluated, for example:
    - All operations leading to the transfer of a WP to the top of the disposal borehole, such as:
        - Drilling the disposal borehole: the number and characteristics of boreholes that would be used for the two alternatives are assumed to be identical, so the costs and risks associated with drilling and construction are not pertinent to the analysis. Drilling costs would differ only if one alternative required more boreholes than the other.
        - Packaging and transportation of radioactive waste to the disposal site, and receipt of casks.
        - Transfer of WPs to the borehole, ready for emplacement.
    - All operations after emplacement of the last WP in a borehole, including:
        - Setting of cement plugs and seals.
        - Closure and monitoring of the disposal facility.
3) The principal differences between the alternatives that are relevant in this analysis are:
    - Use of impact limiters. The wireline method would emplace one package at a time, and if a package were dropped accidentally, an impact limiter fixed to the bottom could readily absorb the kinetic energy on impact, avoiding breach conditions.
    - Use of downhole instrumentation during emplacement. The drill-string emplacement concept includes an instrumented, non-waste-bearing “lead package” as part of each WP string emplaced. This lead package would allow for monitoring of downhole conditions during emplacement. It would also include a designed weak point between the lead package and WPs, to make it easier to remove a string of WPs in the event the lead package gets stuck during emplacement.
    - Number of WPs emplaced per “trip.” In wireline emplacement, WPs are placed one at a time; in drill-string emplacement multiple WPs are connected together and lowered to the EZ as a string. This difference leads to several important distinctions:
        - Wireline emplacement would require many more “trips” in and out of the borehole to emplace the same number of WPs.
        - Drill-string emplacement would require many connections between packages, and between stands of drill pipe, to be made before a trip is completed.

  - Drill-string emplacement leads to much heavier loads being lowered into, and hoisted out of the borehole. At maximum, the load would equal the weight of 40 WPs plus the drill pipe itself. The possibility of dropping such a load produces a higher likelihood of breaching a WP.

- These differences may lead to different outcomes or consequences for each alternative, and are important to consider when comparing the potential performance of each.

A.3 Objectives and Performance Measures

As discussed above, PRA and MUA have been used extensively for more than 30 years to support a variety of decisions including some related to nuclear waste management. As a result, a great deal of information already exists on the objectives that have been considered relevant for nuclear waste management decisions. Objectives used in previous studies were reviewed, focusing on those that have the potential to differentiate between modes. Table A-2 summarizes that review and identifies objectives that are relevant to the comparison of DBD emplacement modes.

For objectives determined to be directly applicable to this analysis, and potentially discriminating, performance measures (metrics) were developed. Metrics provide an unambiguous “scale” for estimating how well each alternative performs against each objective, defined in terms that can be evaluated by technical experts and can be compared meaningfully by decision-makers.

Table A-2. High-level objectives considered for use in comparing emplacement modes.

Objectives	Relevance to Evaluation of Emplacement Modes
Health and Safety Impacts May include impacts to the public and/or to workers, from radiological exposures and/or from other hazards (e.g., transportation, occupational), from hazards encountered during normal operations, during off-normal operations, and/or after emplacement operations are complete	Considered through criteria for radiological releases. Workers and the public will not be exposed to significant radiological risks during normal operations, or off-normal operations if a remote disposal location and appropriate engineering measures are used. Post-emplacement risks will not differ based on emplacement mode.
Costs May include DOE costs and costs potentially covered by the nuclear waste fund (including facilities capital costs, operational costs, and impact mitigation/compensation costs), additional costs borne by utilities (e.g., for on-site waste management and impacts on utility operations), costs to other Federal or State Agencies (e.g., DOE Defense program)	Considered through costs for emplacement activities, including costs associated with addressing off-normal events. All other costs are the same for all emplacement modes, including costs for transportation of wastes to the site, drilling the emplacement boreholes, closing the boreholes and any long-term monitoring required.
Timeframe for Disposal of Target Waste Streams May include time to first disposal and/or time required for full disposal of all relevant waste streams	Considered through time required to dispose of a set quantity of waste, both through normal operations and with the potential occurrence of off-normal events.
Ability to Meet Waste Acceptance Criteria May include criteria related to the timely acceptance of waste for disposal, the feasibility of developing and deploying the required technologies, the rate at which wastes can be emplaced and/or the total amount of waste that can be emplaced.	Non-discriminating between options considered because disposal throughput and disposal capacity are determined externally, and the required technologies are readily available.
Environmental Impacts May include impacts during operations and after closure, reversible and/or persistent ecological impacts, aesthetic impacts, and/or archaeological, historical, and cultural impacts.	Considered indirectly through criteria related to potential radiological releases during off-normal events. Otherwise, environmental impacts are site-specific and will be the same for normal operations and the post-emplacement period for any emplacement mode. Environmental impacts could differ primarily if off-normal events occur.

Objectives	Relevance to Evaluation of Emplacement Modes
Institutional Considerations May include impacts and factors related to the public acceptability of the waste disposal solution, public confidence in the waste management program, temporal and geographic equity, impacts on special subpopulations, etc.	Considered indirectly through radiological consequences associated with off-normal events. Otherwise, many of the institutional considerations are site-specific and will be the same for normal operations and for the post-emplacement period for any emplacement mode.
Flexibility to Accommodate an Uncertain Future May include criteria related to retrievability and/or reversibility, ability to modify the disposal approach in response to technical, policy, and/or regulatory changes	Not considered because these criteria do not differentiate among emplacement modes.
Social and Economic Impacts Impacts may be positive or negative. May include criteria related to public anxiety and nuclear-related stigma, costs to the host community of any anti-nuclear activities, local employment benefits and/or payments to host community	Not considered because these criteria do not differentiate among emplacement modes. Social and economic impacts would be associated with the disposal facility, but differences in those impacts between emplacement modes are believed to be negligible.
Other Management Considerations May include criteria related to DOE, Utility, and/or other Governmental management and control requirements; factors related to safeguards and security both during operations and after emplacement	Not considered because these criteria do not differentiate among emplacement modes. Most other management considerations typically evaluated would be relevant to a comparison of sites, or to a comparison of deep borehole disposal to other disposal options, but they would not be significantly affected by the choice of emplacement mode.

Based on a review of commonly-used high-level objectives (Table A-2) and considering the key differences between emplacement modes outlined above and discussions with the expert panel described in Section A.1.3, three metrics were identified for use in this analysis:

1) Radiological releases, measured using a yes/no metric on whether detectable levels of radiation would be found. As discussed below, this is a significant simplification of potential consequences that could be associated with the breach of a WP. This simplification makes the analysis more tractable but means that if this factor becomes a critical element that discriminates between options, further analysis of the more detailed consequences may be warranted.

2) Total cost to emplace 400 WPs (the anticipated number of WPs that would be disposed of in a single deep borehole), as measured by the total costs of handling and emplacement. The estimates include any opportunity costs of lost disposal capacity, i.e., costs to dispose of remaining WPs in a different borehole.

3) Total time required to emplace 400 WPs. This metric is set by assuming the rate at which WPs can be delivered to the disposal site. Although this rate is important for costing of

normal operations, it may not be discriminating between emplacement options because the rate would be determined by system capacity upstream of the disposal operations. Time required to address or remediate off-normal operations is also considered.

A fourth possible metric, occupational safety, was also considered. Occupational safety risks during normal operations are assumed to be consistent with standard practices in oilfield operations and nuclear materials handling. That is, surface operations performed by workers, for either emplacement mode, would be either essentially the same as tasks performed: 1) at boreholes throughout the oil and gas industry, or 2) in handling packaged nuclear materials such as is done at licensed near-surface disposal facilities. In addition, rigorous safety procedures would be followed and expected worker injuries would be very low under both emplacement options, so “normal” occupational safety risks were determined not to be discriminating between the options. It was also noted that the greatest radiological risks to workers would mainly be a function of whether radiological releases occur from breached WPs, so the performance metric of “radiological releases” also provides information on the potential for risks to workers. The exclusion of normal occupational risks (which are non-discriminating) does not imply that worker risks are irrelevant to DBD operations or the DBFT.

A.4 Uncertainties Affecting Performance

Each emplacement mode being considered has the potential to perform differently on each of the three performance metrics identified above. However, evaluating how each emplacement mode performs is complicated by uncertainties:

- Uncertainty about whether operations will proceed as planned, and if not then:
  - Uncertainty about what can go wrong and the probabilities for off-normal events
  - Uncertainty about the capability to mitigate the consequences of off-normal events
- Uncertainty about the costs, timing, and occupational safety for normal operations.
- Uncertainty about the impacts from off-normal events, in terms of radiological releases, occupational safety risks, and the time and/or cost to mitigate or remediate these events.

Each type of uncertainty was addressed in this analysis.

A.4.1 Uncertainty About the Occurrence of Off-Normal Events

The questions of what can go wrong during emplacement, how likely those off-normal events are, and what would be done in response to those events are the primary concerns and uncertainties in this evaluation. Appendix B describes a hazard analysis developed to identify off-normal events importance to performance, and quantify the likelihood of occurrence of each of those events.

The hazard analysis identified four key “top level failures” that have the potential to lead to adverse consequences. Table A-3 shows those top level failures for each emplacement mode. Each of these is of concern because it leads to costs and lost-time impacts, and to the potential for a WP to be breached and radiological release to occur.

Table A-3. Off-normal events considered for each emplacement mode.

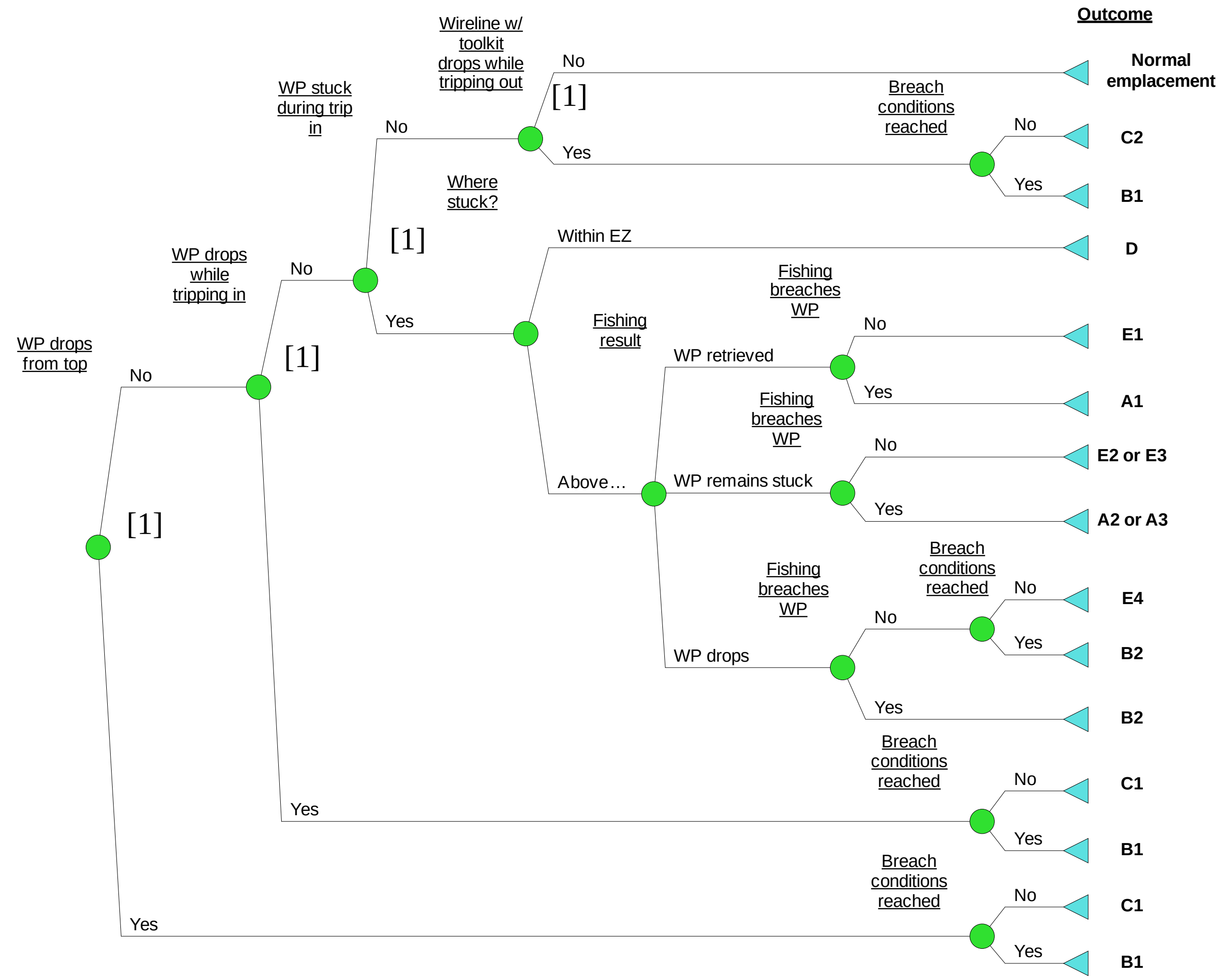
Wireline Emplacement	Drill-String Emplacement
Drop waste package from surface	Drop packages while assembling WP string
Drop waste package during trip in	Drop string and packages tripping into hole
Waste package gets stuck	WP/drill string get stuck during trip-in
Drop wireline during trip out	Drop drill string on WPs during trip-out

Other potential off-normal events were identified and discussed with the expert panel (Section A.1.3). Some of these were adopted, especially to define uncertainties related to stuck packages and fishing, while others were determined to not be material to the comparison of emplacement modes, and deferred for possible future study.

If any one of the off-normal events identified in Table A-3 occurs, uncertainty remains about what would happen next. Figures A-2 and A-3 show event trees that summarize the sequence of events that would follow occurrence of any one of the off-normal events.

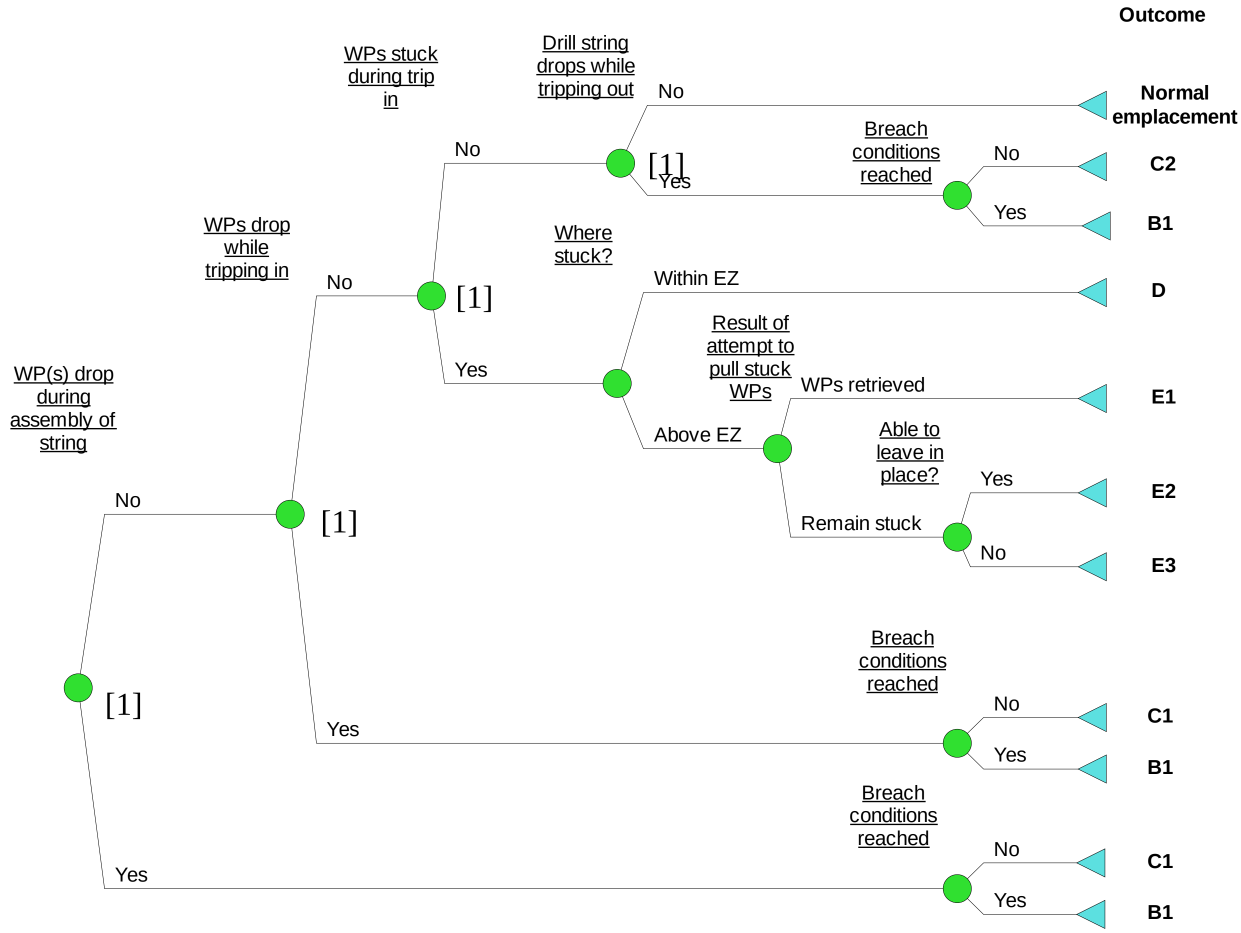
The events along the top of each figure, moving left to right, include the four off-normal events. For each, the top branch indicates the desired favorable outcome (no drop, package not stuck, etc.) and the lower branch indicates an off-normal event. As indicated in the figures, the probabilities for each of these events are calculated in the fault trees described in Appendix B.

Subsequent to any off-normal event, there are one or more dependent events that can lead to different outcomes (Figures A-2 and A-3). For each off-normal event involving a drop, there is uncertainty about whether a WP is breached by the fall. If a WP or WP string is stuck during emplacement, there is uncertainty about where it is stuck, and the ability to retrieve it successfully. These event trees are one product of the expert panel introduced in Section A.1.3.



Notes: [1] indicates the probability of the event comes from fault tree calculations described in Appendix B. "EZ" is the emplacement zone or disposal zone.

Figure A-2. Wireline event tree, per waste package, with outcomes illustrated.



Note: [1] indicates the probability of the event comes from fault tree calculations described in Appendix B. “EZ” is the emplacement zone or disposal zone.

Figure A-3. Drill-string event tree, per waste package string, with outcomes illustrated.

A.4.2 Uncertainty About Impacts for Normal Operations

Radiological releases under normal operations are zero, by definition.

Estimates for the costs of disposal under normal operations for each emplacement mode are described in Appendix C. While many of the costs associated with each option are uncertain, the costs of the drill rig or wireline unit are by far the largest contributors to overall costs. As these costs are time-dependent, that makes the total time required to emplace packages the most important cost-determining factor. Because the estimated costs for the emplacement modes are correlated through numerous common factors (e.g., labor costs) there is less uncertainty in the cost difference between options than there is in the costs of the options themselves (e.g., if the costs for one are much higher than the estimate in Appendix C, it is likely that the costs for the other will also be much higher).

The time required for completion of emplacement is constrained by factors unrelated to emplacement mode and will be the same for both modes assuming normal operations, as discussed in Appendix C. The initial cost estimates for normal operations were developed by project staff, and were updated to reflect review by the expert panel introduced in Section A.1.3.

A.4.3 Uncertainty About Impacts for Off-Normal Operations

Figures A-2 and A-3 identify the outcomes associated with each of the off-normal event pathways that might occur during emplacement. Those outcomes are:

- **"A" outcomes: One or more WP(s) breached above the EZ.** Outcomes A1, A2, and A3 differ in terms of the disposition of the breached WPs, and thus differ in costs for remediation. All three outcomes include plugging and sealing the borehole, disposing of all equipment used (which may be contaminated), and decontaminating the site.
  - A1: Breached WPs fished and removed.
  - A2: One or more WPs not successfully fished and instead left in place above EZ; long term monitoring implemented.
  - A3: One or more WPs not successfully fished and instead removed along with the guidance casing.
- **"B" outcomes: One or more WP(s) breached within the EZ**. The breached WP(s) would be left in place, the borehole plugged and sealed, equipment discarded, and the site decontaminated. Outcomes B1 and B2 differ in terms of the events leading up to a breached WP in the EZ, and thus differ in response costs:
  - B1: Breach occurs as a result of dropping a WP or WP string, or dropping wireline or drill-string onto emplaced WPs
  - B2: Breach occurs after a fishing event (e.g., fishing breaches the WP and leads to a WP drop into the EZ)
- **"C" outcomes: Unbreached but possibly damaged WP(s) in the EZ**. Either WP(s) are dropped into the EZ without resulting in a breach, or the drill pipe or wireline was dropped onto emplaced WPs without resulting in a breach. Outcomes C1 and C2 differ in terms of whether fishing or retrieval of drill pipe or wireline is required. In both cases, the interval is cemented and emplacement is assumed to continue above the bridge plug. The events leading up to the outcome thus differ in response costs:
  - C1: WP(s) no fishing of wireline or drill pipe
  - C2: The drill pipe or wireline also drops and must be fished / retrieved
- **"D" outcome: One or more WP(s) become stuck within the EZ but before reaching the intended disposal depth**. The unbreached WP(s) are left in place, the interval is cemented, and the borehole is sealed and plugged. Under this situation, the borehole would not be used for any additional disposal.

- **"E" outcomes: One or more WP(s) become stuck above the EZ**. Attempt is made to fish the stuck WP(s), and no WP(s) are breached by fishing or as a result of the fishing attempt. Outcomes E1, E2, E3, and E4 differ in terms of the result of the fishing attempt. In all cases, after fishing the EZ would be cemented, the borehole completed, sealed, and plugged, and there would be no additional disposal in the borehole.
  - E1: WP(s) successfully fished / removed
  - E2: One or more WPs not successfully fished, and instead left in place above EZ.
  - E3: One or more WPs not successfully fished, and instead removed along with the guidance casing
  - E4: One more WP(s) drop to bottom of EZ during fishing; no breach occurs

Estimates for the costs and length of time required to respond to each of these outcomes are described in Appendix C. Similar to the costs for normal emplacement, while the costs associated with each option are uncertain, many response costs are common to both emplacement modes, many are time-dependent, and the delays associated with the occurrence of off-normal events are not generally dependent on the emplacement mode. So again, the cost differences between emplacement modes in responding to off-normal events are stable relative to the much larger uncertainty in the response costs themselves. Those cost differences will remain whether response takes longer and costs more than the initial estimates, or whether response is faster and costs less. By considering mainly the cost differences, it is sufficient to consider only the initial mean or "best estimate" of the costs to respond to off-normal events.

A.5 Initial Analysis

This section of the report details the initial inputs and the analysis results, which were calculated and reviewed during the three-day expert panel workshop in August, 2015.

A.5.1 Model Inputs – Fault Trees and Failure Probabilities

Table A-4 summarizes the initial failure probabilities used in this analysis. These probabilities were calculated using the fault trees (Appendix B) and event trees, implemented in SAPHIRE software (Smith et al. 2012).

Table A-4. Failure probabilities used in the initial analysis.

Failure event	Initial Value
WP drops from top of borehole during wireline emplacement	2.60E-07 per WP
WP drops while tripping in during wireline emplacement	5.09E-05 per WP
WP gets stuck while tripping in during wireline emplacement	2.81E-06 per WP
Wireline drops onto emplaced WPs while tripping out during wireline emplacement	9.04E-07 per WP
One or more WPs drop from top of borehole during assembly of the WP string for drill-string emplacement	4.08E-04 per WP string *
WP string drops while tripping in during drill-string emplacement	1.60E-04 per WP string *
WP string gets stuck while tripping in during drill-string emplacement	5.61E-05 per WP string *
Drill-string drops onto emplaced WPs while tripping out during drill-string emplacement	1.39E-04 per WP string *
* The initial analysis assumes strings of 40 WPs for drill-string emplacement. The sensitivity of the results to this assumption is discussed in Section A.6.2.	

Basic Event Probabilities Used to Calculate Top-Level Failure Probabilities

As described in Appendix B, off-normal events can result from basic events such as actions (e.g., human errors), component failures (e.g., winch failures), or a combination of basic events. The predicted frequency of off-normal events is calculated using fault trees that organize basic events. Components are typically characterized as either active (items that must operate either continuously or on-demand for the system to function properly) or passive (items which perform a function but do not actively operate). Failure probabilities/frequencies for active components can be developed from industry and governmental reliability databases for electro-mechanical equipment; failure probabilities for passive components are often determined by an engineering calculation (fragility or damage analysis) using mechanistic models.

For this study, initial fault trees were developed by the project team and were extensively modified by the expert panel discussion described in Section A.1.3. The panel identified new possible failure pathways, suggested engineering design modifications that would reduce the likelihood, or even eliminate other failure pathways. The fault trees shown in Appendix B represent the final results with the modifications made by the expert panel.

The expert panel also offered insights into how to categorize the basic events, as an alternative to detailed assessment or development of individual failure rates. Performing a detailed assessment for each fault tree will require reliability data collected for each of the components (basic events). Several reliability data sources are available for a detailed assessment, such as the Offshore Reliability Data Handbook (OREDA 2009). For this study, the basic events are assigned to categories. Table A-5 shows this categorization of the basic events and the initial probability that was assigned for each. The categorization is discussed further in the following paragraphs.

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Table A-5. Basic event probabilities used in the fault trees for the initial analysis.

			Wireline				Drill-String				
	Probability of occurrence	**Rate (probability per...)**	**Drop from surface**	**Drop during trip in**	**Drop during trip out**	**WP stuck**	**Drop from surface**	**Drop during trip in**	**Drop during trip out**	**WP stuck**	**Basis / discussion**
Misassembly of WP or cable head connection is sufficient to lead to failure of connection	1.00E-01	trip		x	x						Not every misassembled part leads directly to failure. Conservative input (high probability of failure given misassembly) used for initial analysis
Lead package in WP string fails to detect a collapsed casing	1.00E-01	trip								x	Ability of the sensor / lead package to detect and provide warning of a collapsed casing before contact is untested and unproven. Conservative value (high probability of failure) used for initial analysis
WP falls a short distance while attached to wireline	5.00E-02			x							Expert panel discussion: occurs about once in 20 descents.
Human error - Diagnosis											See text for discussion of human error
Wireline damage not detected	4.00E-03	trip		x	x						
Cable head or WP connection mis-assembly not detected	4.00E-04	trip		x	x						
Debris dropped in borehole during operation not noticed or reported	4.00E-04	dropped object				x				x	
Operator fails to notice or respond to signal that casing has collapsed	2.50E-04	trip								x	Signal would be generated by the lead package in a drill-string emplacement
Human error - Action											See text for discussion of human error
Blind ram left open	2.50E-04	WP	x								
Attempt to open blind ram at wrong time	2.90E-04	WP	x								

	Probability of occurrence	Rate (probability per…)	Wireline				Drill-String				Basis / discussion
			Drop from surface	Drop during trip in	Drop during trip out	WP stuck	Drop from surface	Drop during trip in	Drop during trip out	WP stuck	
Attempt to open shipping/transfer cask door at wrong time	2.90E-04	WP	x								
Attempt to operate wireline winch in wrong direction	2.50E-04	trip	x								
Inadvertently close shipping/transfer cask door	2.50E-04	trip		x	x						
Inadvertently close wellhead control feature (e.g., BOP)	2.50E-04	trip		x	x						
Attempt to release WP at wrong time	2.50E-04	trip		x							
Attempt to release cable head at wrong time	2.50E-04	trip		x	x						
WP or cable head connection misassembled	2.50E-04	trip		x	x						
Failure to correctly run caliper log	2.50E-05	trip				x				x	
Inadvertently open basement slips	2.50E-04	WP					x				
Inadvertently open elevator ram	2.50E-04	WP					x				
Inadvertently open rig slips	2.50E-04	pipe stand						x	x		
Inadvertently open pipe ram	2.50E-04	pipe stand						x	x		
Debris falls into borehole from worker activity	2.50E-04	trip				x				x	Requires that a worker drops something (a human error action); but probability is reduced because the drop has to happen over a protected borehole and the item must be large enough to result in a WP getting stuck.

	Probability of occurrence	Rate (probability per…)	Wireline				Drill-String				Basis / discussion
			Drop from surface	Drop during trip in	Drop during trip out	WP stuck	Drop from surface	Drop during trip in	Drop during trip out	WP stuck	
WP drop while attached is sufficient to break wireline	1.00E-03	trip		x							Expert panel: Wireline break due to dynamic overtension is rare relative to the occurrence of the small drop that leads to overtension event. Can be mitigated by slower descent.
Door interlock failure (general)	1.00E-03	trip	x	x	x						See Appendix B for discussion of the interlock systems.
System interlock failure	1.00E-03	trip	x	x	x		x	x	x		
Active component generic failure rate (per demand)											
Caliper log fails to detect collapsed casing	1.00E-04	trip			x				x		
Wireline Winch Failure	1.00E-08	WP or trip	x								*Undeveloped* event; further resolution would require more detailed assessment that identifies the individual components of the winch.
Draw works failure	1.00E-08	WP or trip					x	x	x		*Undeveloped* event; further resolution would require a more detailed assessment that identifies the individual components of the winch.
Wireline damage and fatigue sufficient to lead to a break if not detected	1.00E-04	trip		x							Damage can occur via several mechanisms, including human error. This probability combines damage mechanisms and the probability that the damage is sufficient to lead to a wireline break.

	Probability of occurrence	Rate (probability per...)	Wireline				Drill-String				Basis / discussion
			Drop from surface	Drop during trip in	Drop during trip out	WP stuck	Drop from surface	Drop during trip in	Drop during trip out	WP stuck	
WP joint under-torqued such that it will fail immediately if used	1.00E-04	WP joint					x				WP joints are more complicated than pipe joints, and so problems are more likely in creating WP joints. Initial analysis set probability of an "immediate" failure and the probability of a later failure to the same value.
WP joint under-torqued such that it will fail during use (but not immediately)	1.00E-04	WP joint						x			
WP joint cross-threaded such that it will fail immediately if used	1.00E-04	WP joint					x				
WP joint cross-threaded such that it will fail during use (but not immediately)	1.00E-04	WP joint						x			
Passive component generic failure rate (per demand)	1.00E-05										
WP connection mechanism fails to recognize load		trip		x							
Gauge ring fails to remove debris that is large enough to cause a WP to get stuck		trip				x				x	Requires both that the gauge ring does not remove all concrete debris, and that the debris that remains is of sufficient size and strength to result in a WP getting stuck.
"Other" debris in borehole sufficient to result in WP stuck	1.00E-05	trip				x				x	Sources of "other" debris: friction from WP rubbing on casing; debris entering through the borehole fluid.

	Probability of occurrence	Rate (probability per…)	Wireline				Drill-String				Basis / discussion
			Drop from surface	Drop during trip in	Drop during trip out	WP stuck	Drop from surface	Drop during trip in	Drop during trip out	WP stuck	
Rigging failure	1.00E-05	WP					x				Based on typical probability for heavy lifts in nuclear facilities (10^{-4}) modified for experience typical of drilling rigs (better than 10^{-4}).
Pipe joint under-torqued such that it will fail immediately if not detected	1.00E-05	pipe joint						x			API pipe joints are easy to complete correctly. Connecting (and disconnecting) drill pipe joints is a common activity.
Pipe joint cross-threaded such that it will fail immediately if not detected	1.00E-05	pipe joint						x			
Elevator failure during drill pipe lift	1.00E-06	pipe stand						x	x		
WP string released prematurely	1.00E-05	trip						x			
Casing collapse	5.70E-07	hour				x				x	Expert panel discussion: assume 1 in 100 wells has a casing collapse in the first 2 years. Use this to estimate a failure rate per hour.

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Higher Frequency of Failure: 10^{-3} and Greater

Events in these categories are expected to occur with relatively high frequency, ranging from 10^{-3} to 10^{-1} per trip. Three events are assigned initial probabilities greater than 10^{-2}, and the remaining events in this category are primarily human errors. Two events with an initial probability of 10^{-1} are conditional probabilities – they are estimates of the likelihood that an error, if it occurs, will lead to a failure significant enough to drop a WP. For example, "cable head misassembly" is identified as a basic event for wireline emplacement. As discussed below, that event would be a human error, with a baseline probability of 10^{-3} of occurring. However, it is recognized that not every problem that is a "cable head misassembly" leads to dropping a WP, so we have the conditional event shown in the top row of Table A-5: the probability that the misassembled cable head fails and drops a WP. With no data to support a detailed estimate of this likelihood, it was assigned a high initial probability which will be explored in sensitivity analyses (see Section A.6).

Human Error Rates

Inspection of the fault tree shows that about 50% of basic events for wireline emplacement and about 30% for drill-string emplacement are attributed to human error events. A simplified approach to carrying out human reliability analysis has been developed by the Nuclear Regulatory Commission (NRC) and Idaho National Laboratory, called the SPAR-H method (Gertman et al. 2005). The SPAR-H method is commonly used to predict human error probabilities (HEPs) in nuclear power plants. It uses eight performance shaping factors (PSF) (stress, task complexity, operator experience, etc.) to determine the HEP for a certain task or event. For any human event, the baseline probability is multiplied by factors depending on the different PSF levels. The various PSF levels are determined from worksheets provided in the SPAR-H manual (Gertman et al. 2005). For diagnosis tasks, the baseline probability is 10^{-2}, and for action tasks the baseline probability is 10^{-3}. Initial assessment of HEPs (SNL 2015, Section 5) adopted these baseline probabilities without evaluating the PSF levels associated with each task.

As a follow-up activity, for this report PSF levels were evaluated for each task using the low power/shutdown (LP/SD) SPAR-H worksheets. These worksheets have been used to determine HEPs for dry cask storage at nuclear power plants. For DBD, insights from NUREG-1774 (Lloyd 2003) allow for several assumptions about PSF levels. NUREG-1774 surveyed crane operating experience from nuclear power plants and reported on the various off-normal events that occurred, including events attributed to poor human performance. Off-normal events attributed to poor human performance accounted for 73% of all events from 1969 to 2002. When only "very heavy loads" (e.g., loads in excess of 30 tons) are considered, poor human performance accounts for 56% of all off-normal events. As noted in NUREG-1774: "Potential reasons for the reduction in error rate for very heavy loads could be the increased level of attention, extent of pre-job briefings, operator training, operator experience of those associated with very heavy load lifts" (Lloyd 2003). Based on these findings, several assumptions about PSF levels can be made. In the SPAR-H worksheets, the following assumptions are made about PSFs:

- Experience/training – Operators and workers will have a PSF level of "high."
- Procedures – Well defined so that PSF level is "nominal."

- Work processes – given the risk associated with emplacement and handling of HLW, communication, work planning, and safety culture should have a PSF level of "good."

In addition, 10 CFR Part 60.162 provides physical requirements for all personnel performing the disposal of HLW. If Part 60 is applied to the DBFT, the affected PSF is:

- Fitness for duty – All personnel have a "nominal" PSF level.

Of the other four PSF levels, further assumptions can be made about their level or there is insufficient information to properly assess them at this time. Those are:

- Available time – Application of this PSF to the present study depends on the action. The operator may have "barely adequate time" to react (e.g., detecting collapse while lowering WP) or "extra time" (e.g., diagnosing WP/cable head connection).
- Complexity – Application of this PSF to the present study depends on the action. Diagnosis may be "obvious" (e.g., significant wireline damage) or "moderately complex" (e.g., determining if a WP or drill-string thread is cross-threaded).
- Stress/stressors – There is insufficient information to apply this PSF to the present study because DBD has never been performed and it is difficult to determine what conditions or circumstances may exist that can positively or negatively affect operators and personnel,
- Ergonomics/human-machine interactions – There is insufficient information to apply this PSF to the present study; because DBD has never been performed it is difficult to determine how ergonomics and human-machine interactions (HMIs) could positively or negatively affect operations.

This analysis is applied to both wireline and drill-string emplacement analysis.

Lower Frequency of Failure: 10^{-4} and Smaller

Failure probabilities for the components that make up the two emplacement modes are difficult to obtain. Failure rate data for specific wireline and drill-string operations remain largely proprietary and not readily available. Furthermore, the precise makeup of these two emplacement modes is not fully defined and will continue to evolve as potential failure modes are identified and engineered mitigation measures are incorporated. Achieving a higher level of fidelity for the fault trees and event trees could be time-consuming, and was not attempted given the focused purpose of this analysis. Preliminary baseline order-of-magnitude failure rates were proposed as starting points for discussion and review by the expert panel.

As discussed above, the expert panel spent significant time and effort refining the fault trees, both the structure of the trees and the frequency of the basic events. These discussions led to the estimated failure probabilities used in the initial analysis. Extensive sensitivity analyses were also conducted and are described in Appendix B

A.5.2 Model Inputs – Event Tree Probabilities

In addition to the failure probabilities shown above, the analysis required estimated probabilities for all of the events represented in the event trees shown in Figures A-2 and A-3. The initial probabilities were developed through the expert panel discussion: these probabilities and their bases are shown in Table A-6. Sensitivity of the analysis results to these probabilities, and to the basic event probabilities in the fault trees, are described in Section A.6.

Table A-6. Event probabilities used in the initial analysis.

Event	Initial Value and Basis
Conditional probability that a WP or WP string is stuck above the EZ, given that it gets stuck	**50% for both wireline and drill-string.** Panel discussion result. More likely to have casing collapse or debris issues lower in the borehole than in the upper part. Given the borehole casing plan and depth, assume any collapse (or debris) occurs in the crystalline rock portion of the borehole (the lower 3 km). Assume collapse or debris issue is equally likely at any location within this 3 km zone. Of this zone, 1 km is considered to be the "seal zone" and 2 km is the EZ; the amount of the EZ that is "available" as a location where a WP could get stuck depends on how many WPs are already emplaced. Initial value is based on the median WP or WP string: half the EZ contains WPs, so 1 km of EZ and 1 km "above the EZ" are the equally likely potential regions where a package could get stuck.
Fishing results (wireline only), *if stuck by casing collapse:*	**90% chance of successful retrieval, 7% chance WP remains stuck, 3% chance WP drops as a result of fishing efforts.** Panel discussion result. Fishing generally has a high success rate (90%). If the WP is stuck by a collapsed casing, it is less likely that fishing can "free" a WP to fall than it remaining stuck (if it cannot be retrieved). 2:1 ratio of the remaining probability (7% and 3%) represents a simple rank-sum transformation to estimated probability from rank
Fishing results (wireline only), *if stuck by debris*	**90% chance of successful retrieval, 3% chance WP remains stuck, 7% chance WP drops as a result of fishing efforts.** Panel discussion result. Similar to the discussion for fishing after a casing collapse, but with debris, if the WP is not successfully retrieved, it is *more* likely that fishing will inadvertently "free" a WP to fall than it remaining stuck.
Result of attempting to pull stuck WP string with drill-string	**95% chance of successful retrieval if stuck by debris; 97% chance if stuck by casing collapse.** Panel discussion result. It is more likely that WPs stuck during drill-string emplacement can successfully be retrieved than it is that WPs stuck during wireline emplacement can successfully be fished, because WPs remain attached to the drill-string, so "fishing" for them is not necessary. It is slightly more likely that WPs stuck on a casing collapse can be successfully removed than that WPs stuck by debris can be removed, because the drill-string design includes a weak spot between the lead WP and the WP string, so if the lead package is stuck (more likely with a casing collapse), the WPs above it can be freed and removed.
Fishing breaches a WP (wireline only)	**3%** Panel discussion result. A WP can be breached by fishing if it is hit sufficiently hard by the drill-string while attempting to attach to the package. Every time there is an attempt to attach to the WP, there is the potential for human error leading to hitting the WP. Using a human error probability of 10^{-3} per attempt, assuming that any

Event	Initial Value and Basis
	human error leads to a WP breach, and assuming a fishing "session" would include up to 30 separate attempts to connect to the WP give the initial probability of 3%.
Able to leave a WP in place that is stuck above the EZ and cannot be fished	**50%** Arbitrary. Baseline cost estimates suggest it is less expensive to remove the WP(s) and the guidance casing together than to leave WPs above the EZ, but the ability to do so successfully is uncertain. Assumption is that an appropriate decision would be made at the time based on risk and cost factors. For this analysis, 50% is used. (Note that this applies to the outcomes listed as "E2 or E3" and "A2 or A3" on the wireline event tree as well as to the event labeled "able to leave in place" on the drill-string event tree.)
Breach conditions reached as the result of a drop (wireline)	**0%, regardless of where the drop occurs.** Based on the low package mass, initial stress and strain calculations, and the design requirement for an impact limiter on each WP.
Breach conditions reached as the result of a drop (drill-string)	**100%, regardless of where the drop occurs.** Based on the high mass of the WP string and the drill pipe, and initial estimates of terminal velocity, energy and stress/strain calculations.

A.5.3 Model Inputs – Impact on Performance Metrics

If emplacement operations proceed without any problems, wireline emplacement was estimated to cost about $23.5 million and to require about 430 days of operations; drill-string emplacement was estimated to cost about $41.9 million and also to require about 430 days of operations. Table A-7 summarizes each possible outcome identified on the event trees in terms of the three performance metrics: occurrence of radiological releases, durations, and costs.

These cost estimates were developed by the project team and were reviewed with the expert panel. Appendix C describes the cost assumptions and contains the more detailed cost calculations.

Table A-7. Impacts on performance metrics for each outcome.

Outcomes	Radiological Release	Wireline		Drill-String	
		Days	Cost ($million)	Days	Cost ($million)
A1	Yes	965	308	965	346
A2	Yes	1330	309	1330	328
A3	Yes	966	309	1005	350
B1	Yes	945	302	945	325
B2	Yes	1330	314	1330	337
C1	No	409	25	409	43
C2	No	407	29	407	44
D	No	323	29	323	42
E1	No	600	45	600	74
E2	No	965	92	965	120
E3	No	601	46	640	78
E4	No	600	44	600	54
Normal	No	430	24	430	42

A.5.4 Results

Combining the failure and event probabilities with the impact of each outcome on the performance metrics, the initial analysis indicates that drill-string emplacement has an expected differential cost of $20.2 million over wireline emplacement. While it is more likely to lead to incident-free emplacement of 400 WPs in a borehole, it is more likely to result in a radiological release than is wireline emplacement (by a factor of about 52). The most likely adverse outcome for wireline emplacement involves off-normal events that result in delays but not radiological releases nor a need to abandon the borehole, while the most likely adverse outcome for drill-string emplacement involves radiological releases.

Table A-8 provides details. The top portion of the table summarizes the expected outcomes in terms of the three performance metrics: expected costs, expected time, and the probability of radiological releases. Other rows in the table provide the probability of each of the individual outcomes, and, for each potential failure mode, the probability of that failure occurring before 400 WPs are successfully emplaced.

Table A-8. Initial analysis results: wireline compared to drill-string emplacement of 400 packages in one disposal borehole.

	Initial Results	
	Wireline	**Drill-String**
Probability of incident-free emplacement of 400 WPs	**97.83%**	**99.24%**
Approximate total costs if successful ($ million)	**23.5**	**41.9**
Expected performance against the defined performance metrics		
Expected value of costs ($ million) for outcomes weighted by probabilities, considering both normal and off-normal events	23.7	43.9
Expected total time of operations (days) for outcomes weighted by probabilities, considering both normal and off-normal events	430	434
Aggregated probability of radiation release	1.74E-05	7.08E-03
Outcome Probabilities		
Probability of a failure that leads to radiation release (Outcomes A1–A3, B1 & B2)	**1.74E-05**	**7.08E-03**
Outcome A1: Stuck above EZ/breached/fished/no more disposal	1.52E-05	0.00E+00
Outcome A2: Stuck above EZ/breached/fishing failed/leave in place	5.90E-07	0.00E+00
Outcome A3: Stuck above EZ/breached/fished with casing/no more disposal	1.12E-06	0.00E+00
Outcome B1: Drop causes breach in EZ/complete hole/no more disposal	0.00E+00	7.08E-03
Outcome B2: Fishing causes breach in EZ/complete hole/no more disposal	5.06E-07	0.00E+00
Probability of a failure that does not result in a radiation release but requires abandoning the borehole (Outcomes D & E1 – E4)	**1.09E-03**	**5.61E-04**
Outcome D: Stuck in EZ/complete borehole/no more disposal	5.62E-04	2.80E-04
Outcome E1: Stuck above EZ/no breach/fished/no more disposal	4.91E-04	2.66E-04
Outcome E2: Stuck above EZ/no breach/fishing failed/leave in place	8.18E-06	7.01E-06
Outcome E3: Stuck above EZ/no breach/fished with casing/no more disposal	1.55E-05	7.01E-06
Outcome E4: Drop to EZ during fishing/no breach/complete/no more disposal	1.64E-05	0.00E+00
Probability of a failure that leads to costs and delays, but does not require abandoning the borehole (Outcomes C1 & C2)	**2.07E-02**	**0.00E+00***
Outcome C1: Drop into EZ/no breach/continue disposal	2.04E-02	0.00E+00*
Outcome C2: Drop wireline/pipe into EZ/no breach/continue disposal	3.62E-04	0.00E+00*
Top level failure probabilities (likelihood of each of these types of failures occurring before 400 WPs are successfully emplaced)		
Drop one or more WPs from top	1.04E-04	4.08E-03
Drop one or more WPs during trip in	2.04E-02	1.60E-03
Drop wireline or drill-string on trip out	3.62E-04	1.39E-03
WP or WP string stuck	1.12E-03	5.61E-04

* These outcomes are judged to be very unlikely because of the severe consequences from dropping a drill string.

A.5.5 Drivers of Initial Results

The most likely off-normal outcome for drill-string emplacement is Outcome B1: a breached WP in the EZ. This results from the relatively high likelihood that a WP string will be dropped (see the bottom four rows of Table A-8) and the initial estimate that any WP string that is dropped will lead to a breach and a radiation release, and that if drill pipe is dropped onto emplaced packages, a breach will occur. Section A.6 discusses the results of sensitivity analyses exploring both of these factors.

For wireline, the most likely off-normal outcome is C1: an unbreached WP in the EZ. This results from the relatively high likelihood that a WP will be dropped while tripping in and the initial estimate that a single WP dropped during wireline emplacement will not breach. The relatively high likelihood of a drop while tripping in, is in turn a function of the fact that 400 WPs must be lowered one at a time, so there are 400 trips in wireline emplacement, and the relatively high frequency of wireline failure due to dynamic overtension.

The impact from dropping a package during wireline emplacement would be mitigated using impact limiters attached to each package. The terminal sinking velocity of a package (Section 5.4), the potential effectiveness of impact limiters (Section 5.5), along with the robustness of package design concepts (Sections 3.2 and 5.1) lead to an insignificant probability of breach due to a drop of a single package. For dropping a WP string during drill-string emplacement, there is high likelihood of a breach (see bounding analysis in Section 5.6). An analysis of the sensitivity of overall results to uncertainty about the likelihood of package breach from drop events, is discussed in the following section.

A.6 Sensitivity Analysis

Sensitivity analyses were conducted to explore the impacts of changes in various inputs, and to test whether there are credible circumstances where the initial analysis preference for wireline emplacement over drill-string emplacement would be reversed. The first set of sensitivity analyses focused on the event probabilities, the second set focused on the failure probabilities. A final sensitivity analysis on the number of WPs per string for drill string emplacement is also discussed.

Appendix B includes details for each of these sensitivity analyses, including the specific probabilities tested and the results in a form similar to Table A-8.

A.6.1 Sensitivity to Event Probabilities

Sensitivity to four of the key event probabilities was explored.

S1. Sensitivity to Uncertainty About Where WPs Get Stuck (above or within the EZ)

Using the logic described for estimating the initial probability described in Table A-6, two sensitivity cases were identified. They represent the maximum and minimum credible conditional probabilities for being stuck above the EZ ($p = 1$ or 0.33).

The results are insensitive to these changes. Although doubling the conditional probability of being stuck above the EZ does double the probability of a radiation release for wireline emplacement, that is the only notable difference in the comparison, and the probability of a radiation release remains approximately 400 times lower than the probability of a radiation release for drill-string emplacement.

S2. Sensitivity to Uncertainty About the Challenge of Removing Stuck Waste Packages

These analyses considered both the possibility that the initial values overestimate the general success rate at WP fishing or removal (so the probability of fishing / retrieval success was decreased to 50% for wireline, 65% for drill-string), and the possibility that fishing WPs that are stuck during wireline emplacement is much more challenging than removing WP strings that are stuck during drill-string emplacement (probability of fishing success for wireline was decreased to 50%; remained at 95% for drill-string).

The results are insensitive to these changes. Changing the fishing success rate slightly changes the relative probabilities of Outcomes A and B for wireline emplacement, and of Outcomes E for drill-string emplacement. But these are small variations that depend on where the WP ends up after fishing. These differences do not affect the overall comparison of emplacement modes.

S3. Sensitivity to Uncertainty About the Likelihood of Breaching a WP While Attempting to Fish or Remove a Stuck WP or WP String

Experts identified fishing for WPs that were stuck during wireline emplacement as an area of large uncertainty. Although fishing is usually successful, there is a chance that the fishing attempt itself will lead to a WP breach. The basis for the initial estimate of a 3% chance of breaching a WP during fishing is discussed above in Table A-6. Sensitivity analyses considered lower (0.3%) and higher (10%) probabilities that fishing leads to breach, and also considered the possibility of breaching a WP while attempting to remove a stuck WP string (for drill-string emplacement).

The results are sensitive to these changes. Because fishing is the only mechanism by which a WP can be breached during wireline emplacement, changes in this probability translate directly to changes in the probability of a radiation release for wireline emplacement. For drill-string emplacement, there are many larger contributors to the possibility of breaching a WP, so the effect of increasing the probability of a breach during retrieval is negligible. For wireline operations, considering an exaggerated case where the probability of breaching a WP while fishing is 99% (versus the initial 3%), the probability of radiation release is about 12 times lower than for drill-string emplacement. And even under those assumptions, the expected costs of wireline emplacement remain about $19 million less than drill-string emplacement.

S4. Sensitivity to Uncertainty About the Likelihood of WP Breach from Drop Events

This set of sensitivity analyses explored the impact of assuming both lower probability of breach conditions for drops of WP strings (drill-string emplacement) and simultaneously higher probability of breach conditions for drops of a single WP (wireline emplacement).

The results are sensitive only to dramatic changes in these breach probabilities. If the probability of breaching one or more WP(s) when dropping a WP string is decreased to 50% (from 100%), and the probability of breaching a single WP when dropped during wireline emplacement is increased to 5% (from zero), the difference in the probability of radiation release from drill-string emplacement is a factor of 3 greater than for wireline. If the probability of breach from a dropped string was 15% and from a single dropped WP was 5%, the overall probability of radiation release from the two emplacement modes would be the same. As in all other sensitivity analyses, the expected cost differences remain large and in favor of wireline emplacement.

A.6.2 Sensitivity to Failure Probabilities

Sensitivity to seven of the key failure probabilities of different types is explored. Additional details of the sensitivity analyses, including tables of intermediate numerical results, are provided by SNL (2015).

S-F1. Sensitivity to the Conditional Probability that an Error Leads to a Failure

There are several potential failures that require human error, and for that human error to occur at a specific time (e.g., dropping a tool while working over an open borehole), or for that error to lead directly to a failure (e.g., misassembling a cable head such that it fails immediately when put into service). The initial probabilities are based on a “conservative” assumption that there is a high probability that an error results in a failure (about a 10% chance of immediate failure given occurrence of the error). In this set of sensitivity analyses, both higher and lower conditional probabilities of failure given the initial error are explored.

The results are insensitive to these changes.

S-F2. Sensitivity to the Frequency of Human Errors

Human errors play an important role in all the fault trees. As described above, estimating human error rates is complicated, and each could be the subject of a detailed study. The initial rates used here are the baseline probabilities from NUREG-6883 (Gertman et al. 2005). This sensitivity analysis explores the impact of reducing the frequency of all human errors by a factor of 10.

The results are insensitive to these changes. This is likely a result of the presence of interlock systems in the design that reduce the likelihood that human errors lead directly to adverse outcome. Sensitivity case S-F4 explores the effect of the interlock system.

S-F3. Sensitivity to Operational and Design Changes Aimed at Reducing Specific Risks

The fault trees can identify the key event(s) for each type of failure – the basic or intermediate events that are the most important factors driving the overall probability of failure. For wireline emplacement, a key risk is the potential for dynamic overtension leading to a wireline break. Experts at the workshop mentioned that this risk is relatively common and that it is typically mitigated, when necessary, by reducing the descent rate. This sensitivity analysis assumed that operational changes are made and the probability of a dynamic overtension failure decreases by a factor of 10.

The results are sensitive to this change. Reducing the chance of a cable break reduces the chance that a WP is dropped on the trip in by almost an order of magnitude. This increases the likelihood of emplacing 400 WPs without incident to 99.6% (compared to the initial probability of 97.8%).

S-F4. Sensitivity to the Effectiveness of the Safety Control (interlock) System

As discussed above, the interlock system will be designed to provide a specified level of protection from failures, managing risk at the level of the intermediate failures in the fault trees. Interlock systems can achieve failure rates ranging from 10^{-2} to 10^{-4}. This set of sensitivity analyses explored both ends of this range.

The overall results are insensitive to this change, although the likelihood of specific failure events is sensitive. In particular, the probability of dropping a package from the top of the borehole during wireline emplacement changes by almost an order of magnitude if the interlock effectiveness changes by an order of magnitude. This results from the fact that the dominant failure mechanism here is an overtension failure caused by winding the winch the wrong way against the stops, which is mitigated by the interlock system. If the interlock is less effective, the top level failure rate goes up. These lead to only very small changes at the level of the performance metrics.

S-F5. Sensitivity to the Likelihood that WP(s) Become Stuck by Debris in the Borehole

The fault trees identify the basic events relating to a WP being stuck by debris as important drivers of the overall failure probability for both emplacement modes. This set of sensitivity analyses explored the impacts of reducing or increasing those basic event probabilities by a factor of 10.

Wireline results, in particular, are highly sensitive to these changes. This results because: 1) getting stuck by debris is the main way in which a WP can get stuck, so increasing the probability of being stuck by debris increases the probability of being stuck at all; and 2) the only pathway by which a WP can be breached during wireline emplacement is if it gets stuck and is breached while attempting to fish. Changes to the probability of being stuck by debris affect the overall probability of incident-free emplacement of 400 WPs. The probability of incident-free emplacement decreases to 97.4% for wireline emplacement when the debris-stuck probability increases 10-fold, which increases the probability of radiation release by an order of magnitude. Even in this case, that probability of radiation release is about 100 times less than the probability of release from drill-string emplacement, and the expected cost differential remains about $20 million.

S-F6. Sensitivity to the Likelihood of Rigging Failure While Assembling WP Strings

In the initial analysis we identified rigging failure as a key basic event that would need to be carefully managed for drill-string operations. We assumed that a system with a failure (drop) rate of 10^{-5} per lift could be designed and implemented. Recognizing this as a potential challenge, this sensitivity analysis looked at the results of a rigging failure rate of 10^{-4} per lift.

Results are sensitive to this change. The probability of incident-free emplacement of 400 WPs with drill-string operation decreases to 96% (from 99%) and the probability of a radiation release increases to 4×10^{-2}. This represents a significantly higher risk and highlights the importance of rigging safety if drill-string emplacement is to be implemented.

S-F7. Sensitivity to the Frequency of Casing Collapse

The two emplacement modes expose successful emplacement to very different chances of encountering a casing collapse, simply because of the length of time required to assemble a string of 40 WPs (during which an undetected collapse could occur). This set of sensitivity analyses explores the effects of both higher and lower frequencies for casing collapse.

Overall results are insensitive to these changes. Although increasing the probability of casing collapse does increase the probability that a WP string will become stuck during drill-string emplacement, the relative ease with which that problem can be addressed (the high likelihood of successful retrieval with no additional risk of breach) means that this change has little effect on expected costs, or the likelihood of radiation releases. The probability of incident-free emplacement of 400 WPs by drill-string operation decreases to 96% (from 99%) and the probability of a radiation release increases to 4×10^{-2}. This represents a significantly greater risk and highlights the importance of casing collapse detection if drill-string emplacement is to be implemented.

A.6.3 Sensitivity to Number of WPs in a WP String for Drill String Emplacement

Because of the high probability of a WP breach if a string of 40 WPs is dropped, a sensitivity analysis of the number of WPs in each string was considered. In particular, the expert panel asked if it was possible to reduce the number of WPs enough that an impact limiter could be designed to eliminate the chance of breaching a WP if the string was dropped. It was noted, however, that this mitigation would address only the likelihood of breaching a WP if dropped from the top, or of breaching a WP that is dropped without the drill string attached while tripping in, and that it would require more trips to emplace the same number of WPs. At most, decreasing the number of WPs per string could decrease the risk of breaching a WP by a factor of 2.5 per each trip. The decrease in risk per trip is overwhelmed by the increase in risk from the greater number of trips required.

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Appendix B. Fault Trees for Wireline and Drill-String Emplacement Off-Normal Events

The aggregate probability for the top event in each fault tree, as calculated using SAPHIRE software (Smith et al. 2012), is shown in Tables B-1 and B-3 for wireline and drill-string emplacement, respectively. The top events calculated in this way are:

- Drop a WP from the surface (or a WP string, for drill-string emplacement)
- Drop a WP (or a WP string) during the trip in
- Get a WP stuck (or a WP string)
- Drop a wireline (or drill pipe string) onto WPs on the trip out

The basic events or failures that could initiate these top events are quantified in the fault trees (Figures B-1 through B-8). These events were initially developed by describing emplacement in a sequence of steps, then identifying the failures that could occur at each step. Engineering or procedural measures were added to the emplacement concept, where practical, to prevent or mitigate the identified failures. The resulting sets of basic events were arranged using fault tree logic, and the fault trees were reviewed by an expert panel (described in Appendix A). The following discussion presents the fault trees and computes the top event probabilities. The sensitivity study results that are summarized, are described in more detail by SNL (2015).

Safety Control (Interlock) System – An integrated system of state sensors and actuator controls would be essential to manage reliability for both wireline and drill-string emplacement. The system would be designed using software that provides needed reliability for each emplacement function. The level of design, testing, and maintenance needed to achieve safety system performance objectives depend on the nature of the processes being controlled. Safety control systems can be simulated by combining functional relationships representing mean time between failures, reliability and redundancy, switch checks, daily verification procedures, continuous diagnostics, etc. Standards are available for rating functional safety systems at different levels of performance (MTL 2002; ISO 2006, 2010).

At the current stage in the DBFT design study, differences in interlocks are not distinguishable; thus, all interlocks have equal probabilities. Interlock failure rates are adopted from NUREG-0612 (George 1980), which are between 10^{-2} and 10^{-3}. The interlock failure rate used to calculate the probabilities in Tables B-1 and B-3 is nominally 10^{-3} (except where larger values are used for certain situations where less interlock performance is needed). The upper limit is explored in the sensitivity analyses.

Quality Assurance/Quality Control – A QA/QC system would be implemented for all aspects of deep borehole disposal. The grading or level of controls placed on systems, structures and components would depend on their risk significance. In this analysis QA/QC is assumed throughout, although specified for only one process (assembly of wireline release mechanisms).

Corrosion – The environment within the borehole, such as brine solution and high temperature, may be corrosive to the wireline, cable head, drill string, and WPs. In the current conceptual stage of the design, no quantitative analysis has been completed that can be applied to the fault trees. When a borehole site, fluid environment, emplacement method, and emplacement materials have been determined, then it will be possible, and necessary, to consider corrosion of the various downhole components.

Discussion of fault trees is organized by emplacement method: wireline or drill-string emplacement, in the following sections.

B.1 Fault Trees for Wireline Emplacement

Note that the following analysis was developed for a wireline emplacement concept that has since evolved. Specifically, the overall concept described in Section 3 of this report is evolved somewhat from the previous version (SNL 2015, Section 2). The most important differences are related to surface handling and transfer of WPs:

- Separate transportation and transfer casks (compared to a dual-purpose, double-ended cask described previously).
- Use of sliding or rotating-carousel plate shields for the cask used to transfer WPs to the wellhead (instead of sliding lower doors which are pressure-rated for use in well control).
- Wellhead design with gate valve and annular BOP (instead of ram-type BOPs).

The hazard analysis that follows is equally applicable to the newer conceptual design information, and the conclusions of the emplacement mode selection study described in Appendix A are still valid.

Drop a Waste Package from the Surface (Figure B-1)

Dropping a WP through the wellhead, when not connected to the wireline, would be caused by human error. A safety control (interlock) system is proposed that would prevent drops in the event of human error by disabling opening of control valves or other features, depending on the state of the system. Thus, if the wireline is not connected and tensioned, wellhead control features would not open. The interlock system would use measurements of the actual state of each component (open, closed, stuck, connected, tensioned, etc.) and the control input, as input to programmable logic. The wireline winch status, the load sensor in the wireline tool string, and the tool depth would also be included, and the winch drive mechanism and brakes would be controllable.

In addition to interlocks, other features could be incorporated in the design such as using a common plug for actuation and safety circuits, and passive features to prevent opening the wellhead while bearing the weight of the package. Such features have not been included in the fault trees (FTs). Dropping a package due to wireline winch failure would be rare because the hydraulic drive system does not free-wheel, and there are two brakes (in a typical setup) with reverse operation so that one actuates when pressure is applied and the other when pressure is released. Winch failure is represented by a single basic event, but this is an incomplete picture of winch failure which is a so-called *undeveloped* event. Full assessment of winch failure would require an assessment for each of the various components that make up the winch. For winch failure, a philosophy similar to that for single-failure-proof cranes should be applied (Porse 1979). Rather than decompose this gate into its various components, it is treated as a basic event for now with a probability equal to 10^{-8} and an *undeveloped* event indication (represented by a diamond under the event box in Figure B-1).

Sensitivity Analysis – As noted in Table B-1, the driving cut set for this FT is when operator attempts to operate the winch in the wrong direction and the system interlock fails to prevent this action. For the first sensitivity case (WL-SURFACE-S1 in Table B-2), the upper bound for the interlock failure rate is applied (10^{-2} as given in NUREG 0612). Computing the top event failure rate with the upper bound, the result is that the top event probability also increases by an order of magnitude.

For the WL-SURFACE-S2 sensitivity case, wireline winch failure is varied. When it is increased from 10^{-8} to 10^{-7} per WP the effect is minimal, but at 10^{-6} wireline winch failure becomes the primary driver for this FT. But based on the expert panel inputs, wireline winch failure rate is not expected to deviate by more than order of magnitude from the value listed in Figure B-1. It should be noted that compared to other FTs, the failure rates produced by the sensitivity analysis are still lower than the other FT failure rates. Therefore, this sensitivity analysis should have a low impact on event tree outcome probabilities (see Appendix A).

The third and fourth sensitivity cases compute the combined effect from increasing the probabilities for both system interlock and winch failures. As expected, with both failure probabilities increased to their upper bounds, the top event failure probability also increases. For the WL-SURFACE-S3 sensitivity case, interlocks are the primary driver and for the WL-SURFACE-S4 sensitivity case, wireline winch failure becomes the primary driver. Sensitivity case S4 produces the highest top event failure probability among these cases.

Surface drop without wireline attached is rare ($< 10^{-10}$ per WP) because of redundant features of the handling/transfer system, so sensitivity analysis of this FT branch was not further explored.

Drop Waste Package During Trip In (Figure B-2)

Cable break due to dynamic overtension is the most likely cause of dropping a package during the trip in. Cable damage is associated with age, cumulative number of trips, depth and tension, temperature, and corrosion. Cable damage is routinely managed using a ductility test, starting with the free end of the cable, and cutting off cable that fails the test. Using such testing, fatigue in the classic sense of breakage due to extended service, should be very unlikely. In this event, wireline break occurs due to localized damage caused by momentary overtension events when a tool or package hangs up briefly during descent, then breaks free, falls and is arrested by the wireline. Routine inspection and maintenance would be important for wireline emplacement, even using modern cables such as the Schlumberger Tuffline®.

The service load limit (50% of maximum tensile strength) used in wireline operations accommodates some limited accumulation of damage. No cable splices would be permitted in emplacement operations, or any other wireline operations taking place above WPs exposed to falling objects in the borehole. Fishing and stripping (lowering a drill string over a wireline connected to a stuck tool) frequently cause cable damage and would disqualify a cable from further use for emplacement.

Cable break is also correlated with sheave failure, or when the cable jumps out of a sheave. High-quality sheaves with cable retention locks would be used and inspected and maintained regularly. Emplacement operations would not be conducted in cold weather when ice could accumulate on the wireline, sheaves, or support equipment.

A wireline could also break if a wellhead control feature such as a valve, is closed inadvertently onto the cable. The safety control (interlock) system would be relied on to disable such functions during the trip in, subject to override in the event of a well control emergency.

Another way to drop a WP is inadvertent actuation of the package release (between the tool string and the WP) or the cable head weak point or release (allows the cable to disconnect from a stuck tool string). Remotely operable release mechanisms would be designed so they cannot release when under full load, i.e., while they are supporting the buoyant weight of the package. Another approach would be to use a release mechanism such as that discussed in Section 3.3, with a thermal actuation time that would permit detection and correction. Such a passive feature could be more reliable than the safety control (interlock) system, and could decrease the probability of inadvertent human-caused actuation resulting in a drop so that it is insignificant (10^{-8} per trip).

The package release mechanism would be assembled by the wireline operators for each trip in, so there is a possibility of human error that could lead to dropping a package under load. A QA program would be applied with inspections and testing, but the possibility of misdiagnosing a faulty assembly remains. The same risk is conservatively associated with the cable head weak point or release mechanism for every trip in, although this feature would only be reassembled after being used in response to an off-normal event. This reflects the possibility of defect aging, or random differences in loading conditions on successive trips.

Sensitivity Analysis – As seen in Table B-1, the most likely cause of failure that leads to a package drop is due to dynamic overtension of the cable. Expert elicited probabilities for these events seem conservative and it is possible that with the Schlumberger Tuffline® cable, the "sufficient to break" event can be lowered by at least an order of magnitude. Exploring this possibility, the wireline overtension break event probability was decreased to 10^{-4} and 10^{-5} per WP (sensitivity case WL-TRIPIN-S1 in Table B-2). For 10^{-4} per WP the top event probability is reduced by an order of magnitude and the overtension event remains the primary driver. For 10^{-5} per WP there are four drivers to the top event probability of 1.41×10^{-6} with approximately equal probability: dynamic overtension (5.0×10^{-7}), wireline damage (4.0×10^{-7}), inadvertent operation of transfer closure (2.5×10^{-7}), and inadvertent closing of wellhead control valve or ram (2.5×10^{-7}).

Sensitivity of the interlocks upper bound probability is assessed in case WL-TRIPIN-S2 (Table B-2). When the interlock failure probabilities are set to 10^{-2} per WP the top event probability does not change significantly, but the highest top event probability is produced for this sensitivity case. A similar effect is observed when the wireline damage and fatigue break (sensitivity case WL-TRIPIN-S3) is increased by an order of magnitude. Note that for both of these cases, S2 and S3, the overtension event remains the primary driver for the top event probability.

Sensitivity cases WL-TRIPIN-S4 and S5 assume the Schlumberger Tuffline® overtension failure decreases by two orders of magnitude. In WL-TRIPIN-S4, the interlock failure probabilities are increased by an order of magnitude. When the interlock probabilities are increased and overtension break is lowered, the top event probability decreases by an order of magnitude and the two interlock failure events become the primary drivers. Similarly, when the wireline damage break failure event is increased by an order of magnitude and assuming the decreased failure rate of the Schlumberger Tuffline®, the wireline break event becomes the primary driver.

For these different sensitivity cases, the overtension event has the most significant effect on the top event probability. Accordingly, more analysis of overtension events and wireline responses could reduce model uncertainty.

Dynamic overtension and wireline damage are probably the greatest sources of uncertainty in this FT. For dynamic overtension experts at the workshop stated that the risk is relatively common and is typically mitigated, when necessary, by reducing the descent rate. Drop dynamics are uncertain but with tougher wireline, such as the Schlumberger Tuffline® cable, it is thought that the incidence of cable break from dynamic overtension would be reduced. A similar assumption could be made regarding wireline damage and fatigue, but without more application-specific information on corrosion and the condition of the borehole, this assumption was not used in this analysis. Note that the probability of cumulative damage or fatigue damage is time-dependent and not a simple point estimate as shown in Figure B-2.

Waste Package Gets Stuck (Figure B-3)

Cement residue from installation of cement plugs with the coiled tubing rig, is the most likely source of debris that could cause a WP to become stuck. To maximize reliability, the emplacement path in the guidance casing would be requalified by running a gauge ring with junk basket, before and after each cement plug installation (before to ensure that the bridge plug does not get stuck, and after to detect and remove cement residue). An acoustic caliper log would also be run (a separate trip) prior to emplacement to evaluate for solids accumulation on the wall of the guidance casing. This log is informative, and runs faster than a conventional arm-caliper log. If settling or other solids accumulation is prevalent, a different emplacement fluid with better aging properties would be circulated into the hole. Barite is known to settle and would not be desirable as an ingredient in emplacement fluid.

One way that tools get stuck in geothermal wells is when pressure is reduced in high-temperature zones and liquid water behind the casing flashes to steam, damaging the casing. Whereas WPs generate heat, this failure mechanism is unlikely in disposal boreholes if heat output is limited and the hole is circulated occasionally during operations. Below a depth of approximately 2.2 km the formation pressure (and the pressure in a fluid filled borehole) exceeds the critical point of water so boiling cannot occur.

Getting stuck means that additional wireline pull (up to the weak point limit at the cable head, or the tensile limit of the cable at the surface) along with reverse circulation, is insufficient. Reverse circulation in the upper part of the guidance casing (above the reverse circulation port at nominal depth of 3 km; Figure 3-1) could substantially increase the up-force for retrieval.

If initial efforts at fishing with wireline tools are unsuccessful, a workover or drilling rig would be mobilized. The stuck package would be engaged by fishing tools, starting with a tool designed for the fishing neck on the package. If fishing efforts are still unsuccessful then the fishing string would be withdrawn (if necessary, cut off using cutting tools run on wireline inside the pipe), and the string recovered by pulling the guidance casing. This would require construction of a rig basement with specialized equipment for securing the package to the casing (in which it is presumably stuck) and cutting the casing so that the package can be removed into a transfer/transportation cask. This outcome is included in the discussion of off-normal outcomes in Appendix C.

The use of impact limiters could confer significant safety benefits (minimizing the likelihood of breach for dropped packages). Limiters would be designed conservatively with tapers, cowling, etc., so they cannot catch on the casing and cause the package to become stuck. Also, whereas most limiters would deform under static load after emplacement (under the weight of a stack of packages) they would be designed not to become stuck after collapsing (see Section 5.5).

Further, the deformable elements would have a breakaway feature so that if they did get stuck, the package could be pulled away and removed from the borehole.

Casing collapse would likely occur slowly, over a period of hours to weeks, which could make detection from the surface difficult. The fastest deformation would be most likely soon after installation (and detected before emplacement). If the crystalline basement is in a state of highly deviatoric stress, closure could occur over a few years (based on experience with crystalline rock in geothermal systems). Where stress conditions are known, downhole *in situ* temperature is in the expected range, corrosion is understood, and boreholes are relatively straight (avoiding casing wear at doglegs) casing failure is likely to be rare.

Sensitivity Analysis – There are two main drivers for the WP stuck event. A WP could get stuck due to casing collapse during the short time after the caliper log is run but before or during lowering of a WP ($p = 1.7\times10^{-6}$ per WP). In addition, a WP could get stuck on cement debris that is not picked up by the junk basket ($p = 1.0\times10^{-6}$). Both of these events were examined by sensitivity analysis.

When either of these events is increased by an order of magnitude, the top event probability also increases by an order of magnitude, and that basic event becomes the primary driver for the FT. The other basic events in this FT have insignificant probabilities and sensitivity analysis was not explored.

Casing collapse is a significant uncertainty and similar to wireline damage, may be time dependent. It is also possible that this is an *undeveloped* event that can be broken down into elements of the casing construction, seismic activity, pressure and temperature effects, etc. Further analysis of casing collapse and the possibility of new detection strategies, is warranted.

Concrete debris has been estimated based on expert experience, but the presence of cement debris will largely depend on specifics of borehole construction, cement type, cementing method, and so on.

Note that Figure B-3 differs from the corresponding fault tree in the FY15 *DBFT Specifications* report (SNL 2015), most significantly with respect to the credit taken for running a gauge ring prior to emplacing each waste package by wireline. The change reflects insight that a gauge ring can detect and potentially recover all types of junk and not just cement debris. This change propagates through the risk model and decreases the probability of getting stuck leading to breach of a waste package, by approximately 8-fold (Section A.5). Hence, the wireline method is another 8 times less likely than the drill-string method to cause a radiological release (i.e., from 52 to approximately 400 times less likely).

Drop Wireline During Trip Out (Figure B-4)

Dropping the wireline or tool string on a WP while tripping out, after the package is successfully emplaced on the bottom, is similar to dropping while tripping in, except: 1) the dynamic overtension mechanism cannot occur, and 2) the package release mechanism is already released. There are three equally contributing drivers for this fault tree that are related to wireline break/shear. Two of these drivers are when a transfer cask closure or wellhead control feature is inadvertently operated and shears the wireline. The other driver is wireline damage and fatigue that leads to wireline break.

Sensitivity Analysis – Similar to other FTs, the interlock failure rates are increased according to probabilities reported in NUREG-0612. When both the wellhead control interlock failure probabilities are increased, the top event probability is increased by an order of magnitude and these two events become the primary drivers for the top event probability.

As seen in Table B-2, a similar effect is observed when the wireline damage and fatigue event is increased by an order of magnitude. This event also becomes the primary driver for the top event failure probability for this sensitivity case.

All failure events associated with the cable head release are relatively small (on the order of 10^{-9} per WP) so sensitivities of these failure rates were not explored further.

As mentioned for the trip-in FT, wireline damage is an important uncertainty and the probability was estimated by the expert panel. These FTs are static and do not account for time dependent damage accumulation, but instead rely on expert judgment as to expected performance.

Although the inadvertent release branch of this FT was identified as insignificant, this conclusion is derived from an underlying assumption about human performance in assembly of the mechanism. Discussion of the SPAR-H worksheets is provided in Appendix A, and most of the PSFs hold true here. Two of the PSFs that would most notably be affected are complexity, and ergonomics/HMIs, which may be crucial for this event. If the task is highly complex and the ergonomics/HMIs are difficult, then this branch of the FT could increase by two orders of magnitude and would then become a contributing factor.

Table B-1. Summary of top-event probabilities for wireline fault trees.

Fault Tree	Failure Probability	Primary Responsible Events
Wireline Emplacement		
Drop waste package from surface	2.60E-07 (per package)	Overtension due to winding the wrong way against the stops.
Drop waste package during trip in	5.09E-05 (per package)	Wireline break due to dynamic over-tension if the package momentarily hangs up.
Waste package gets stuck	2.81E-06 (per package)	Contributing causes: casing collapse after caliper log has been run and before or during lowering of a WP; WP gets stuck from concrete debris not picked up by junk basket.
Drop wireline during trip out	9.04E-07 (per package)	Contributing causes: cask door or wellhead control feature shears wireline; wireline damage failure.

Table B-2. Sensitivity analysis for wireline emplacement fault tree basic events.

Sensitivity Case	Basic Event(s)	Initial Probability	Sensitivity Probability	Failure Probability of Top Event for Sensitivity Case
Surface Drop: Initial Failure Probability = 2.60E-07				
WL-SURFACE-S1	System interlock failure	1.00E-03	1.00E-02	2.51E-06
WL-SURFACE-S2	Wireline winch failure (drive, brake, drum, etc.)	1.00E-08	1.00E-06	1.25E-06
			1.00E-07	3.50E-07
WL-SURFACE-S3	System interlock failure **and**	1.00E-03	1.00E-02	2.60E-06
	Wireline winch failure (drive, brake, drum, etc.)	1.00E-08	1.00E-07	
WL-SURFACE-S4	System Interlock Failure **and**	1.00E-03	1.00E-02	3.50E-06
	Wireline Winch Failure (Drive, Brake, Drum, etc.)	1.00E-08	1.00E-06	
Trip-in Drop: Initial Failure Probability = 5.09E-05				
WL-TRIPIN-S1	WP drop overtension is sufficient to break wireline	1.00E-03	1.00E-04	5.91E-06
			1.00E-05	1.41E-06
WL-TRIPIN-S2	Cask closure (as applicable) interlock failure	1.00E-03	1.00E-02	5.54E-05
	Wellhead control (e.g., BOP) interlock failure	1.00E-03	1.00E-02	
WL-TRIPIN-S3	Wireline damage and fatigue sufficient to break	1.00E-04	1.00E-03	5.45E-05
WL-TRIPIN-S4	WP drop overtension is sufficient to break wireline **and**	1.00E-03	1.00E-05	5.91E-06
	Cask closure (as applicable) interlock failure **and**	1.00E-03	1.00E-02	
	Wellhead control (e.g., BOP) interlock failure	1.00E-03	1.00E-02	
WL-TRIPIN-S5	WP drop overtension is sufficient to break wireline **and**	1.00E-03	1.00E-05	5.01E-06
	Wireline damage and fatigue sufficient to break	1.00E-04	1.00E-03	
Stuck: Initial Failure Probability = 2.81E-06				
WL-STUCK-S1	Casing collapse after caliper log test	1.71E-06	1.00E-05	1.11E-05
WL-STUCK-S2	Junk basket fails to catch concrete or other debris	1.00E-05	1.00E-04	1.18E-05
Trip-out Drop: Initial Failure Probability = 9.04E-07				
WL-TRIPOUT-S1	Cask closure (as applicable) interlock failure	1.00E-03	1.00E-02	5.40E-06
	Wellhead control (e.g., BOP) interlock failure	1.00E-03	1.00E-02	
WL-TRIPOUT-S2	Wireline damage and fatigue sufficient to break	1.00E-04	1.00E-03	4.50E-06

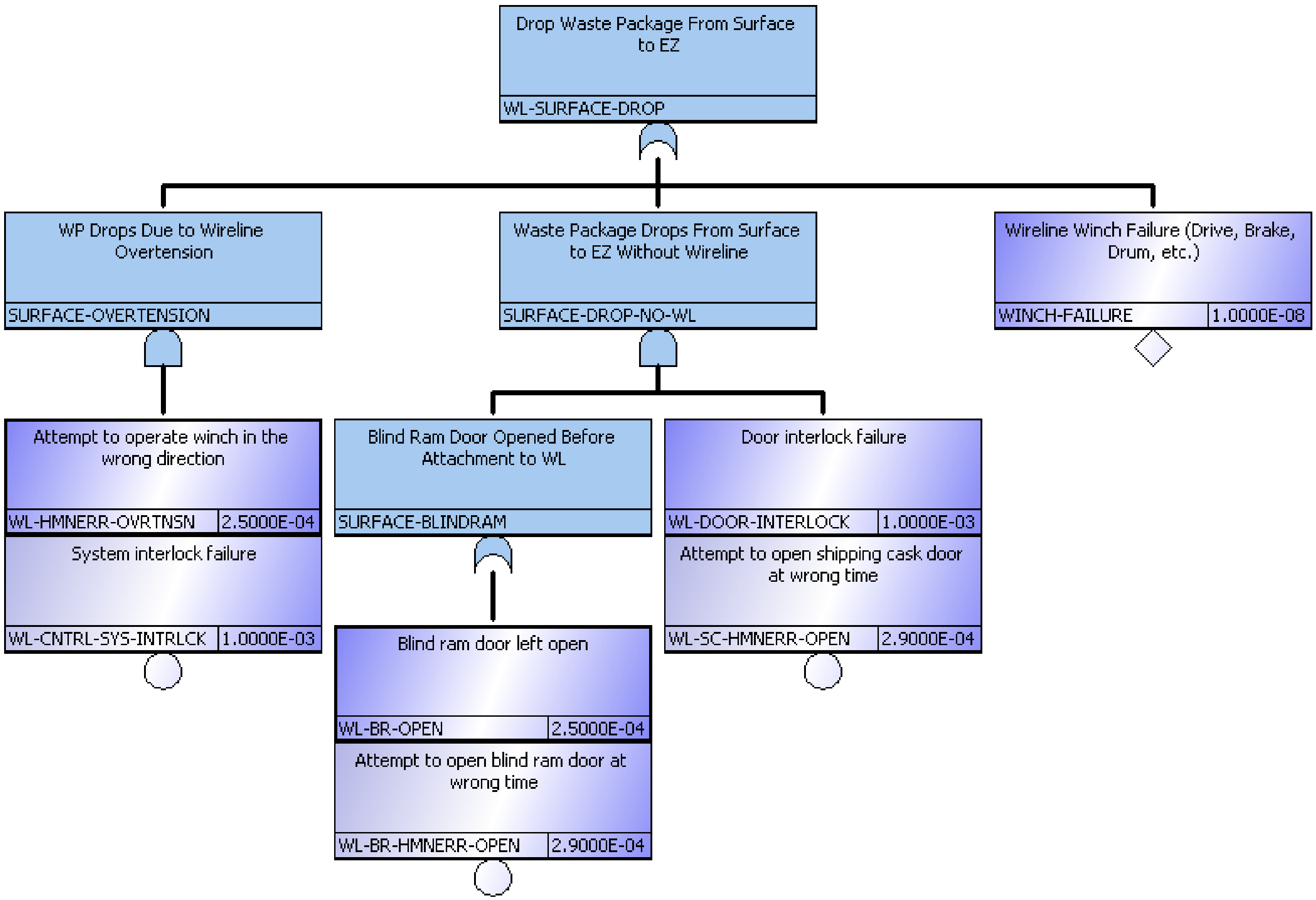

Figure B-1. Fault tree for dropping waste packages from the surface to the disposal zone, with wireline emplacement.

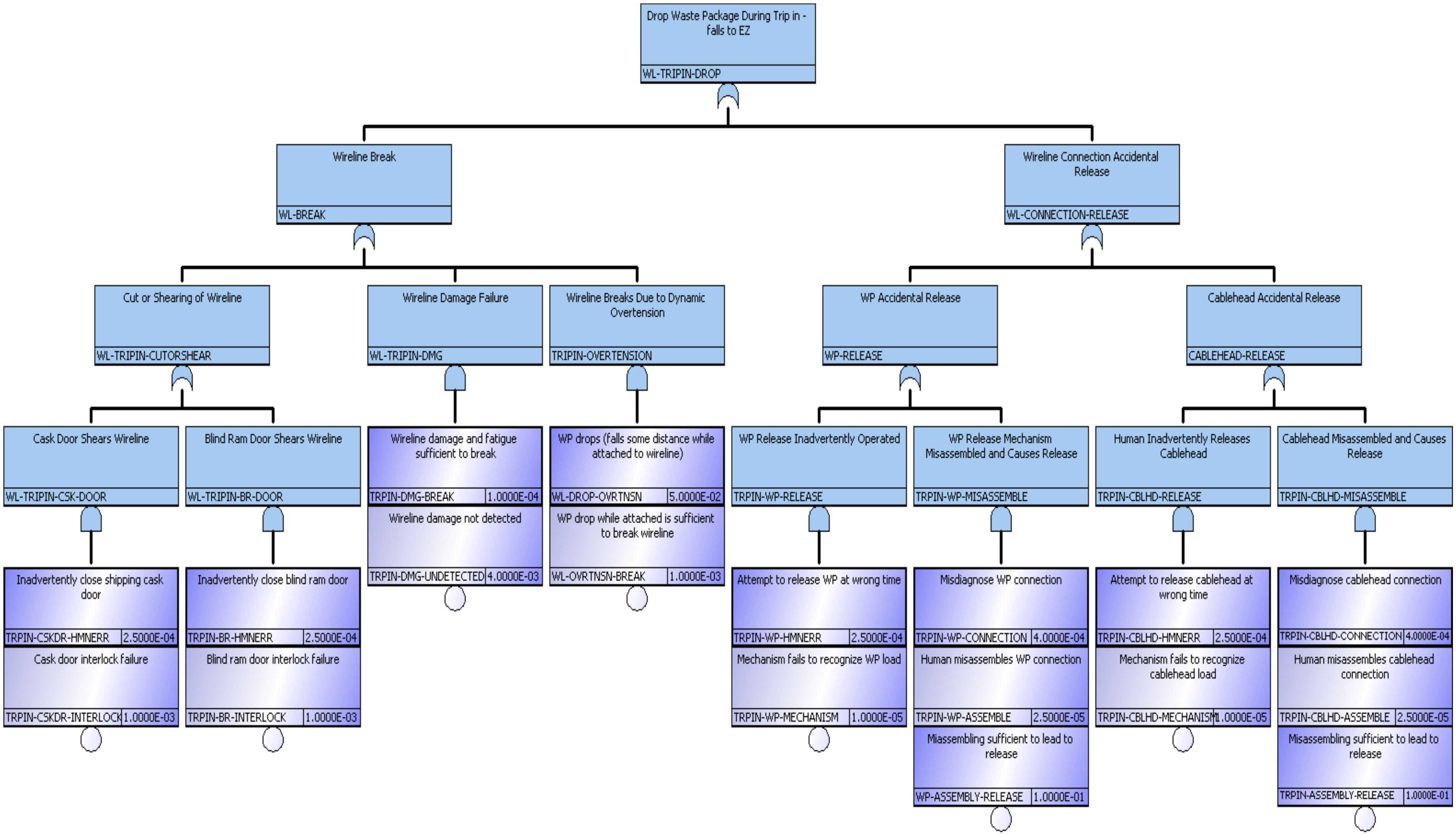

Figure B-2. Fault tree for dropping waste packages to the disposal zone, during the trip in, with wireline emplacement.

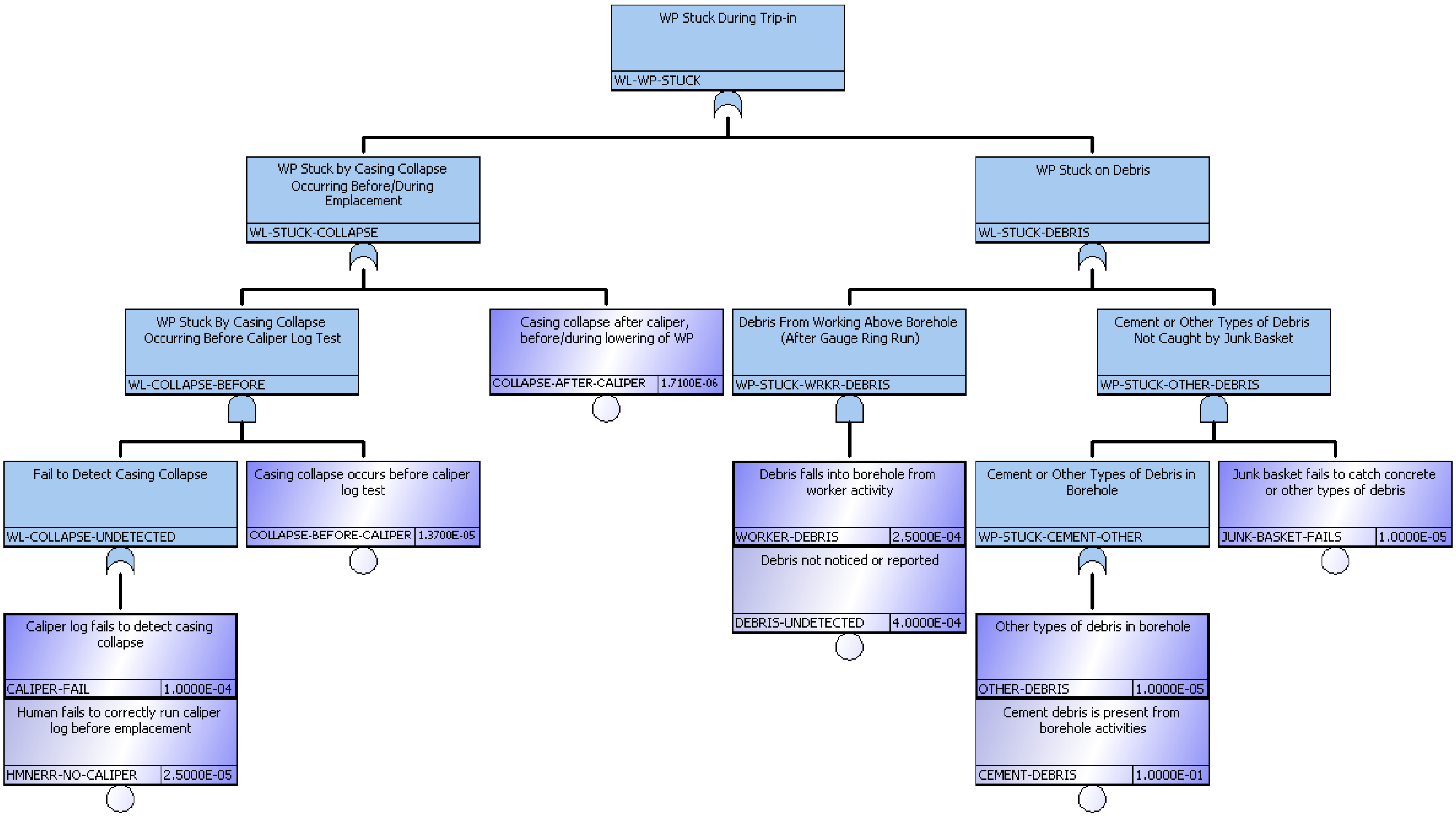

Figure B-3. Fault tree for getting stuck on the trip in, with wireline emplacement.

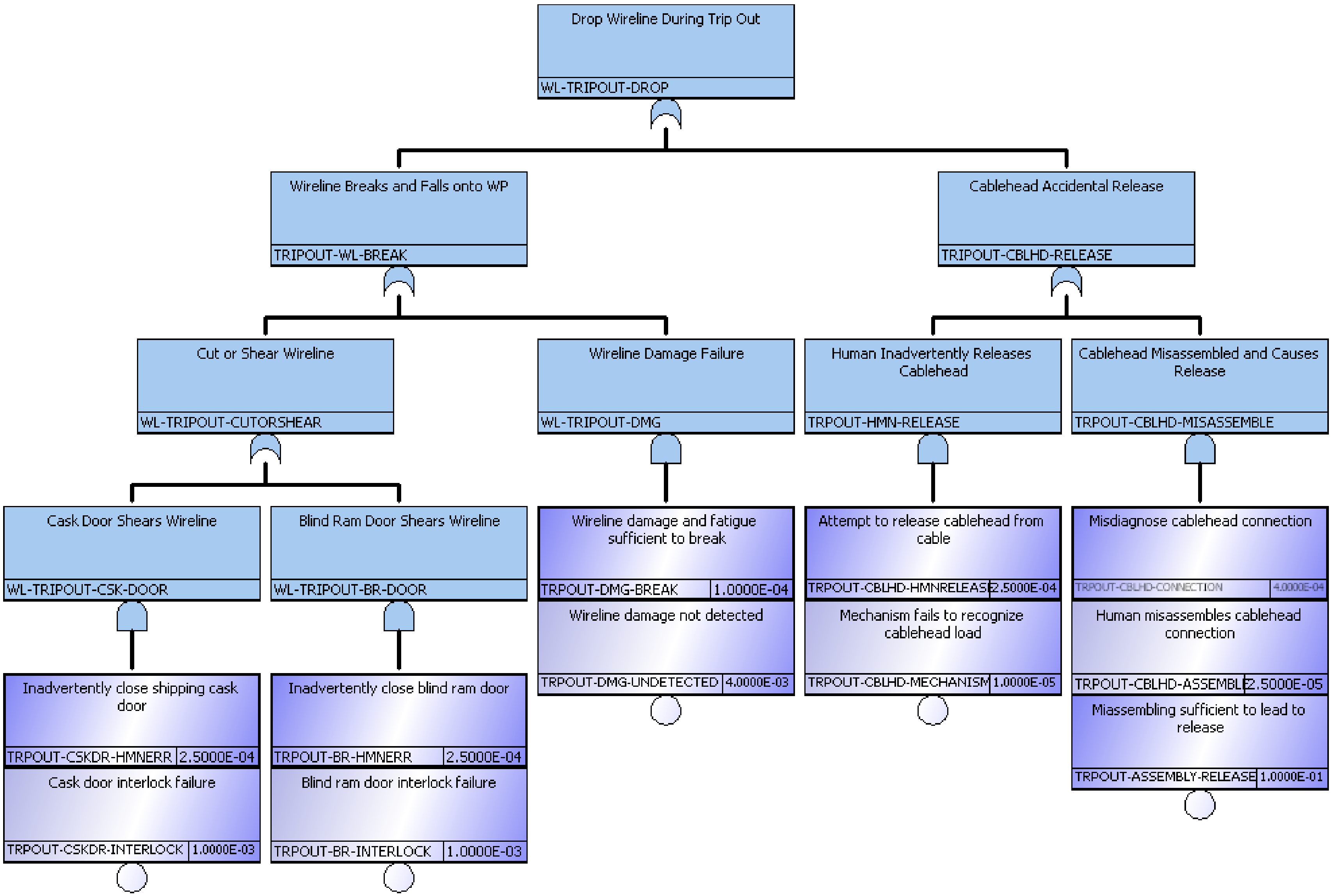

Figure B-4. Fault tree for dropping the wireline (and attached tools) on the trip out, with wireline emplacement.

B.2 Fault Trees for Drill-String Emplacement

Drop a Waste Package String from the Surface During Assembly (Figure B-5)

Inadvertent and simultaneous opening of the basement slips and the elevator ram, by human error, would be controlled by the safety control (interlock) system in a manner similar to wireline emplacement, discussed above.

Failure of the rig draw works would be unlikely because both drive motor failure and failure of redundant brake systems would have to occur. A more complete assessment of draw works reliability might include other components, in lieu of *undeveloped* events. Rigging failure, on the other hand, is much more likely. Whereas the probability of rigging failure leading to drop in nuclear facilities has been estimated at 10^{-4} per lift (e.g., this is typical for preclosure safety analysis in the Yucca Mountain license application), drops are much less common on drilling rigs and workover rigs. These rigs are numerous, they are relatively mature engineered systems, and they perform many thousands of repeated lifts with failure frequency on the order of 10^{-6} per lift. For handling WPs the panel adopted 10^{-5} acknowledging that nuclear regulations could apply. To achieve additional reliability, the hoist and rigging used to assemble WP strings could be engineered to reduce or eliminate single-point failures, as outlined in NUREG-0612. One way to do this could be to use a top-drive rig, and to use the drilling elevator (rather than a cable hoist) to lift the WP string.

For consideration of improper makeup of threaded joints between WPs, large-diameter casing threads were assumed (see Section 2.6.7) because they are more easily cross-threaded than drill pipe threads. Monitoring joint makeup would be an important function of the safety control system, based on automated matching of torque-rotation histories. Visual inspection would also be used. Bad joints could fail immediately when put under load (when slips and elevator ram are opened), or they could fail later as discussed below for the trip in.

With gamma-emitting WPs in the basement, no worker access would be possible, and the equipment (slips, tongs, blowout preventers, mud control) would need to be engineered for reliability, or at least self-recovery. For example, power tongs are known to lock up requiring operator intervention. Another question with tongs is whether one could slip, allowing the other tong to rotate the package string in the slips. The safety control (interlock) system would monitor string movement axially and in rotation, especially during joint makeup or breakout.

Another mishap that could rotate the string is inadvertent rotation of the rotary table on the rig floor, with a kelly attached to the package string. This condition is possible through human error if a conventional rig is used, unless a means other than a kelly (e.g., a tong) is used to make up the joint between the breakaway sub and each package. Neutralizing the rotary table and monitoring by the safety control (interlock) system, is also possible.

Sensitivity Analysis – The main driver for this FT is rigging failure, with other cut sets providing insignificant contributions to the top event probability (less than 1%). Sensitivity case DS-SURFACE-S2 shows that the top event failure rate is very sensitive to the rigging failure rate. As the rigging failure probability increases or decreases by an order of magnitude, so does the top event failure probability. Noting this sensitivity, steps would be taken to ensure the lowest practicable rigging failure rate is achieved.

For sensitivity case DS-SURFACE-S1, the interlock system failure rate is set to the higher limit provided in NUREG-0612. The top event probability is not significantly affected by this change, but the contribution to the top event failure probability for under-torqued and cross-threaded joints is no longer insignificant. Note that with the upper limit for interlock failure probability applied consistently, the interlock failure rate for the basement slips and BOP would also be increased, but this branch of the FT is insignificant.

The draw works sensitivity is explored in case DS-SURFACE-S3. For the draw works failure event, the top event failure probability isn't substantially affected by this event until the failure rate is 10^{-6} or higher.

Drill string surface sensitivity cases DS-SURFACE-S4 and S5 assume that the probability of rigging failure is decreased by an order of magnitude (to 10^{-6} per WP). When the interlock probabilities are assigned the upper limit value from NUREG-0612, then the interlocks and the rigging failure all become drivers for the top event failure probability. Similarly, when the draw works probability is set to its highest sensitivity value (from DS-SURFACE-S3), then the rigging failure and draw works failure are equal drivers for the top event failure probability.

Drop Waste Package String During Trip In (Figure B-6)

Failure of the elevator used with the rig draw works to lower the string for insertion of each pipe stand, is a potentially important cause of drops. The probability of failure on each lift is on the order of 10^{-6} as discussed above, because an elevator is essentially a passive device, and elevators of similar types are used on drilling rigs everywhere.

Failure of the rig slips, and the BOP used as a backup, could occur due to human error but is backed up by the safety control (interlock) system. When a new pipe stand is added, the pipe in the borehole must be lowered to make room for the pipe section that is to be added. The average number of pipe stands (lifts) on the trip in is 138 (for triple stands, and the EZ between 3 and 5 km).

Failure of bad joints between WPs caused by cross-threading or under-torqueing as discussed above, is also included on the trip in because the string will flex in response to borehole deviation. The expert panel assumed that the probability of failure for each joint during the trip in (conditioned on no immediate failure) is equal to the probability of immediate failure.

Bad joint failure for drill pipe is similar to WP joints, but potentially less likely because pipe joints are designed for repeated makeup and breakout. These joints would be made up by automated equipment on the rig floor (iron roughneck) and the safety control (interlock) system would be used to detect and remediate cross-threaded or under-torqued joints. Failure of the rig draw works resulting in runaway during a lift is very unlikely because the hoist has redundant brakes and safety features such as load limiters and over-limit controls that mitigate failure conditions. Drill pipe joint-makeup events while attached to the draw works are repeated 138 times during a trip in.

Reliability of the release mechanism for package strings is discussed in Section 2.6. A higher reliability device (failure probability 10^{-5} per trip in) was assumed by the expert panel.

Another potential failure mode is breach of WPs due to overloading when setting the string on bottom, for example if the operator "crashes" the string at full lowering speed. The panel judged this to be a relatively insignificant risk, and assigned a damage control function to the lead package which would deform and absorb energy, and possibly send a signal to the operator at the surface that when damage occurs. Accordingly, it is not included in the fault tree (Figure B-6).

Sensitivity Analysis – The main driver for this FT is elevator failure during the lift when the draw works is attached to the string. Sensitivity of the top event failure probability to elevator failure is demonstrated in DS-TRIPIN-S1. When the probability is increased to 10^{-5}, the failure rate also increases by an order of magnitude, as seen in Table B-4.

In sensitivity case DS-TRIPIN-S2, the premature WP release event is increased by an order of magnitude. The failure probability nearly doubles and this event becomes a significant contributor to the top event probability. For this sensitivity case, this event and the elevator failure are nearly equal contributors to the top event probability.

Sensitivity case DS-TRIPIN-S3 tested the under-torqued and cross-threaded WP joints that lead to the WP string fall into the borehole. The failure probability increases by about 1.5 when the probability of failure is increased by an order of magnitude for both events. With the failure probability increased, these two events become considerable contributors, but the elevator failure event remains the primary driver.

When the draw works failure probability is increased by two orders of magnitude (from 10^{-8} to 10^{-6}) draw works failure and elevator failure become the primary drivers for this FT, as seen in sensitivity case DS-TRIPIN-S4 (Table B-4.)

Waste Packages Get Stuck (Figure B-7)

The definition of getting stuck is different from wireline emplacement because the pipe string is already connected, so large pulling capability is assured (at the tension limit of the release mechanism). The available force is much greater, especially in the first few minutes or hours after a potential stuck condition is recognized, making the likelihood of becoming stuck significantly less than for wireline. Also, the lead package (lowermost) in a string would have a weak point (with strength less than the release mechanism) so that if it became stuck on the trip in, the WPs could be separated from the lowermost package by pulling, and recovered.

For drill string emplacement, WP strings are more likely to become stuck in collapsed casing than to become stuck by debris in the borehole. This is because the time interval between qualification of the borehole (gauge ring with junk basket, and acoustic caliper, run on wireline) and the trip in is significantly greater for drill-string operations (at least 40 days compared to less than a day), so the potential for a collapse significant enough to cause a WP string to become stuck is higher. For reasons discussed above, given casing collapse, the probability of getting stuck is less than for wireline.

If initial efforts to pull free are unsuccessful (with reverse circulation) then the drill string would be disconnected (by cutting tools run on wireline inside the drill pipe, if necessary) and the string recovered by pulling the guidance casing. This would require the addition of specialized equipment to the rig basement to secure the stuck packages to the casing, then cut the casing between packages so they can be removed one at a time. This outcome is included in the discussion of off-normal outcomes in Appendix C.

Sensitivity Analysis

As seen in Figure B-7 and noted above, a casing collapse occurring with telemetry failure is the main driver for this FT. The failure rate for telemetry seems conservative, but this capability is developmental. If the telemetry failure probability is decreased by an order of magnitude then the top event failure rate is also decreased by an order of magnitude. If telemetry failure is decreased by two orders of magnitude (from 10^{-1} to 10^{-3} per trip in) then the top event failure probability is further decreased as seen in case DS-STUCK-S1 (Table B-4). For this sensitivity case, gauge ring failure becomes the primary driver for this FT when the telemetry failure probability is 10^{-3}.

Case DS-STUCK-S2 shows that if the gauge ring failure probability is increased by an order of magnitude, the effect on the top event failure rate is minimal. This event becomes more of a contributor to the top event, but the telemetry failure remains the primary driver.

Drop Pipe String During Trip Out (Figure B-8)

On the trip out there would be no joints to make up, and the pipe joints in the string would already have served for the trip in. The important risks would then be associated with drops. The principal cause of drops would be elevator failure, which is unlikely as discussed above. A secondary cause would be failure of the rig slips and the BOP used as a backup, due to human error, but this is backed up by the safety control (interlock) system. Similarly, failure of the rig draw works is very unlikely as discussed for the trip in.

Sensitivity Analysis – As observed for the trip in fault tree (comparing Figures B-5 and B-8) the primary driver for the top event failure probability is the elevator failure event. When the elevator failure probability is increased by an order of magnitude, the top event failure rate also increases by an order of magnitude. When the draw works failure event is increased by two orders of magnitude, the top event failure rate nearly doubles and this event and elevator failure are equal drivers for the top event failure.

Failure of the rig slips, and the BOP used as a backup, could occur due to human error but is backed up by the safety control (interlock) system, and is not further explored. As noted previously when the interlock failure probability is set to 10^{-2} per NUREG-0612, the top event failure rate is not affected.

Table B-3. Summary of top-event probabilities for drill-string fault trees.

Fault Tree	Failure Probability	Primary Responsible Events
Drill-String Emplacement		
Drop packages while assembling WP string	4.08E-04 (per string)	Rigging Failure
Drop pipe and WP string tripping into hole	1.60E-04 (per trip)	Elevator failure during lift with draw works attached to string
WP string or pipe string gets stuck during trip-in	5.61E-05 (per trip)	Casing collapse and telemetry failure
Drop pipe string on WPs during trip-out	1.39E-04 (per trip)	Elevator failure during lift with draw works attached to pipe string

Table B-4. Sensitivity analysis for drill-string emplacement fault tree basic events.

Sensitivity Case	Basic Event(s)	Initial Probability	Sensitivity Probability	Failure Probability of Top Event for Sensitivity Case
Surface Drop: Initial Failure Probability = 4.08E-04				
DS-SURFACE-S1	Under-torqued joint interlock **and**	1.00E-03	1.00E-02	4.80E-04
	Cross-threaded joint interlock	1.00E-03	1.00E-02	
DS-SURFACE-S2	Rigging Failure	1.00E-05	1.00E-04	4.01E-03
			1.00E-06	4.84E-05
DS-SURFACE-S3	Draw works failure (drive, brake, drum, etc.)	1.00E-08	1.00E-06	4.48E-04
			1.00E-07	4.12E-04
DS-SURFACE-S4	Rigging Failure **and**	1.00E-05	1.00E-06	1.20E-04
	Under-torqued joint interlock **and**	1.00E-03	1.00E-02	
	Cross-threaded joint interlock	1.00E-03	1.00E-02	
DS-SURFACE-S5	Rigging Failure **and**	1.00E-05	1.00E-06	8.80E-05
	Draw works failure (drive, brake, drum, etc.)	1.00E-08	1.00E-06	
Trip-in Drop: Initial Failure Probability = 1.60E-4				
DS-TRIPIN-S1	Elevator failure during lift	1.00E-06	1.00E-05	1.40E-03
DS-TRIPIN-S2	Waste package string released prematurely	1.00E-05	1.00E-04	2.50E-04
DS-TRIPIN-S3	Under-torqued joint between WPs sufficient to fail **and**	1.00E-04	1.00E-03	2.30E-04
	Cross-threaded joint between WPs sufficient to fail	1.00E-04	1.00E-03	
DS-TRIPIN-S4	Draw works failure (drive, brake, drum, etc.)	1.00E-08	1.00E-06	2.97E-04
			1.00E-07	1.72E-04
Stuck: Initial Failure Probability = 5.61E-05				
DS-STUCK-S1	Lead package doesn't detect collapse (telemetry failure)	1.00E-01	1.00E-02	6.81E-06
			1.00E-03	1.88E-06
DS-STUCK-S2	Gauge ring fails to catch concrete or other types of debris	1.00E-05	1.00E-04	6.51E-05
Trip-out Drop: Initial Failure Probability = 1.39E-04				
DS-TRIPOUT-S1	Elevator failure during lift	1.00E-06	1.00E-05	1.38E-03
DS-TRIPOUT-S2	Draw works failure (drive, brake, drum, etc.)	1.00E-08	1.00E-06	2.76E-04
			1.00E-07	1.52E-04

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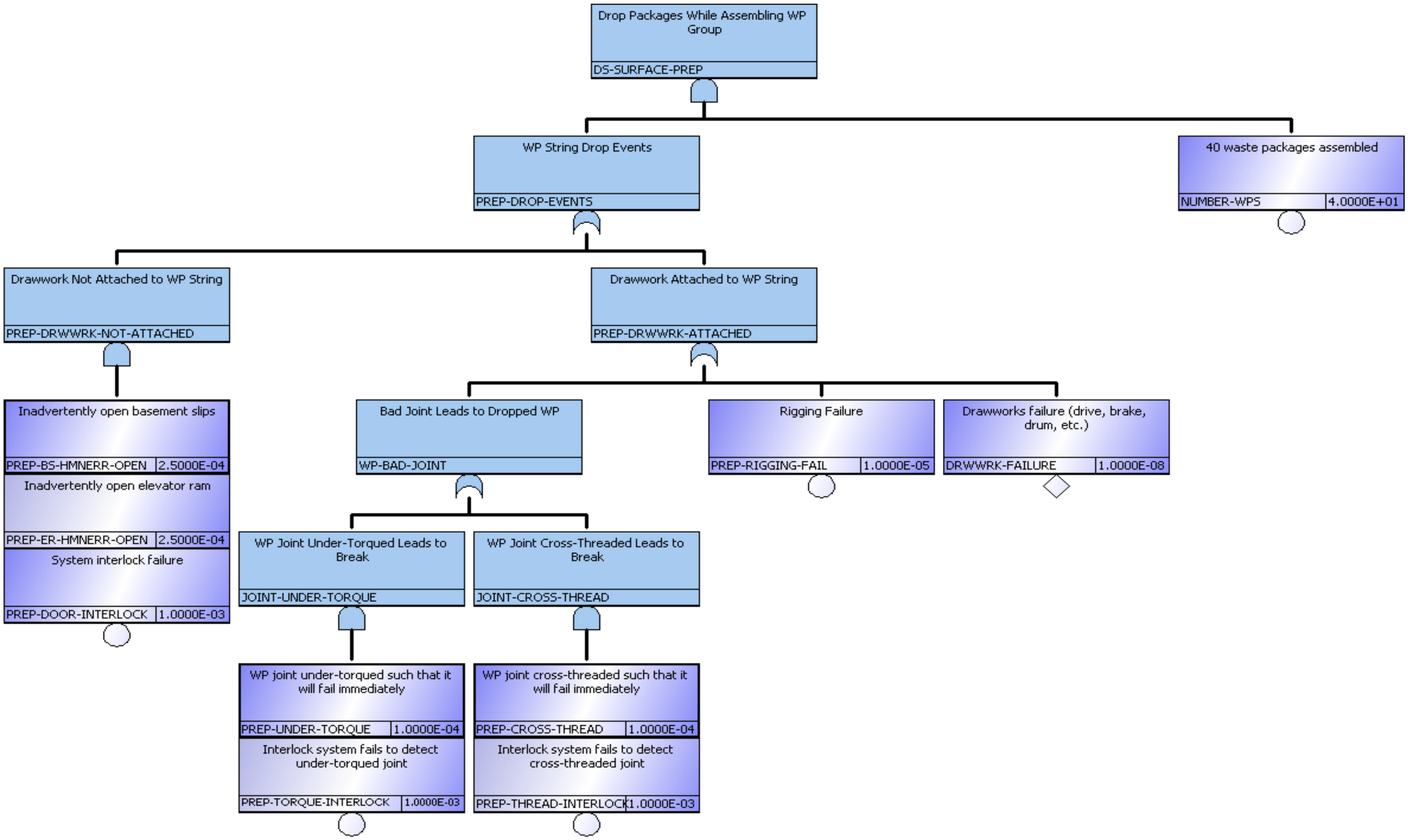

Figure B-5. Fault tree for dropping a waste package string from the surface to the disposal zone, with drill-string emplacement.

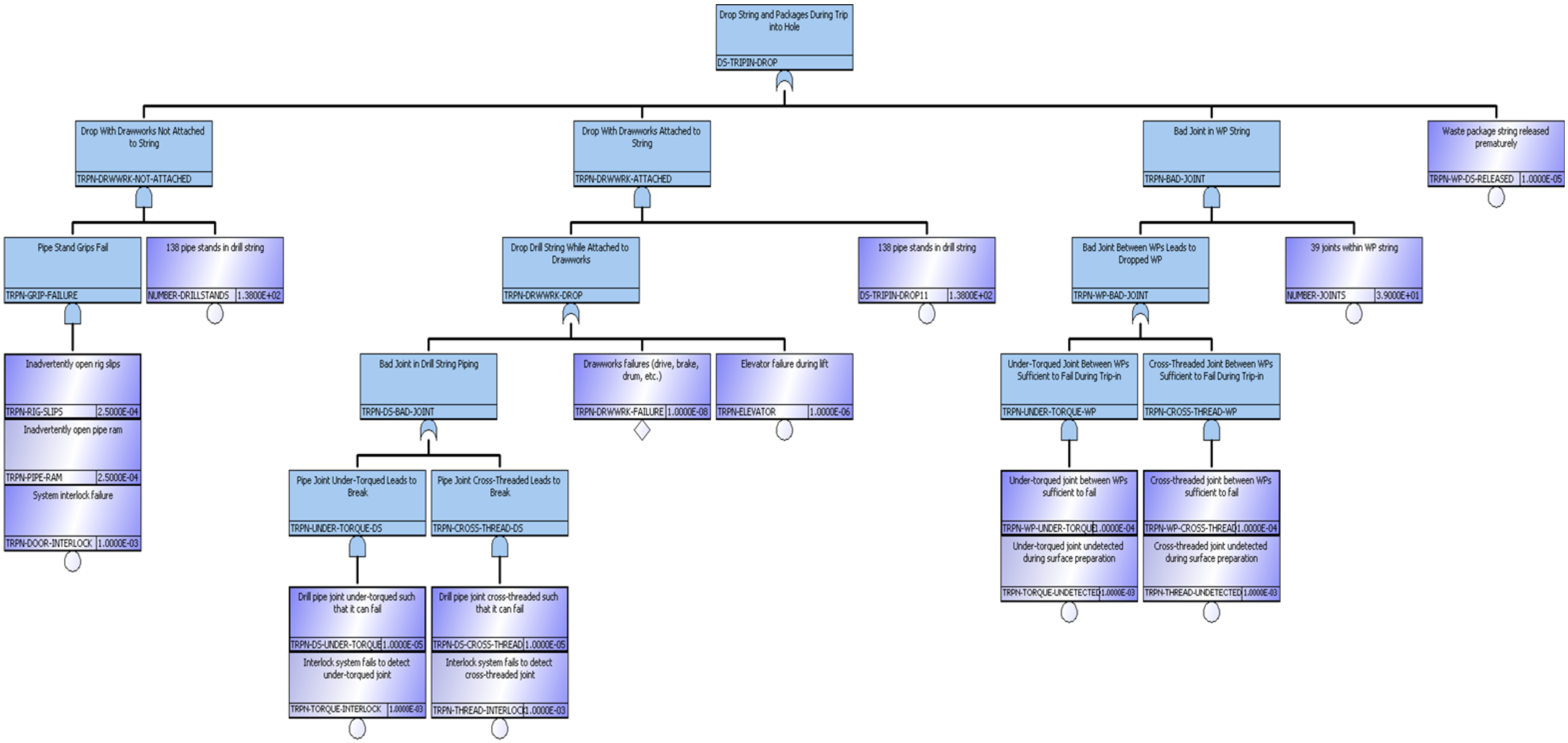

Figure B-6. Fault tree for dropping a string of waste packages to the disposal zone, during the trip in, with drill-string emplacement.

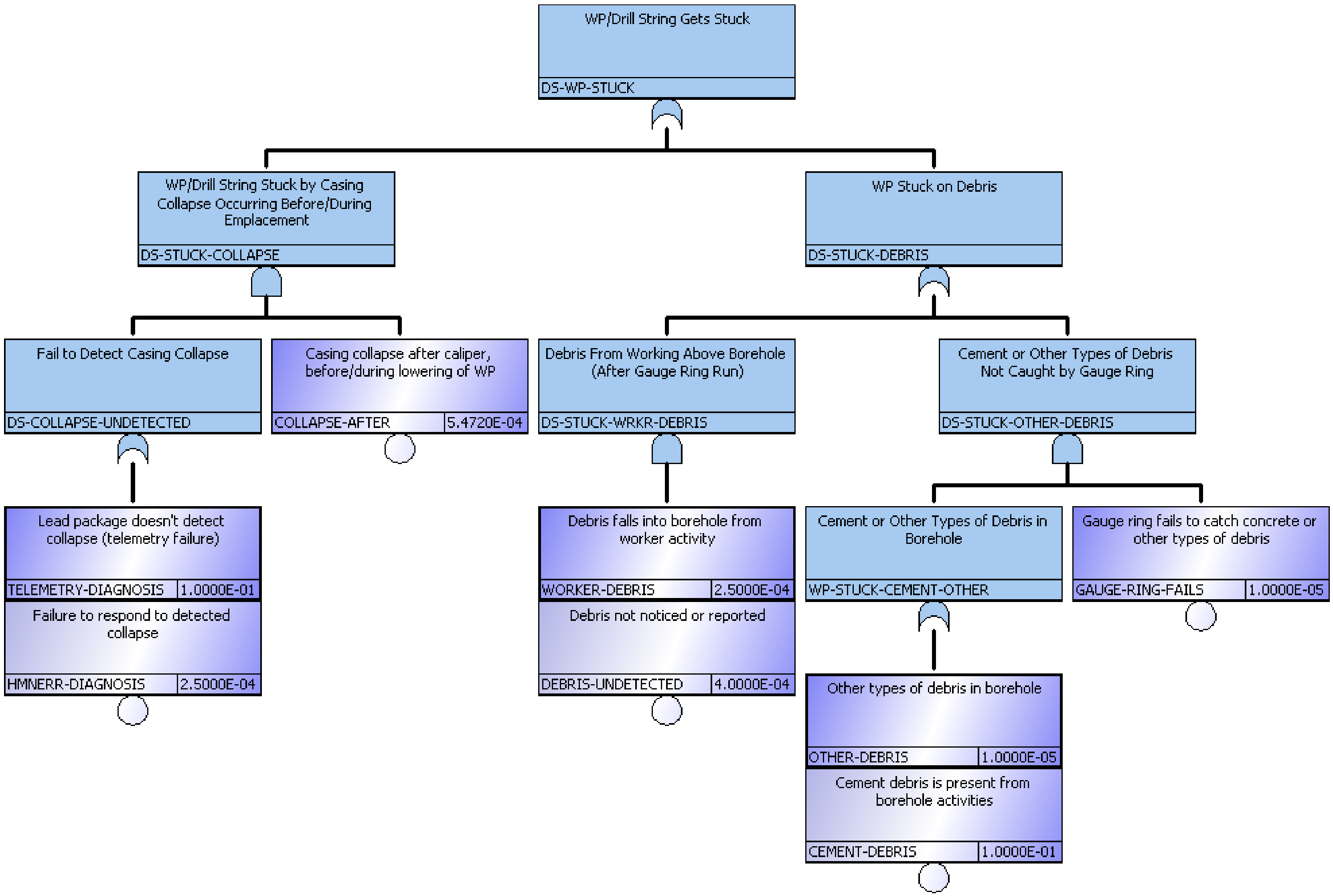

Figure B-7. Fault tree for getting stuck on the trip in, with drill-string emplacement.

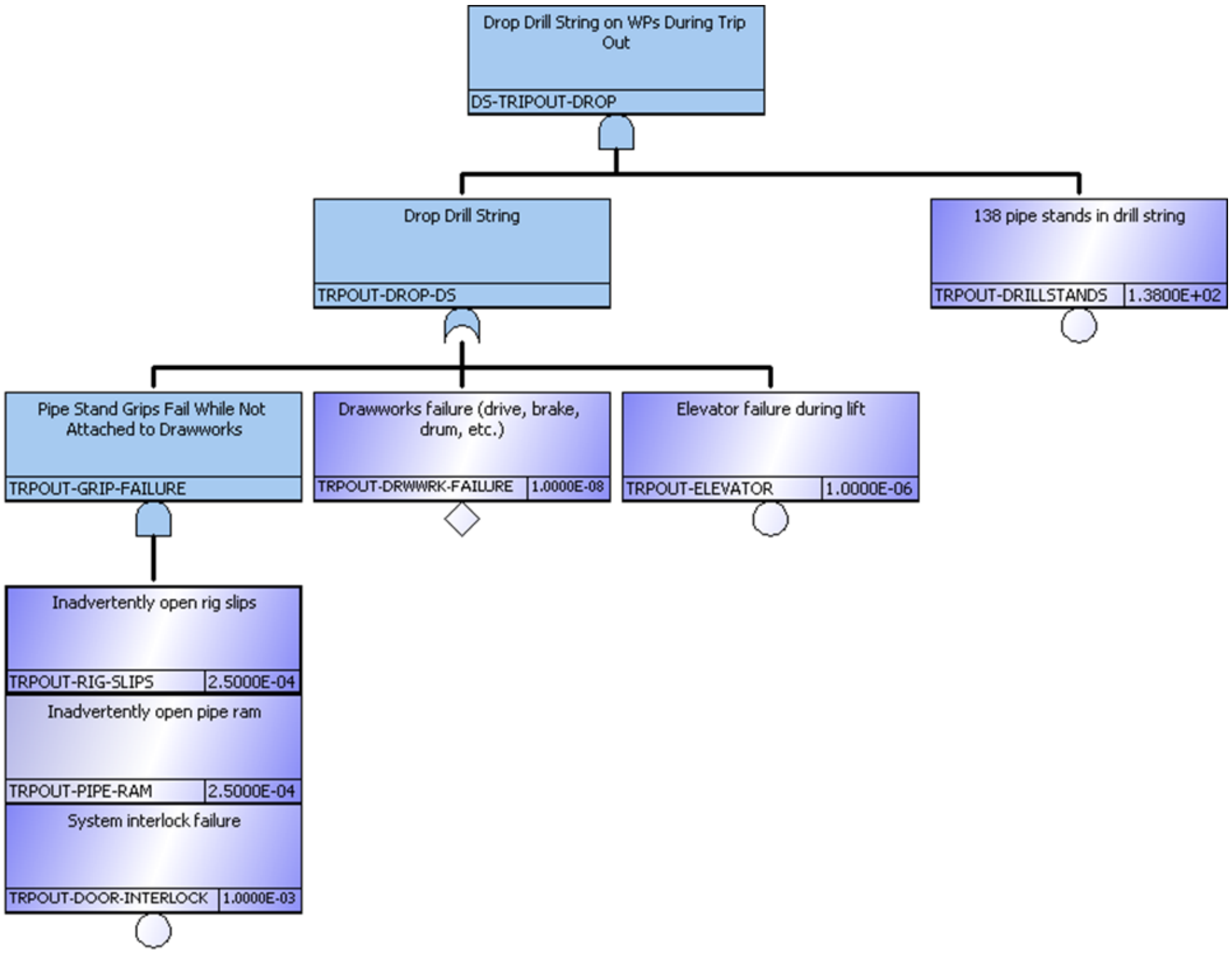

Figure B-8. Fault tree for dropping the pipe string on the trip out, onto waste packages, with drill-string emplacement.

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Appendix C. Normal and Off-Normal Cost Estimates for Design Selection Study

This appendix describes rough-order-of-magnitude (ROM) cost estimates for two WP emplacement method options for deep borehole disposal: drill-string and wireline. It summarizes major cost drivers, considers some alternatives, and identifies major uncertainties in the estimates.

C.1 Cost Estimates – Normal Operations

Description of the emplacement method options comes from Section 2.9. The intended use of cost information is the cost-risk study described in Appendix A, with the principal objective of recommending one of the emplacement methods.

The project costs estimated here are for emplacement operations only, and do not include costs that are common to both options, including drilling, constructing, plugging and sealing the emplacement borehole, and transporting WPs to the disposal site.

C.1.1 Cost Drivers – Normal Operations

Time Dependence

Much of the cost for either option will be tied to time-related charges; that is, daily rental for a drill rig, wireline unit, or other major components. This is a linear cost so any reduction in time required pays a defined benefit. Note that many cost categories in the estimates are lumped, for example, the daily drill rig cost includes not only rental on the rig, but fuel, transportation, supervision, camp costs, and all the other miscellany required to operate the rig.

The time needed to complete emplacement operations in each borehole will be primarily determined by the rate at which WPs are delivered to the site, currently estimated at one canister per day. If that rate were increased, it could help to drive down emplacement costs.

Geography

The disposal site will likely be in a remote location, and all drilling and service companies require a mobilization charge. For one-time moves such as the drill rig or the wireline unit this may not be a major cost factor, but for repeated, periodic operations the total mobilization cost could be significant.

For the specific case of coiled-tubing cement jobs for the wireline option, a very large reel of tubing is required approximately every 40 days. Transport of this reel requires special permits and has limited routes available, driving up mobilization/demobilization costs.

For this study geography is assumed not to be a major cost factor, if the site is located in a region with an active oilfield service industry, on level ground (see topography attributes in Arnold et al. 2014), and if good roads are constructed and maintained.

Site Conditions

The nature of the ground around the borehole will also affect site preparation and construction costs. Some site preparation will already have been done for the rig that drilled the borehole, but hard bedrock close to the surface could significantly increase construction costs. For this study, surface geology is assumed to be deep, consolidated soils or weathered sedimentary rock in which construction of roads, pads, and the basement for drill-string operations can be performed simply and safely.

Temperature

Heat generating WPs will not be thermally hot enough to affect performance of telemetry packages, cable head, or release mechanisms during emplacement operations. The maximum *in situ* temperature of 170°C (Table 2-4) without waste heating, requires high-temperature electronics. Commercial logging and production tools operate below 20,000 ft and already have this capability. Heating by certain waste forms will occur throughout emplacement operations, but the tool string will not approach peak temperatures for weeks or months (see Sections 5.2 and 5.3), and downhole temperatures can be controlled if necessary by circulating the borehole fluid.

Accordingly, the cement plugs above each stand of WPs in the EZ (Sections 2.7.4 and 3.1) will not be heated significantly above *in situ* temperature during operations. Note that if these intervals did heat up enough, there would be an impact on cementing costs because retarders (which are expensive) would be used.

Market – One of the strongest predictors of drilling and workover costs is the price of crude oil. When oil prices are high, rigs and services are more expensive. The impact on cost may not be large (e.g., 10 to 15%) but scheduling can be difficult with bookings a year or more in advance. Similarly, casing and other tubular goods could also have long lead times. For this study current market conditions are assumed so that cost impacts are minimal.

C.1.2 Operational Alternatives for Normal Operations

Rent or Buy – Both emplacement method options, drill-string and wireline, use common drilling equipment over long periods but at low frequency (i.e., emplacing one canister per day). Normal drilling operations emphasize speed and efficiency, and equipment requirements change often, so much of the necessary equipment is rented for relatively short periods. For a long-duration project with fixed requirements and repeated operations, it could be advantageous to buy much of the equipment that would be rented on a more conventional job. Rental is the clear choice for a prototype disposal operation of limited duration, but once disposal operations begin on a larger scale, the purchase option could lower costs significantly for both emplacement method options.

For this study, rent-or-buy is possibly the most important choice affecting cost. The estimates are based on rental because it is expected that future decisions to buy and operate major equipment for WP emplacement, would be deferred until after an initial, developmental phase of waste emplacement. Such future decisions would be informed by operational experience. Also, the rent-or-buy choice would likely affect both emplacement options in the same way (e.g., lower project cost with bought equipment) so the impact on this study is less than might be suggested by comparison of rental vs. purchase costs.

Drill-String Emplacement of Single Packages

The reference concept is to build strings of up to approximately 40 WPs and run them into the borehole on drill pipe. After each string is emplaced, a bridge plug and a 10-meter cement plug are set to support the next package string (and to support the guidance casing). Making up the threaded connections between packages requires unmanned slips and power tongs below the drill rig, adding to the depth and complexity of the basement (Section 2.9).

This discussion leads to the question whether it could be more efficient for the drill-string method, to run each single package into the hole on drill pipe as it is delivered. This could simplify the equipment and procedures used to emplace packages by the drill-string method, but it has two major drawbacks. The trip time was estimated to be on the order of 32 hours (Section 2.9), so emplacement would be schedule driven and would likely not keep up with deliveries. In addition, the additional trips in and out of the borehole with drill pipe would increase the probability of an accident that could breach a WP (e.g., dropping the string) substantially (see Section A.6.3). Accordingly, for this study the drill-string method is estimated using strings of 40 packages.

Basement for Wireline Option

The current concept for wireline emplacement uses an above-ground radiation shield around the wellhead. The WP shipping cask would be placed on top of the shield by a crane. The wellhead could also be installed below grade to decrease the height of the lifts needed (and reduce the risk of package breach from a drop event). Given the assumption of safe and simple excavation conditions, the cost of either configuration would be the same.

Access for a Coiled Tubing Rig

Cement plugs would be emplaced using a coiled tubing rig. If coiled tubing operations were impractical, a workover rig would be needed to emplace cement through drill pipe. This would mean that a site configuration like the drill-string option would be needed, including a basement. For this study, site location and access are assumed to allow use of any equipment including coiled tubing.

C.1.3 Cost Uncertainties for Normal Operations

Costs are divided into time-dependent and one-time categories. Daily rates for the various rentals (drill rig, wireline unit, crane, tongs, slips, etc.) should be reasonably reliable (e.g., +/-30%) but duration of the borehole waste emplacement project may be less predictable.

Cost of the periodic cementing and plugging operations, as discussed above could be significantly different from these estimates if the site location or access is problematic.

One-time costs for site preparation and construction of the pads, basement, radiation shield, control room, etc. also depend on site conditions. Moreover, detailed designs for these features have not been developed. Accordingly, estimates for these items have relatively large uncertainties. Also, any efficiencies gained with experience from loading and completing repeated disposal boreholes, are not incorporated in these estimates.

C.1.4 Cost Estimate Summary for Normal Operations

A breakdown of ROM cost estimates is provided in Table C-1. The predominant cost items are daily rental costs for the workover rig, or for the wireline rig and coiled tubing rigs.

For drill-string operations, the same workover rig estimated for emplacement would be used to seal and plug the hole (hook load for borehole completion is only slightly higher than for handling a drill string). For wireline emplacement operations, a similar workover rig would be needed to seal and plug the hole after emplacement. Hence, the mobilization/demobilization and daily rig costs for completion activities are the same for both emplacement methods, and are not included in these cost estimates. Other completion costs, such as sealing and plugging materials and placement, are also not included.

The wireline rig would be the Schlumberger Tuffline® 18000 skid-mounted winch, or comparable equipment, which would be truck mounted or installed at the surface near the borehole. A more conventional wireline and winch system could be used at lower cost, but would have less load capacity and would be more prone to cable damage (Section 2.9).

Project duration (time dependence discussed above) is the principal cost driver, and estimates for shorter durations are shown in Figure C-1. These were calculated by increasing the rate of WP delivery and emplacement from one per day, to 2, 3 and 4 per day, for the total of 400 WPs. These average throughput rates could be achieved by the wireline and drill-string emplacement options, considering estimated trip times (SNL 2015).

Setting of 10 cement plugs in the EZ, using either coiled tubing (for wireline) or drill pipe (for drill-string emplacement operations) has a fixed duration of 30 days, which allows approximately 3 days for each plug to cure. Thus, the total duration of normal emplacement operations for either method is estimated to be 430 days.

Table C-1. Cost estimate breakdown for waste package emplacement options

Waste Package Emplacement Cost Estimates		
Number of waste packages	400	
Project duration	430	days
Number of intermediate plugs	10	
Drill-String Option		
Time-Dependent Costs	**Daily Rate**	**Subtotal**
Drill rig (workover)	$ 75,000	$ 32,250,000
Crane	$ 6,000	$ 2,580,000
Iron roughneck	$ 3,000	$ 1,290,000
Power tongs	$ 1,000	$ 430,000
Power slips	$ 3,000	$ 1,290,000
BOP stack	$ 2,500	$ 1,075,000
Subtotal		$ 38,915,000
Intermediate plugging costs	**Each**	**Subtotal**
Bridge plugs	$ 20,000	$ 200,000
Cementing	$ 40,000	$ 400,000
Wireline cementing surveys	$ 80,000	$ 800,000
Subtotal		$ 1,400,000
One-Time Costs		
Build pad and basement		$ 500,000
Build structural frame		$ 100,000
Build transfer track system		$ 1,000,000
Subtotal		$ 1,600,000
Total Drill-String Emplacement Project Cost		**$ 41,915,000**
Wireline Option		
Time-Dependent Costs	**Daily Rate**	**Subtotal**
Wireline unit	$ 37,000	$ 15,910,000
Crane	$ 6,000	$ 2,580,000
BOP stack	$ 2,500	$ 1,075,000
Subtotal		$ 19,565,000
Intermediate plugging costs	**Each**	**Subtotal**
Bridge Plug	$ 20,000	$ 200,000
Coiled-tubing unit and cementing	$ 200,000	$ 2,000,000
Wireline cementing surveys	$ 80,000	$ 800,000
Subtotal		$ 3,000,000
One-Time Costs		
Build headframe		$ 500,000
Build pad and control room		$ 350,000
Build radiation shield enclosure		$ 100,000
Subtotal		$ 950,000
Total Wireline Emplacement Project Cost		**$ 23,515,000**

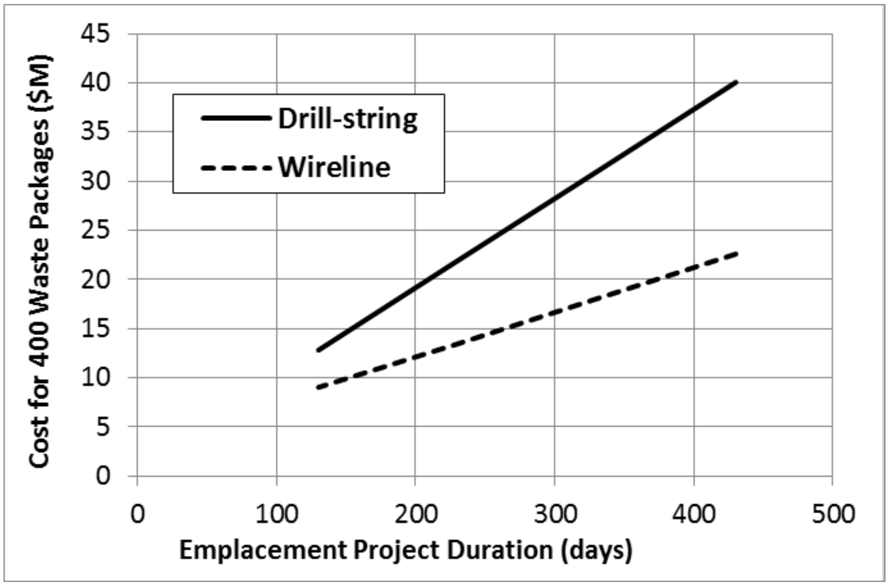

Figure C-1. Project cost vs. duration, for drill-string and wireline options.

C.2 Cost Estimates for Off-Normal Outcomes

Costs are estimated for accidents that occur only during waste emplacement in a single borehole (and not during drilling and construction, setting cement plugs during emplacement, and final sealing of the borehole). These costs are for special operations subsequent to accidents, identified as five scenarios A through E, plus three more related cases (Tables C-2 and C-3). The estimates do not include costs that would occur with normal operations such as sealing and plugging the disposal borehole, and de-mobilization.

Estimated costs range over more than an order of magnitude depending on whether WP breach is detected, leading to decontamination and disposal of contaminated fluids, drill rig, and other equipment. Regulatory delay of either 1 or 2 years is also incorporated after an accident depending on whether breach has been detected.

C.2.1 Off-Normal Outcomes

"A" Outcomes – One or more WP(s) breached above the EZ

One or more WPs is breached above the EZ, i.e., above approximately 3 km depth. Breach is defined as detection of anomalous radiation downhole (e.g., gamma tool in wireline tool string or drill-string instrumentation package), or in mud returns. Once a radiation leak has been verified, all operations will come to a complete stop with no further insertion or withdrawal of tools in or from the borehole, and no fluid circulation. Complete stop is necessary to protect rig workers, because it is assumed that decontamination and radioactive waste management facilities are not yet available at the site.

It is assumed that no additional WPs will be emplaced in a borehole after breach. Instead, that activities will focus on stabilizing the spread of contamination at the surface and in the subsurface, retrieval of waste from above the EZ, sealing and plugging of the borehole, and management of the low-level waste (LLW) accumulated at the surface.

One of the first activities after breach is detected will be purchase of all rented equipment by the operator because contamination is very likely if it has not occurred already. This will decrease or eliminate standby charges during remediation planning. It is assumed that purchase provisions, in the event of a verified radiation leak downhole, are incorporated into all equipment contracts. Estimated costs for writeoff of the drill rig and related equipment, or writeoff of a wireline truck and coiled-tubing rig, are $30M and $20M, respectively. These costs are uncertain and could vary from $15M to $50M.

Once the equipment is operator-owned, a skeleton crew will maintain it in operable condition and maintain site security. All equipment on site including any drill rig, mud and cement handling equipment, wireline truck, and/or coiled-tubing rig, is assumed to be contaminated at this point such that it cannot be moved. Eventually it will be used for fishing, pulling casing, sealing and plugging activities, during which it is likely to become further contaminated. Ultimately it will be decontaminated and disposed of as LLW.

After a 2-year delay for regulatory review and remediation planning, response facilities will be built (Section C.3), and fishing operations will be conducted to retrieve the WP(s) to surface. If wireline emplacement was in use when the WPs became stuck, the wireline will be detached and retrieved, and a drill rig mobilized to the site. If drill-string emplacement was in use, the drill string will be withdrawn, decontaminated, stored temporarily, and used for fishing. If withdrawal is not possible, the string will be removed in sections. Fishing duration of 20 days is assumed because successful fishing will likely be accomplished in this time frame (and increasingly likely to be unsuccessful if protracted).

Emplacement fluid would be circulated out of the hole during fishing operations. It is assumed that 3 hole volumes, plus the original volume, will be circulated and stored at the surface (totaling 3,400 m^3; see Section C.3) to remove subsurface contamination to the extent possible.

The outcome then differs according to whether fishing successfully removes WPs stuck above the EZ (A1 and A3) or fishing fails and one or more WPs are left in place (A2) (Table C-2). In both cases additional costs are incurred for fishing, building and operating radiological response facilities, LLW management, disposal of the drill rig and related equipment, loss of disposal borehole capacity, and long-term site monitoring (100 years). If WPs are recovered they will be decontaminated to the extent possible, inspected, and shipped back to the point of origin for remediation. If fishing fails, an additional delay of 1 year is assumed for regulatory review, then the borehole will be sealed and plugged (following a modified plan).

A requirement is assumed for long-term monitoring at the site for at least 100 years, whether or not the stuck WPs are successfully fished, because of the radiological release. This cost could include monitoring wells and periodic sampling. The 100-year time horizon is selected for this study. Monitoring, well pumping, and other activities could extend beyond 100 years depending on site-specific factors.

"B" Outcomes – One or more WP(s) breached within the EZ

One or more WPs is breached within the EZ. For Outcome B1, this occurs because one or more packages are dropped to the EZ, or a wireline or drill-string is dropped onto packages in the EZ. For Outcome B2, one or more packages becomes stuck above the EZ, and fishing is unsuccessful causing one or more breached packages to fall into the EZ.

As described above, once a radiation leak has been verified all operations will come to a complete stop with no further insertion or withdrawal of tools in or from the borehole, and no fluid circulation. It is assumed that no additional WPs will be emplaced in a borehole after breach, and that activities will focus on stabilizing the spread of contamination at the surface and in the subsurface, sealing and plugging of the borehole, and management of the LLW accumulated at the surface.

As noted above one of the first activities after breach is detected will be purchase of all rented equipment by the operator, using purchase provisions incorporated into all equipment contracts. Estimated costs for writeoff of the drill rig and related equipment, or writeoff of a wireline truck and coiled-tubing rig, are $30M and $20M, respectively. Once the equipment is operator-owned, a skeleton crew will maintain it in operable condition and maintain site security.

All equipment on site including any drill rig, mud and cement handling equipment, wireline truck, and/or coiled-tubing rig, is assumed to be contaminated at this point such that it cannot be moved. Eventually it will be used for sealing and plugging activities, during which it is likely to become further contaminated. Ultimately it will be decontaminated and disposed of as LLW.

After a 2-year delay for regulatory review and remediation planning, response facilities will be built (Section C.3), and several volumes of borehole emplacement fluid will be circulated through the hole (totaling 3,400 m^3) to remove subsurface contamination to the extent possible. The borehole will then be sealed and plugged (following a modified plan).

A requirement is assumed for long-term monitoring at the site for at least 100 years, which could include monitoring wells and periodic sampling. The 100-year time horizon is selected for this study. Monitoring, well pumping, and other activities could extend beyond 100 years depending on site-specific factors.

“C” Outcomes – Unbreached but possibly damaged WP(s) in the EZ

Waste packages are dropped and come to rest intact unbreached within the EZ. A radiological survey will be conducted to verify the unbreached condition of the WPs, using either a wireline tool run within drill pipe (for drill-string emplacement), or a detector that is part of the wireline tool string (wireline emplacement). The outcome differs as to whether junk (either drill pipe or wireline, depending on emplacement method) is dropped on top of them (C2) or not (C1).

After 1 year of replanning and regulatory review, if the WPs are free of junk then a cement plug will be installed and emplacement will continue (C1). No loss of disposal capacity is assumed.

Any junk present (C2) will be fished using a drill rig. For drill-string emplacement operations, the same rig will be used. For wireline operations, a rig will be mobilized to the site then de-mobilized when fishing is complete. Fishing will be performed with moderation so as not to breach WPs, and junk may be left in the hole if appropriate. Fishing duration of 20 days is assumed because successful fishing will likely be accomplished in this time frame. A cement plug will then be installed and emplacement will continue. Any WPs fished from the hole because they are attached to large pieces of junk, will be inspected and shipped back to the point of origin for remediation. For costing it is assumed that only one WP is recovered during fishing.

"D" Outcome – One or more WP(s) become stuck within the EZ before reaching the intended disposal depth

One or more WPs become stuck in the EZ during emplacement. A radiological survey will be conducted to verify the unbreached condition of the WPs, using either a wireline tool run within drill pipe (for drill-string emplacement), or a detector that is part of the wireline tool string (wireline emplacement). The wireline or drill string will then be detached and withdrawn. The drill string will not be used to push down on WPs (to free them) because they are already located in the EZ, and because there will be no further emplacement in any borehole where stuck conditions occur.

The drill rig and associated equipment, or the wireline and coiled-tubing rigs and their associated equipment, will be de-mobilized during replanning as a cost-saving measure. Although keeping a rig on site during replanning and regulatory review could help stabilize the stuck WPs, for costing it is assumed that they are setting on the bottom (i.e., at total depth, or on a cement plug). After a 1-year delay for replanning and regulatory review, a workover rig will be mobilized to the site. The EZ below the stuck WP(s) will be cemented to the extent possible, then the borehole will be sealed and plugged, without emplacing additional WPs. The cementing, sealing, and plugging activities (including casing removal) are within the scope of normal operations and are not costed here (Hardin 2015).

"E" Outcomes - One or more WP(s) become stuck above the EZ

One or more unbreached WPs are stuck above the EZ. WPs stuck using drill-string emplacement are assumed to be stuck in full connected strings. A radiological survey will be conducted to verify the unbreached condition of the WPs, using either a wireline tool run within drill pipe (for drill-string emplacement), or a detector that is part of the wireline tool string (wireline emplacement).

For wireline emplacement operations, the wireline will then be detached and withdrawn, and a drill rig will be mobilized to the site. For both drill-string and wireline operations, the drill rig will be used with drill pipe to stabilize the fish to the extent possible, to reduce the likelihood that the WP(s) will fall. The drill string will not be used to push down on the fish because that could push WPs through and drop them to the bottom.

After a 1-year delay for regulatory review and remediation planning, fishing operations will be conducted to retrieve the WP(s) to surface. Fishing duration of 20 days is assumed because successful fishing will likely be accomplished in this time frame (and increasingly likely to be unsuccessful if protracted).

The outcome then differs according to whether fishing successfully removes WPs stuck above the EZ (A1) or fishing fails and one or more WPs are left in place (E2) (Table 1). In both cases additional costs are incurred for fishing and loss of disposal borehole capacity. If WPs are recovered they will be decontaminated to the extent possible, inspected, and shipped back to the point of origin for remediation.

If fishing fails (E2) an additional delay of 1 year is assumed for regulatory review, then the borehole will be sealed and plugged (following a modified plan). Costs will include long-term site monitoring (100 years) which could include monitoring wells and periodic sampling. The

100-year time horizon is selected for this study. Monitoring, well pumping, and other activities could extend beyond 100 years depending on site-specific factors.

C.2.2 Cost Estimates for Off-Normal Outcomes

Estimated costs (Table C-3) range from a few millions (Outcomes C1 & C2) to approximately $300M (Outcomes A1, A2 & and B). The most important cost driver is WP breach with contamination of the borehole and surface equipment. The costs for radiological response and LLW management are detailed further in Section C.3. The next most important cost driver is leaving WP(s) above the EZ, with the expense of failed fishing, and the requirement for long-term monitoring. Another driver is rig standby time where it cannot be avoided, for example, stabilizing WP(s) stuck above the EZ.

Table C-2. Normal and off-normal outcomes for drill-string or wireline emplacement (from Jenni and Hardin 2015, Table 2).

			Performance metrics			
Outcome		Additional assumptions	Occupational safety	Detectible radiation levels in borehole	Reasons for additional costs	Time to emplace 400 WPs
A *A1 =* *A2 =* *A3 =*	Breached WP(s) stuck above EZ *Successfully fished* *Left in place* *Removed inside guidance casing*	Borehole is either: 1) decontaminated, sealed and plugged after WP(s) are removed (*A1 and A3*); or 2) decontaminated to the extent possible, sealed/plugged and monitored with WP(s) left in place (*A2*).	To be discussed with expert panel and data, estimates, or assumptions developed as necessary. Primary occupational risk may be risk of radiological exposures if servicing emplacement equipment	Yes	For *A1 and A3*, include fishing, decontamination, LLW management, additional costs to seal and close in a contaminated environment, and loss of disposal capacity. For *A2* add costs for long-term (100-year) monitoring.	Time for normal operations, or for remediation of off-normal events.
B *B1 =* *B2 =*	Breached WP(s) in EZ *Breach from dropping WP(s), or dropping wireline or drill-string onto WP(s)* *Breach from unsuccessful fishing above the EZ, with drop into the EZ*	Borehole decontaminated, and completely sealed and plugged with WP(s) in place in the EZ.		Yes	For *B1* include decontamination, LLW management, additional costs to seal and close in a contaminated environment, and loss of remaining disposal capacity. For *B2* add the cost of fishing above the EZ.	
C *C1 =* *C2 =*	WP(s) dropped into EZ unbreached, or junk dropped onto emplaced WP(s) which remain unbreached *Only WP(s) dropped* *WP(s) dropped with drill string attached, or drill-string or wireline dropped onto WP(s)*	Unbreached packages will be left in place and the disposal interval sealed/plugged (*C1*), unless dropped while connected to a drill string (*C2*). Dropped drill pipe (junk) will be removed, and packages also if they are attached. (Retrieved packages will be tested/repackaged). The borehole remains suitable for emplacement of additional wastes.		No	Delay and loss of disposal capacity if a disposal interval is not filled (*C1*). For *C2* add fishing costs for drill string and any attached WPs.	
D	Unbreached WP(s) stuck in EZ	No fishing; borehole sealed/plugged above stuck package; emplacement continues above seal/plug.		No	Delay, loss of disposal capacity.	
E *E1 =* *E2 =* *E3 =* *E4 =*	Unbreached WP(s) stuck above EZ *Successfully fished* *Left in place* *Removed inside guidance casing* *Fishing unsuccessful, WP(s) drop to EZ*	Borehole is either: 1) sealed and closed after package(s) are removed unbreached (*E1 and E3*); or 2) sealed, plugged, and monitored with unbreached package(s) left in place above the EZ (*E2*); or sealed and plugged with WP(s) in EZ (E4).		No	Delay, fishing costs, and loss of disposal capacity (*E1*). For *E2* add costs for long-term (100-year) monitoring.	
F. Normal operations, emplacement of 400 WPs						
F1	Drill-string emplacement		See above	Normal operations	~$18.4 million (differential)	430 to 470 days
F2	Wireline emplacement				0	

Table C-3. Estimated costs for off-normal outcomes of deep borehole waste emplacement.

Costs for Off-Normal Outcomes

Normal rig day rate	75000	$/day
Standby rig rate	30000	$/day
Fishing rate	5000	$/day
Owned rig maint. rate	5000	$/day
# WPs per wireline run	1	
# WPs per string (DS)	40	

	Drill-String		Wireline		
Outcomes	**Days**	**Cost**	**Days**	**Cost**	**Notes**
A1: WP(s) stuck above DZ, breached; fish WP(s) successfully, complete borehole sealing/plugging, no more disposal in this borehole.					
Drill rig or wireline/coiled tubing rig write-offs		$ 30,000,000		$ 20,000,000	Implement early for drill-string mode; could range from $15-50 M
Standby maintenance of operator-owned equipment	730	$ 3,650,000	730	$ 3,650,000	
Fishing	20	$ 1,600,000	20	$ 1,600,000	
Build response facilities		$ 116,000,000		$ 116,000,000	
Response operations		$ 46,000,000		$ 46,000,000	
Waste management		$ 52,000,000		$ 52,000,000	
Handle and remediate WPs fished from borehole		$ 20,000,000		$ 500,000	Assume 40 WPs per drill-string emplacement; one for wireline
Loss of disposal capacity		$ 20,000,000		$ 20,000,000	Expected loss is half of new borehole cost ~$40M (any string or WP)
Long-term site monitoring		$ 36,000,000		$ 36,000,000	
Outcome A1 cost	**965**	**$ 346,207,500**	**965**	**$ 307,507,500**	Include half of normal emplacement cost ($22.6M or $40.0M)
A2: As for A1 but WP(s) not successfully retrieved, but left in place above DZ; partially plug and seal borehole, no more disposal in this borehole.					
A1 outcome	965	$ 346,207,500	965	$ 307,507,500	
Additional standby	365	$ 1,825,000	365	$ 1,825,000	
Credit packages not recovered or requiring remediation		$ (20,000,000)		$ (500,000)	Assume that all packages remain stuck and are left in place
Outcome A2 cost	**1330**	**$ 328,032,500**	**1330**	**$ 308,832,500**	
A3: As for A1 but WP(s) successfully retrieved with guidance casing; complete borehole plugging/sealing, no more disposal in this borehole.					
A1 outcome	965	$ 346,207,500	965	$ 307,507,500	
Configure rig for remote handling of stuck packages inside casing		$ 1,000,000		$ 1,000,000	
Additional fishing time	40	$ 3,200,000	1	$ 80,000	Packages removed at the rate of one per day
Outcome A3 cost	**1005**	**$ 350,407,500**	**966**	**$ 308,587,500**	
B1: WP(s) breached within DZ; no fishing, cement interval, complete borehole plugging/sealing, nore more disposal in this borehole.					
Standby	730	$ 3,650,000	730		Maintain owned rig in place during response planning
Build response facilities		$ 116,000,000		$ 116,000,000	
Response operations		$ 46,000,000		$ 46,000,000	
Waste management		$ 52,000,000		$ 52,000,000	
Drill rig write-off		$ 30,000,000		$ 20,000,000	Implement early for drill-string mode; could range from $15-50 M
Loss of disposal capacity		$ 20,000,000		$ 20,000,000	Expected loss is half of new borehole cost ~$40M (any string or WP)
Long-term site monitoring		$ 36,000,000		$ 36,000,000	
Outcome B1 cost	**945**	**$ 324,607,500**	**945**	**$ 301,757,500**	Include half of normal emplacement cost ($22.6M or $40.0M)

Outcomes	Drill-String Days	Drill-String Cost	Wireline Days	Wireline Cost	Notes
B2: As for B1 but WP breach in DZ is after fishing attempt above the DZ; cement interval, complete borehole plugging/sealing, nor more disposal in this borehole.					
B1 outcome	945	$ 324,607,500	945	$ 301,757,500	
Fishing	20	$ 1,600,000	20	$ 1,600,000	
Standby (incl. de-mob/mob rig)	365	$ 10,950,000	365	$ 10,950,000	Drill rig mobilized WPs stuck using wireline (use standby rate)
Outcome B2 cost	**1330**	**$ 337,157,500**	**1330**	**$ 314,307,500**	
C1: WP(s) dropped into DZ (without drill pipe or wireline), no breach; cement interval, continue emplacement.					
Rig mob./demob.		$ 1,000,000		$ 1,000,000	
Loss of disposal capacity		$ 2,000,000		$ 2,000,000	Assume small (5%) loss of new borehole cost of ~$40M (half of one interval between plugs is cemented without WPs)
Outcome C1 cost	**409**	**$ 42,819,250**	**409**	**$ 25,339,250**	Include 95% of normal emplacement cost ($22.6M or $40.0M)
C2: Junk (drill pipe or wireline) on top of WPs in DZ, no breach; fish junk and packages if attached, cement interval, continue emplacement.					
Rig mob./demob.				$ 1,000,000	Use special rig for fishing wireline, then de-mob.
Fishing	20	$ 1,600,000	20	$ 1,600,000	
Handle and remediate WPs fished from borehole		$ 500,000		$ 500,000	Assume one waste package is recovered during fishing
Loss of disposal capacity		$ 4,000,000		$ 4,000,000	Assume larger (10%) loss of new borehole cost of ~$40M (one interval between plugs is cemented without WPs)
Outcome C2 cost	**407**	**$ 43,823,500**	**407**	**$ 28,263,500**	Include 90% of normal emplacement cost ($22.6M or $40.0M)
D: WP stuck in DZ, no breach; cement interval, complete borehole plugging/sealing; no more disposal in this borehole.					
Rig mob./demob.		$ 1,000,000		$ 1,000,000	
Loss of disposal capacity		$ 10,000,000		$ 10,000,000	Assume 25% loss of new borehole cost of ~$40M (any string or WP; avg. travel through DZ is half, risk is over half that distance traversed)
Outcome D cost	**323**	**$ 42,436,250**	**323**	**$ 28,636,250**	Include 75% of normal emplacement cost ($22.6M or $40.0M)
E1: WP(s) stuck above DZ, no breach; fish WP(s) successfully, complete borehole plugging/sealing, no more disposal in this borehole.					
Fishing	20	$ 1,600,000	20	$ 1,600,000	
Standby (incl. de-mob/mob rig)	365	$ 10,950,000	365	$ 10,950,000	Drill rig mobilized WPs stuck using wireline (use standby rate)
Handle and remediate WPs fished from borehole		$ 20,000,000		$ 500,000	Assume 40 WPs per drill-string emplacement; one for wireline
Loss of disposal capacity		$ 20,000,000		$ 20,000,000	Expected loss is half of new borehole cost of ~$40M (any string or WP)
Outcome E1 cost	**600**	**$ 73,507,500**	**600**	**$ 44,807,500**	Include half of normal emplacement cost ($22.6M or $40.0M)
E2: As for E1 but WP(s) not successfully retrieved, but left in place above DZ; partially plug and seal borehole, no more disposal in this borehole.					
E1 outome	600	$ 73,507,500	600	$ 44,807,500	
Long-term site monitoring		$ 36,000,000		$ 36,000,000	
Additional standby	365	$ 10,950,000	365	$ 10,950,000	
Outcome E2 cost	**965**	**$ 120,457,500**	**965**	**$ 91,757,500**	

Outcomes	Drill-String Days	Drill-String Cost	Wireline Days	Wireline Cost	Notes
E3: As for E1 but WP(s) successfully retrieved with guidance casing; complete borehole plugging/sealing, no more disposal in this borehole.					
E1 outome	600	$ 73,507,500	600	$ 44,807,500	
Configure rig for remote handling of stuck packages inside casing		$ 1,000,000		$ 1,000,000	
Additional fishing time	40	$ 3,200,000	1	$ 80,000	Packages removed at the rate of one per day
Outcome E3 cost	**640**	**$ 77,707,500**	**601**	**$ 45,887,500**	
E4: As for E1 but fishing drops WP(s) to DZ, no breach; cement interval, complete borehole plugging/sealing; no more disposal in this borehole.					
E1 outcome	600	$ 73,507,500	600	$ 44,807,500	
(less costs for handling WPs)		$ (20,000,000)		$ (500,000)	
Outcome E4 cost	**600**	**$ 53,507,500**	**600**	**$ 44,307,500**	
F: Normal disposal emplacement and borehole plugging/sealing.	**430**	**$ 41,915,000**	**430**	**$ 23,515,000**	
* Note that for all outcomes, "normal operations" costs are also accrued prior to the occurrence of the off-normal events.					

C.3 Rough Scope/Cost Estimation Basis for Outcomes with Breached Waste Packages

Boundaries of Analysis:

- During emplacement operations WP is breached
- The package breaches at 16,000 ft depth
- The reason for the breach is not relevant to the analysis
- Downhole closure operations (e.g., borehole sealing) are not included

Assumptions:

- Waste form is Cs/Sr capsules.
- Eight Cs-137 capsules release their contents to the mud-filled borehole.
- Each capsule contains 37.5 kCi of Cs-137 (300 kCi total for 8 capsules).
- Randklev (1994 presentation to Nuclear Waste Technical Review Board) inventory gives 50 MCi for all 1332 Cs-137 capsules in 2020.
- Due to high gamma radiation from Cs-137, many operations must be in shielded facilities and operated remotely.
- Due to transferrable contamination (if contaminated mud dries), many waste management (WM) operations must be in negative-pressure HEPA filtered facilities.
- Due to transferrable contamination, personnel working inside negative-pressure building in respirators.
- Assume original mud volume, plus 3 additional volumes are circulated to remove Cs from borehole ($850 \times 4 = 3{,}400$ m^3).
- Assume 95% of Cs removed by mud circulation, 5% remains in borehole.
- Assume solidification increases volume of mud by 33% (total solidified mud volume ~4,500 m^3).
- Average specific activity of cesium in solidified mud: 300 kCi/4,500 m^3 $\times$ 0.95 = 63 Ci/m^3.
- Solidified drilling mud (at 63 Ci/m^3) would be Class C LLW at generation.
- Assume 100 m^3 for pulled casing
- Volume of personal protective equipment is 5% of total volume
- Volume of waste from decommissioning of facilities assumed as 25% of total volume and will be Class A LLW
- Assume borehole location is several hours drive from major city

Other Inputs:

- Mud volume is ~ 850 m^3 (22" to 1,500 m and 16" from 1,500 to 5,000 m)
- 4.5" drill pipe has volume of 52 m^3 for 5 km of pipe (18,000 lb/m^3)
- Squeegeed casing and drill pipe will be Class A LLW
- Drill rig weight is equivalent to 135 m^3 of steel
- Very limited contamination of drill rig – possibly disposed in industrial landfills as allowed under 10CFR20.2002.

Facts about Cs-137:

- Managed as gamma-emitter (Cs-137 (half-life 30.2 years) decays by beta to Ba-137 (half-life ~2 minutes) which decays by gamma

- Rule of thumb dose rate: 0.33 rem/hour/Ci at 1 meter (from direct gamma, inhalation dose will be much higher)
- Highly soluble in water as chloride salt or melt

Overview of Response Actions:

- Release of Cs-137 will be detected in downhole detectors (wireline or drill-string instrumentation) or mud handling equipment
- All operations stop
- Emergency Operations Center engaged
- Mud handling equipment enclosed in high-density polyethylene, personnel surveyed, etc.
- Response & Closure Plan written, approved – 1 year required plus additional regulatory review
- Build facilities and equipment listed below
- Conduct on-site response and recover operations
- Ship wastes off-site
- Decommission site infrastructure
- Ship decommissioning wastes off-site
- Implement long-term site monitoring program

Response Facilities:

1. Facilities for Management & Personnel – Additional portable buildings for operations management, health physics, industrial safety, response personnel, storage, etc.
2. Facilities for Managing Contaminated Mud
    a. Remote controlled, mud handling system inside a shielded hot cell, that is inside a building with negative pressure. Four shielded tanks for mud storage.
    b. Remote controlled & shielded WM facilities to solidify contaminated mud in 1 m^3 containers, includes shielded storage area for 4,500 1-m^3 containers
3. Facilities for Managing Contaminated Drill Pipe and Casing
    a. Remote controlled, drill pipe and casing handling system inside a shielded hot cell, that is inside a structure with negative pressure, to pull, coat with fixative and cut drill pipe and casing to 3-m lengths, which are stored in 15 m^3 boxes
    b. Storage building for storage of packaged drill pipe and casing
4. Drill Rig Management
    a. Building for long-term storage of packaged drill rig

Response Operations:

- Staffing:
    - Response management & support personnel: 11 people
        - Project management (1)
        - Health physics (2)
        - Industrial safety (2)
        - Security (5)
        - Project controls (1)
    - Response personnel, both drillers and WM personnel: 15 people
- Training and qualifications, procedures, quality assurance, cold test of operations, repairs, etc.

- With shielded, remote-controlled equipment, circulate fresh mud to reduce contamination in borehole; assume 4 borehole volumes of mud (3,400 m^3 total); store in four shielded tanks
- With shielded, remote-controlled equipment, solidify drilling mud with solidification agent; store solid mud in 1-m^3 containers; adds 33% to volume giving ~4,500 m^3; store the 4,500 containers
- Use contaminated drill pipe to seal and close borehole (not costed)
- With shielded, remote-controlled equipment, pull contaminated casing, wipe it down, decontaminate, coat with fixative, and cut into 3-m long sections
- With shielded, remote-controlled equipment, pull contaminated drill pipe, wipe it down, decontaminate, coat with fixative, cut into sections 3 m long, store in 15-m^3 boxes
- Disassemble drill rig, cut drill rig into sections 3-m long; store in roll-offs
- Ship wastes off-site
- Decontaminate remaining facilities
- Ship additional wastes off-site
- Conduct long-term site monitoring

References for Appendix C

Arnold, B.W., P. Brady, M. Sutton, K. Travis, R. MacKinnon, F. Gibb and H. Greenberg 2014. *Deep Borehole Disposal Research: Geological Data Evaluation, Alternative Waste Forms, and Borehole Seals*. FCRD-USED-2014-000332. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

Randklev, E. 1994. “Disposal of Hanford Site Cesium and Strontium Capsules.” Nuclear Waste Technical Review Board, Engineered Barrier System Panel Meeting, Richland, WA. June 15, 1994. (www.nwtrb.gov).

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Appendix D. To-Be-Determined Items for the DBFT

These items (Table D-1) were developed from previous work (SNL 2015) and review (AREVA 2016), and updated for the present conceptual design report. Some are directly relevant to the DBFT engineering demonstration (and thus to a future DBD project), and some are relevant only to DBD and are beyond the scope of the DBFT. It is intended that these TBDs will be tracked going forward during the DBFT design process, for completeness and to facilitate smooth transition to an engineering services contractor.

References for Appendix D

AREVA (AREVA Federal Services) 2016. *Task Order 22 – Engineering and Technical Support, Deep Borehole Field Test: AREVA Summary Review Report*. RPT-3014934-000, AREVA Federal Services LLC, Charlotte, NC.

SNL (Sandia National Laboratories) 2014. *Sandia National Laboratories QA Program Interface Document for FCT Activities*. FCRD-TIO-2011-000032, Rev. 3. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition. October, 2014.

SNL (Sandia National Laboratories) 2015. *Deep Borehole Field Test Specifications*. FCRD-UFD-2015-000132 Rev. 1. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition.

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Table D-1. To-be-determined items for DBFT engineering demonstration.

TBD No.	CDR Reference	Description	Work Scope Affected	Working Assumption Basis/Resolution Path for DBFT	Proposed Resolution Path for Radioactive Waste Disposal
TBD-01	§2.3.1 §2.3.2 Table 2-3	To meet industrial safety and health requirements and radiological protection requirements for DBD activities, a broad framework would be used in design, encompassing radiological exposure and dose, nuclear criticality, QA, and so on. The particulars of such a program are beyond the scope of the DBFT, and are TBD.	DBD Only	Not applicable	Define a broader engineering development process and regulatory requirements for DBD.
TBD-02	§2.3.3 Table 2-3	Safeguards and security requirements for DBD of radioactive waste are TBD.	DBD Only	Not applicable	Develop safeguards and security requirements for DBD.
TBD-03	§2.3.4 Table 2-3	QA requirements for DBD are TBD.	All deep bore holes drilled	The UFD R&D program QA program (SNL 2014) will be used with assigned rigor level QRL 3. Data collected from the DBFT will not necessarily be used for future disposal licensing.	Develop QA requirements for DBD.
TBD-04	§2.3.5 Table 2-3	The NEPA is applicable to borehole disposal activities but specific details are TBD.	FTB and DBD	Appropriate NEPA assessment (e.g., categorical exclusion or EIS) will be determined and implemented prior to initiating field activities for the CB and FTB.	10CFR51 may be applicable, which could require an Environmental Impact Statement.
TBD-05	§2.3.5 Table 2-3	Waste disposal boreholes may be classified as injection wells in accordance with 40CFR144, but the applicability of this regulation to future DBD is TBD.	DBD Only	Not applicable	Pursue ruling on applicability of Underground Injection Control requirements to DBD.
TBD-06	§2.3.6 Table 2-3	Disposal activities will be performed in a manner consistent with long-term waste isolation, in accordance with a safety strategy that is TBD.	DBD Only	The DBFT strategy is to prevent package breach during handling, transfer, emplacement and retrieval operations, thereby demonstrating the safety and feasibility of DBD of radioactive waste.	The overall waste isolation strategy will be determined after waste type, engineered system design, and site-specific factors are determined.
TBD-07	§2.3.1 §2.3.7 Table 2-3	Operational requirements for DBD operations are TBD.	DBD Only	Not applicable	To be developed based on experience from the DBFT.

TBD No.	CDR Reference	Description	Work Scope Affected	Working Assumption Basis/Resolution Path for DBFT	Proposed Resolution Path for Radioactive Waste Disposal
TBD-08	§2.3.8 Table 2-3	Select drilling and construction methods that will lead to successful completion, promote waste isolation performance, and achieve characterization objectives.	CB, FTB, and DBD	Drilling and construction of the CB and FTB will allow collection of needed data.	The methods to be used and the types of data to be collected are TBD, and will be based on DBFT experience.
TBD-09	§2.3.8 Table 2-3	Design requirement that ensures sufficient service life for construction materials used in DBD boreholes is TBD (see TBD-32).	DBD Only	Service lifetime of materials and components used for constructing the FTB shall be 10 years, considering corrosion, creep, etc. The chemical environment is TBD.	Service lifetime for borehole construction materials may be reassessed based on site-specific information and corrosion testing.
TBD-10	§2.3.9 Table 2-3 Table 2-4	Maximum dogleg severity for waste disposal boreholes is TBD.	FTB and DBD	Maximum dogleg severity is assumed for the DBFT to be 3° per 100 ft (2° per 100 ft. in the upper 1 km) (Table 2-4).	To be developed based on experience from the DBFT.
TBD-11	§2.3.9 Table 2-4	Any requirement for directional drilling for disposal boreholes is TBD.	FTB and DBD	Directional drilling is planned for the FTB but the drilling method will be finalized in the Drilling & Testing Plan.	To be developed based on experience from the DBFT.
TBD-12	§2.3.9 §2.3.10 Table 2-3	Requirements for managing degradation of yield strength, thermal expansion, etc., in DBD are TBD.	DBD only	A heater test is not currently planned for the DBFT.	Management of yield strength, thermal expansion, etc., will be developed using experience from planned DBFT activities.
TBD-13	§2.3.10	Package internal cavity length may be up to 5 m, but the actual length for disposal WPs is TBD.	DBFT Test Packages and DBD	Package overall length for the DBFT is assumed to be up to 4.5 m (fits inside the LWT transport cask, Table 2-3).	Will be addressed in design for a future DBD system, with experience from the DBFT.
TBD-14	§2.3.9 §2.3.10 Table 2-3	WP radial clearance for disposal packages is TBD.	DBFT Test Packages and DBD	The current concept uses a gap that ranges from approximately 11/16” to 13/16” for large (11-inch nominal OD) reference packages. Gap clearance will depend on final design of the test packages, and whether the casing drift drift diameter or nominal ID is used to control the gap.	This will be developed based on experience from the DBFT.
TBD-15	§2.3.10 §2.4 Table 2-3 Table 2-4	The maximum pressure for actual WPs is TBD because it depends on the properties of the emplacement borehole fluid.	FTB and DBD	The DBFT test packages and emplacement/retrieval will be demonstrated using the bounding maximum and minimum depth-averaged	Actual emplacement fluid density will be determined at least in part by experience from the DBFT.

TBD No.	CDR Reference	Description	Work Scope Affected	Working Assumption Basis/Resolution Path for DBFT	Proposed Resolution Path for Radioactive Waste Disposal
		Loaded and sealed WPs shall have negative buoyancy in emplacement fluid (density TBD). The maximum emplacement fluid density for DBD is TBD.		fluid density of 1.3× and 1.0× density of water, respectively.	
TBD-16	§2.3.10 & Table 2-3	For disposal overpacks (if used) and WPs used in DBD, the design safety factor is TBD.	FTB and DBD	A FoS of 2.0 will be used per the stated requirement (Table 2-3) for normal conditions. Off-normal conditions will be evaluated separately.	Determine appropriate FoS for rigging, wireline cable, etc. May be subject to a consensus lifting standard used in the nuclear industry.
TBD-17	§2.4 Table 2-4	The maximum test package temperature in the FTB is assumed to be 170°C.	FTB	Based on assumed surface temperature of 20°C and geothermal gradient of 30°C/km (Section 2.4). Bottom-hole temperature for disposal boreholes will be site-specific.	Not applicable
TBD-18	§2.3.10	Maximum package wall temperature is assumed to be 250°C for DBD.	DBD Only	Not applicable because thermal (heated) testing is not planned for the DBFT (see TBD-12).	Develop requirements for disposal packages based on waste characteristics, package size, and other specifications.
TBD-19	§2.3.10	WP containment longevity is required during operations, but material selection criteria are not determined (see TBD-32).	DBD and DBFT	A material selection decision will be made during design for the DBFT. Longevity is a secondary concern because DBFT test packages which will be retrieved immediately.	Develop requirements for disposal including WP containment longevity, based on site-specific information.
TBD-20	§2.3.10 §2.4 Table 2-4	Leakage control requirements for WPs during DBD operations, and for test packages in the DBFT, are TBD.	DBFT Test Packages and DBD	A leak detection strategy will be used with drop testing, pressure testing, etc., and for the field demonstration. This strategy is TBD during design.	Develop leakage and containment performance requirements for WPs.
TBD-21	§2.3.10	Downhole instrumentation for use during emplacement.	DBD and DBFT	The DBFT will include at least one instrumentation test package with capability as discussed in Section 2.3.10.	Design of downhole instrumentation for DBD will use experience from the DBFT.
TBD-22	§2.3.12 Table 2-3	The need for wellhead BOPs for DBD boreholes and DBFT boreholes is TBD.	FTB and DBD	Test WP emplacement and retrieval equipment will be designed to function with or without BOPs in place on the FTB wellhead. The required pressure rating for DBFT well control is TBD.	Assume BOP equipment will be required. Design the BOP and the BOP controls to ensure protection of WP, drill-string, and/or wireline from inadvertent damage.

TBD No.	CDR Reference	Description	Work Scope Affected	Working Assumption Basis/Resolution Path for DBFT	Proposed Resolution Path for Radioactive Waste Disposal
TBD-23	§2.4 Table 2-4	Waste forms to be considered in a future DBD system are TBD.	DBD Only	No radioactive waste will be used in the DBFT. (Note that the DBFT will explore technologies that might be used for DOE-owned granular waste forms, and HLW in sealed capsules such as the Cs/Sr capsules or HLW glass.)	Resolution path for DBD is out of scope for DBFT and will depend on the disposal mission.
TBD-24	§2.4 Table 2-4	Borehole total depth for DBD is TBD.	DBD Only	Stated DBFT assumption of 5 km (Table 2-4).	Borehole depth for DBD will be developed from site-specific information and experience.
TBD-25	§4.2	Number and types of test packages for the DBFT engineering demonstration.	DBFT	Choose to design, fabricate, test and demonstrate two or more test packages (in addition to one or more instrumentation packages), of one or more designs (e.g., flask-type and internal semi-flush).	Not applicable
TBD-26	Table 2-4	Long-term control and ownership of sites for DBD are TBD.	DBD Only	Not applicable	Site ownership for DBD is beyond the scope of the DBFT.
TBD-27	§2.4	Maximum and minimum weight of disposal WPs are TBD.	DBD Only	For the DBFT, maximum weight for a reference-size test package is estimated based on a load of consolidated SNF rods.	Design of the disposal system for DBD will use experience from the DBFT.
TBD-28	§2.3.11	Emplacement fluid viscosity, density, salinity, and other properties are TBD.	FTB and DBD	Fluid composition for the DBFT demonstration will be selected to be representative of fluid that would be used for DBD boreholes, within the range of fluids evaluated for sinking velocity, and is TBD.	Selection of emplacement fluid for DBD will use experience from the DBFT.
TBD-29	§2.9	Mechanical details of the transfer carrier are TBD. (Note the transfer carrier, as described in Section 2.9.1, is the trolley-like device for moving and positioning the transfer cask under the drill rig.)	FTB and DBD	Not applicable because wireline emplacement is planned.	The emplacement system for DBD will be based on experience from the DBFT.
TBD-30	[Reserved]				

TBD No.	CDR Reference	Description	Work Scope Affected	Working Assumption Basis/Resolution Path for DBFT	Proposed Resolution Path for Radioactive Waste Disposal
TBD-31	§2.3.12 §2.4	Wireline tension (wireline fully deployed, WP, tool string, etc.) shall not exceed the service limit of the wireline and emplacement equipment, with an appropriate FoS.	FTB and DBD	Limit wireline tension to 12,000 lb so that a capstan does not need to be used.	Use experience gained from the DBFT.
TBD-32	§2.3.10	The chemical environment in DBD boreholes during operations and postclosure is TBD (see TBD-9, TBD-19, TBD-40 and TBD-43).	DBD and DBFT	Assume that test packages will be exposed to multi-molal concentrations of chloride, Na, Ca, and possibly Mg ions (see TBD-17 for temperature) but that they will be retrieved immediately.	WP and borehole design for corrosion response will depend on site-specific data, possibly supported by material corrosion testing.
TBD-33	§2.9	The type of damage to WPs caused by drill rig functions during emplacement or fishing operations is TBD.	FTB and DBD	Normal emplacement operations will be demonstrated by the DBFT (fishing is not planned).	If used, this equipment will be developed based on experience and data from the DBFT.
TBD-34	§5.4 §5.5 §5.6	Terminal velocities for disposal applications are TBD.	FTB and DBD	Assume terminal velocity of 3 m/sec does not breach packages on impact.	The emplacement system for DBD will be based on experience from the DBFT.
TBD-35	§2.4 §5.2 §5.3	The time frame for actual disposal is TBD.	DBD Only	No *in situ* thermal test is planned for the DBFT.	Emplacement date for Cs/Sr capsules, for thermal analysis, is assumed to be 2050.
TBD-36	§2.4 §5.3	The permeability of the borehole and surrounding disturbed rock zone is TBD.	DBD Only	Permeability of the DRZ (and host rock) is assumed for thermal-hydrologic analysis (Section 5.3).	Performance of a DBD system will be analyzed using site-specific data and experience from the DBFT.
TBD-37	§2.3.11	Shielding requirements for DBD transportation, handling, transfer, and emplacement equipment are TBD.	DBD Only	Shielding will be simulated by calculating the shielding required for a representative waste and simulating the use of that shielding during the DBFT.	Determine shielding requirements when the waste disposal mission is defined.
TBD-38	§2.3.11	Well control requirements for the transfer cask and associated surface equipment for DBD and for the DBFT are TBD.	FTB and DBD	Pressure rating for the DBFT transfer cask and related equipment, for containing wellbore pressure, will be determined from site-specific data and input from drilling permit regulator.	Determine requirements from DBFT experience, site-specific information, and regulatory input.
TBD-39	§2.3.12	Retrievability and reversibility (as applicable) requirements for future DBD are TBD.	DBD Only	Not applicable	Regulatory input is needed; beyond the scope of the DBFT.

TBD No.	CDR Reference	Description	Work Scope Affected	Working Assumption Basis/Resolution Path for DBFT	Proposed Resolution Path for Radioactive Waste Disposal
TBD-40	§2.3.10	Package containment may be required after DBD boreholes are closed, depending on safety strategy and regulatory requirements (see TBD-19 and TBD-32).	DBD Only	Not applicable	Safety strategy will be developed based on site-specific information and regulatory input.
TBD-41	§2.4 and Table 2-4	WP strings or stacks are limited to 40 WPs, consistent with the reference design, but the configuration for DBD is TBD.	FTB and DBD	Guidance casing will not be loaded by test packages in the DBFT, but the stack limit still applies to protect WPs.	Additional testing and analysis will optimize WP loading arrangements for DBD.
TBD-42	§2.6	Overburden sediments could be overpressured, requiring special well control measures, and possibly exceed the external pressure limit for intermediate casing.	FTB and DBD	Overpressure sufficient to damage casing is unlikely if the wellbore fluid density is reasonably balanced with formation fluid density.	TBD for DBD based on site specific data.
TBD-43	§3.1	Corrosion rate and hydrogen generation rate of materials in the borehole, and the potential for excessive pressure to damage plugs, seals, or packages, are TBD (see TBD-09, TBD-19 andTBD-32).	DBD Only	The FTB will not be plugged/ sealed, and the DBFT will be conducted in a relatively short time, so gas pressure cannot damage plugs or seals.	EZ completion and material selection for DBD will be based on analysis that includes corrosion and gas generation, and is TBD.
TBD-44	§2.3.10	WP end fittings for DBD are TBD.	DBD Only	Threaded connections are required for DBFT test packages: 1) for attachment of latch, impact limiter, etc.; 2) for connecting multiple packages in future tests as applicable; and 3) as backup seals for welded plugs.	Once the design of the WP and emplacement mode for DBD is mature, a determination will be made whether threaded connections are necessary.
TBD-45	§2.3.11	The means of package transport for DBD (e.g., LWT, heavy-haul, rail, etc.) is not determined.	DBD Only	Test packages will be transported for the DBFT by legal-weight truck.	Transportation modes will be determined from site-specific information.
TBD-46	§2.3.13	Compatibility between plugs and seals in the sealing zone, and other components of the DBD system.	DBD Only	Not applicable	TBD for DBD based on a seals R&D program, and possible future *in situ* tests.

TBD No.	CDR Reference	Description	Work Scope Affected	Working Assumption Basis/Resolution Path for DBFT	Proposed Resolution Path for Radioactive Waste Disposal
TBD-47	§2.3.9 Table 2-3 §3.1	The manner of perforating the guidance casing is not yet determined.	DBD and FTB	Refine predictive model for sinking velocity, and develop a perforation scheme for the FTB, with an explicit prediction for a free drop test, and a program for pre-fabricating the perforations.	To be developed based on experience from the DBFT.
TBD-48	§2.3.10 Table 2-3	Waste packages shall maintain mechanical integrity during transport, handling, emplacement, plugging, and sealing. Mechanical load limits for WP design are not yet determined.	DBD and DBFT	Develop a design basis to understand the types of drops that are likely. Mechanical integrity specifications need to reflect needed mechanical integrity.	To be determined once the waste forms to be disposed of are identified, a site is selected, and other engineering features are decided.
TBD-49	§2.7.4 §3.1 §4.1	EZ completion option determines how cementing will be done, as well as the perforation scheme (see TBD-47).	DBD	Use reference concept (Sections 3.1 and 4.1) for the FTB but without cementing the EZ or installing plugs.	Use recommended option 2 (Sections 2.7.4 and 3.1) subject to further design and performance analysis.
TBD-50	§2.3.12 §3.3	Side latch mechanism for transfer cask.	DBD and DBFT	Develop latch mechanism during design.	To be developed based on experience from the DBFT.

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